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Master Thesis

Towards Inclusivity: Virtual Reality Museums for the Visually Impaired

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Abstract

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Visually impaired (VI) adolescents often partake less in leisure activities, such as visiting cinemas, theatres, and museums, than their sighted peers. Art can play an important role in developing the intellectual and personal growth of young people. As such, ensuring that the visually impaired have access to museums and their art from a young age is especially important. Technologies such as virtual reality provide users easy access to virtual content. These technologies often rely on ordinary visual interfaces, meaning the visually impaired do not have (unrestricted) access to them. This thesis aims to develop an altered version of a virtual reality museum that can be adequately experienced by visually impaired teenagers.

The virtual reality museum consists of historic figures and artifacts, which can be interacted with to prompt animations, sound effects, or narrative voice-lines. A between-subjects study was designed in order to explore if narrations and spatialized 'reference' audio combined with haptic feedback is a sufficient replacement for the traditional use of vision. Alongside the visually impaired and the sighted version, a blindfolded version was created, which blocks all vision in its entirety and was played by several sighted participants to get supplementary data to that of the visually impaired.

Although significant differences were found in the mean accuracy of each of the three versions, all three participant groups managed to successfully interact with all virtual objects. The pace at which they did this was statistically equivalent, suggesting the adapted interaction method is just as fast to use, just slightly less accurate. An additional steering method was added for the visually impaired version, which uses auditory and haptic feedback to steer players towards specific virtual objects. This method allowed users to find objects even faster, but due to a lack of clear feedback was found to be somewhat confusing. Even though there was no statistical equivalence in audio understanding, presence, and understanding of the environment, the visually impaired participants positively graded these in the qualitative survey. As such, it can be concluded that even though the visually impaired did not have a fully statistically equivalent experience as the others, they were able to adequately experience the virtual reality museum.

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List of Abbreviations

VI	**V**isually **I**mpaired
SI	**Si**ghted
BF	**B**lind**f**olded
VR	**V**irtual **R**eality
HMD	**H**ead **M**ounted **D**isplay
HRTF	**H**ead-**R**elated **T**ransfer **F**unctions

1 Introduction

It is estimated that 285 million people worldwide have a visual impairment [1]. Visual impairment is defined as an impairment that affects vision that cannot be fixed by any corrective lenses [2]. The most extreme visual impairment is blindness, which 39 million people are conditioned with worldwide. Blindness ranges from legal blindness to complete blindness. Complete blindness means the person is unable to see at all, whereas legally blind people might still be able to differentiate lightness from the darkness. The final category of visual impairments refers to being able to see less than 30% or having a field of view (FoV) of 30 degrees or less [1]. This is referred to as 'low vision' which could cause confusion with the common use of this term. As such, Dandona and Dandona suggested replacing the term 'low vision' with mild or moderate visual impairment [3]. In the Netherlands over 250.000 people have a visual impairment [4], of which 2500 are students [5].

Research showed that adolescents that are visually impaired partake in less leisure activities than their sighted peers. These mentioned activities include visiting cinemas, theatres and museums [6]. Art can serve as a catalyst for intellectual and personal growth in young people and it can significantly impact the way they learn [7]. This is especially important for adolescents, whose internalized values, skills they learn, decisions they make, and dreams they plant have a lifelong impact [8]. As such, it is important for museums and their art to be accessible to everyone from a young age.

Research showed that VI students mainly use computers for schoolwork and looking up non-school-related information. Computers allow them to stay connected with sighted peers and help them cope with their impairment [9]. New technologies increasingly shape children's home lives. Most of these technologies are playful by nature [10]. Findings indicate that virtual worlds offer a variety of opportunities for play (engaging in a recreational activity) and similar interactions, which closely resemble 'offline play' [11]. Virtual play often relies on ordinary graphical interfaces, which VI people do not have (unrestricted) access to. This causes VI individuals to miss out on an important part of youth culture [12].

Inclusivity guidelines were designed to prevent these kinds of disconnections from happening [13]. Inclusivity refers to ensuring a combination of experiences is equally great for each individual. This does not mean that every element should be accessible to everyone. Rather, experiences should be perceived similarly by people with a variety of disabilities and/or personalities. Because online play closely resembles offline play, improving virtual play inclusivity can likely be done with similar success by following real-world play inclusivity guidelines. Sensory Trust, a leading authority on inclusive and sensory design, has published five guidelines for designing inclusive play on their website, which are: 1) Create a rich mix of play opportunities, 2) Engage the senses, 3) Make different types of space, 4) Make it accessible, and 5) Don't forget parents and families [13]. These guidelines can also be applied to virtual experiences. By doing so, people with different disabilities get the chance to interact with multimedia, which in turn makes them feel better included in society [14].

1.1 Problem statement

Many cultural organizations use Augmented Reality (AR) and Virtual Reality (VR) in an attempt to enhance the visitor experience [15]. Art placed in a three-dimensional world has the potential to increase the immersion of the experience, by allowing for a deeper impression. This effect can be especially prominent for children [16]. Presence is the illusion of being in the virtual world. By using convincing images and sound, the user can feel as though they are really there. Although presence can be achieved when only using simulated virtual worlds, Roussou suggests adding interactivity to the virtual experience [17]. This entails that the user is not merely a viewer of the scenery, but can actively participate in the program and directly influence their experience. Walczak, Cellary and White mention how virtual exhibitions allow a variety of audiences, including students and the disabled, to access various localities in an engaging and informative manner [18]. Although VR can make information and experiences more accessible to some, the visually impaired often cannot make use of these technologies due to these technologies' reliance on vision.

Improving technologies for the visually impaired has been investigated for decades. The main focus has mostly been on improving the accessibility of video games, and mobility and navigation training. To make video games more accessible for VI players, audio games were introduced. Audio games use auditory interfaces to represent game elements without the need for visuals [19]. Other types of feedback, such as haptic feedback, can also be used to convey visual information for the user. Auditory and tactile feedback are often used as assistance technologies for the visually impaired [20]. Within this context, when vision is replaced by another sense, it is called cross-modal transfer. When multiple senses are stimulated at once to convey the same message, it is called multi-sensory stimuli [21].

With the rise of technologies such as virtual reality comes the question of what role it can play for the visually impaired. A lot of prior research focuses on how virtual reality can help train VI individuals with e-learning and navigating [22]. To help VI individuals navigate a virtual environment, advanced wearables and (haptic) accessories are often used. A few have also attempted to create virtual reality games that are playable by visually impaired individuals. 'Showdown' was created as one of the first VR games for VI players [23]. The game uses auditory feedback to communicate the location of a ball that the player needed to hit. A follow-up study was later released introducing a collaborative mode to the game, which was tested by both able-bodied and visually impaired players [24]. 'BongoBeats' is a physically active rhythm game targeted toward visually impaired players that requires players to hit notes at the right time [25]. By using a VR set, track-able controllers were easily added to the game, despite the fact that the Head-Mounted Display (HMD) of the VR set was not actually used. Despite the increase in popularity of creating VI suitable VR games, interactive VR exhibitions remain untouched.

1.2 Research approach

That brings us to the main topic of this thesis. This research will investigate how interactive virtual reality museums can be designed so that visually impaired individuals can experience them similarly to how sighted individuals can. To achieve this, three sub-questions need to be discussed:

- Q1: *"How can virtual reality spatial awareness be facilitated for the visually impaired?"*
- Q2: *"How can the controls be adjusted so that VI can successfully interact with the environment?"*

- Q3: *"How can historic figures and artifacts of a virtual museum be represented for the visually impaired?"*

An existing interactive VR museum will be used for the implementation. This VR museum allows for self-exploratory interaction with virtual artifacts and historic figures. Upon interaction, a narrator provides background information about the historic figures, and the objects play an animation or sound effect. Players are able to navigate this virtual world, but this is not an essential part of the experience. As such, the adapted version for VI will focus on the interactivity with the environment.

The first research goal will lead the literature review into spatial audio for the visually impaired. Common techniques for representing location without the use of vision will be discussed. These should help users recognize what can be found in the virtual environment, and where these objects are. The second research goal is to investigate existing technologies for VI. Reviewing which implementation features worked and which did not should provide a direction in which the existing VR experience can be altered to make it accessible for VI visitors of the museum. Sonification and haptics will be discussed for the final research question. These are examples of techniques that are used to represent visual data using non-visual senses. Every object in the environment should be represented in a non-visual way, using one of these techniques. Together, the answers to the sub-questions should help with tackling the main research problem of this thesis:

P: *"Create an altered version of a virtual reality museum that can be adequately experienced by visually impaired teenagers"*.

2 Related Work

2.1 Impact of visual impairments on life

Individuals with a visual impairment experience restrictions in their daily life. Visually impaired children exhibit lower levels of fitness than their sighted (SI) peers [26]. On health-related fitness tests, VI children perform significantly worse than their sighted peers [27]. Although they tend to have proficient motor skills, they often lack the experience to be on the same developmental level as sighted individuals [28]. Because of this, a lot of VI research is dedicated to helping VI with experience-related tasks, such as navigating (virtual) environments [29].

2.1.1 Spatial awareness

In order to successfully navigate an environment, visually impaired individuals need to be aware of their surroundings and their own body. Awareness of the surroundings is also referred to as 'spatial awareness', defined as the ability to accurately locate objects in space, and position the body parts in order to make contact with these objects [30]. VI children tend to struggle with even simple auditory spatial tasks. The capacity of their spatial awareness tends to recover over time until they are adults [31]. To help speed up recovery, several studies attempted to assist VI children with improving their spatial awareness, allowing them to navigate and locate surrounding objects more easily. Freeman et al. used remote audio devices to improve orientation and navigation for the visually impaired [32]. The authors concluded that 'reference' sounds were best received, due to their similarity to real-world sounds. The sound would be played at fixed locations so that they could be used as reference points, allowing VI participants to use audio to navigate. The audio encouraged them to walk closer to the landmark. For presenting information, speech was the preferred method, as non-speech audio might be ambiguous or mistaken for ambient noise. Other common tracking systems, such as Wi-Fi, computer vision and GPS tend to have issues with precision or reception [33]. Technologies such as virtual reality have all trackers built into the equipment, and all spatial awareness training that is done is directly transferable to real life [34]. Virtual reality is a realistic simulation that can be interacted with in real-time, using real-world tracking data, such as the gaze direction of the user. Section 2.3: Virtual Reality further elaborates on the technology. Virtual reality interferes less with the daily life of VI than other tracking systems, while still being very potent [33].

2.1.2 Social lives

Besides the mobility restrictions, social lives are also negatively affected. Adolescents with a visual impairment struggle more with socializing with their peers than sighted individuals [35]. Higher severity of visual impairment is associated with smaller friendship networks and less success with forming romantic relationships [36]. VI individuals might experience low levels of educational achievements, lower workforce participation, and even social isolation [37]. Depression and anxiety are also more common compared to sighted individuals [38].

2.2 Inclusive play

Sensory Trust has published guidelines for designing inclusive play, which can be applied to virtual play as well [13]. The first guideline suggests providing a variety of activities in order to include physical, creative, and social activities. Stimulating all senses benefit the children that partake in the activities, according to the second guideline. The third guideline mentions that children with sensory impairments, such as the visually impaired, also need to be actively taken into account when designing activities. The final guidelines are achieved by making the activities accessible for both the able-bodied, such as friends and family, and the target audience, such as the visually/physically impaired or individuals with autism. Inclusivity is achieved when there is no segregation between separate groups. Segregated design, which refers to designing for only one specific target group, often leads to accessible products that are of lower quality than their inaccessible "mainstream" counterparts. This design model is disliked by many disabled individuals, as they would rather have a similar experience as everyone else. To achieve this, designs should keep these target groups in mind from the beginning [39].

2.2.1 Games for VI

To make video games more accessible for the visually impaired, developers often make use of auditory stimuli. Games that use audio as the main stimuli for communicating gameplay elements are called audio games [19]. Audio games are split up into two different categories: *audio-only* games and *audio-based* games. In audio-only games, there are no visual stimuli at all, whereas in audio-based games there is some supportive visual content that is non-essential for the gameplay [40]. By having some visuals in audio-based games, sighted individuals have a chance to see other people play, and low-vision players might still be able to use their vision to some extent. Audio games often use text-to-speech for communication with the player, while also having simple designs that do not offer the complexity found in regular games [41]. Although audio games are a step in the right direction toward VI inclusivity, they still lack behind regular video games. That being said, some audio games were successful in providing entertainment for visually impaired players. In audio games, audio is used for communicating cues, instructions, and events to the player. All of these can be applied to interactive exhibitions as well. As such, it is valuable to look at examples of existing audio game research to see what worked well and what did not.

Glinert developed a rhythm game that could be played with controllers [2]. These controllers improved the overall enjoyability, although a lack of feedback and instructions caused some frustration among VI players. The author expects that with proper feedback and controls instructions, controllers can be a valuable asset for audio games. 'BongoBeats' followed this advice and used intuitive physical movements for the controls of the game, turning it into an exergame (a portmanteau of "exercise" and "gaming"). Participants had to 'slam' notes on the beat of the song. One flaw of the game was the lack of auditory feedback regarding player performance, where the player would only hear audio of whether they hit or missed a note, without indicating how well it was timed [25].

The next logical step is to create games for virtual reality (VR), where the increased immersion and improved tracking can lead to an overall better user experience. Although very little research has been done on VR VI games, Section 2.8: Virtual Reality Entertainment for Visually Impaired discusses the work that has been done thus far and how promising the results were.

2.3 Virtual Reality

2.3.1 Properties

Virtual Reality (VR) is a simulation of realistic-looking worlds that can be interacted with in real-time. These realistic-looking worlds unify realistic realities with artificial reality. The user's head, hands, and/or limbs are typically measured for the purpose of view control, object manipulation, and locomotion. Head tracking is done using a head-mounted display (HMD), which also contains two lenses allowing the user to see the virtual world with both eyes. Hand tracking is often done using controllers, which also contain buttons that can be pressed for specific interactions. The combination of head and hand tracking can be used to accurately track the user's movements. For additional realism, a virtual avatar or body is sometimes mapped to the user, perfectly replicating the user's real-life movements [42].

2.3.2 Immersion and presence

Virtual reality is often associated with high levels of immersion. Immersion is defined as how capable a system is to influence the involvement of the user [43]. In virtual reality, immersion is achieved by closely representing equivalents of real-world elements in a virtual environment. These real-world elements include human characteristics, such as the field of view and stereoscopic aspects like "surround sounds" [44]. By using a variety of human sensorial channels, virtual reality is able to provide an immersive experience.

Presence refers to "the feeling of being there" [43]. Using virtual reality equipment, users are able to enter the state of presence, which is a psychological, perceptual-cognitive consequence of immersion [45]. To achieve presence, three different criteria need to be met [46]:

- Players become less self-aware and less worried about everyday life or self.
- Players should feel emotionally involved in the game.
- Players should feel viscerally involved in the game.

Immersion has similarities with Czsentmihalyi's concept of flow [47], which can be achieved by finding a balance between the skills of the player and the difficulty of certain challenges. Both immersion and flow result in high engagement, which can be especially beneficial in educational contexts [48]. Virtual reality can thus be an effective tool for making students more engaged in learning [46].

2.3.3 Haptics

Virtual reality HMDs are often accompanied by handheld controllers in commercial VR sets (see Figure 2.1). These controllers are used for most of the interactions, as well as able to provide haptic feedback. Haptics refers to the sense of touch, for example through vibration. This type of feedback is often used for providing feedback after an event has happened. Haptic feedback has also been used for alerting players of upcoming cues [49], as well as conveying spatial information, such as the location of objects [50]. Haptic feedback is argued to be better suited for communicating information than audio [51], as it complements how VI people often use their sense of touch when exploring an environment [52]. Wagensveld and Zaal used haptic feedback to communicate upcoming events through anticipatory cues, as well as communicate immediate actions that the player needed to make. By implementing different patterns and magnitudes of vibrations for these purposes, the game was playable by both sighted and visually impaired players with similar performance [25]. Haptic feedback has also been added to walking canes in several studies with great success [53, 54, 55]. By adding vibration to the canes, participants experienced high levels of immersion [53]. These studies will be further discussed in Section 2.5: Visually impaired Navigation.

FIGURE 2.1: Virtual Reality Set from HTC [56]

Haptics has also been used for very specific use cases for the visually impaired. Most of these implementations aimed toward helping VI individuals with everyday tasks, such as navigating and reading. In these contexts, it is often used alongside audio. Future sections will go deeper into specific implementations that made use of haptics.

2.3.4 Obstacles

Entry barriers

Despite the potential virtual reality has, several factors limit VR's potential. VR has steep entry barriers, making it difficult for newcomers to obtain and utilize virtual reality equipment to their fullest potential. A primary issue is the price of the hardware, ranging from US$300 to US$1500. Because some VR sets are standalone, and some need to be connected to a powerful desktop, the hardware costs vary a lot. Even when the price is not an issue, there are disruptions in the global supply chain causing a massive shortage of equipment [57]. A final obstacle that prevents VR from being a staple in some industries, is that the industries with the most potential also tend to change the slowest. Tourism and healthcare can both benefit greatly from the use of VR, but the healthcare industry especially is acknowledged to be slow to change [58].

Practicalities

Several usability issues emerge when people use VR. Controls are often hard-to-use and specific to one application, meaning previous experiences hardly help. Different VR sets also have different controllers, making learned skills not fully transferable when using other equipment. Deploying the HMD can also be a challenge when dealing with different heights and head sizes [17]. In the case of visually impaired individuals, using VR equipment can be especially difficult if they are by themselves. Several straps need to be slightly adjusted until the HMD fits perfectly, and most VR sets come with long cables that can be easily tangled up in.

Naussea

Motion sickness is a frequent side effect when using HMDs for virtual reality. The cause of this nausea is a sensory conflict, meaning the visuals do not align with the vestibular system. This nonalignment is also referred to as oscillopsia, which means that the visual world appears to swim about or oscillate in space and is a manifestation of a loss of perceptual stability of the environment [59]. This is especially present when the user moves a lot during the virtual reality experience [60].

Early virtual reality applications often used joysticks or walk-in-place for moving around, which caused severe motion sickness. Bozgeyikli et al. came up with the now widely used Point & Teleportation technique to combat motion sickness in VR [61]. By having the user first point at the position where they want to teleport to, motion sickness is significantly reduced. This is because the user has more control over where and when the locomotion will happen. Since moving from one place to another is instantaneous, there is less sensory conflict. The main issue with this method for the visually impaired is that this method heavily relies on precise manual aiming using VR controllers.

Sensory conflicts do not only occur when moving around. In a perfect world, the visuals of the user are perfectly aligned with the real-world position and rotation of the HMD. Latency, however, also sometimes referred to as ’lag’, between the HMD and the virtual reality application can cause severe sensory conflicts. These synchronization issues can occur when VR experiences are computationally expensive, or when the trackers lose track of the HMD/controllers. Latency of especially the display causes oscillopsia and nausea [59]. Low latency not only causes less nausea but it was also proven to increase the feeling of presence [62]. It is to be expected that visually impaired individuals experience less motion sickness since most VR-related cases of sensory conflicts are caused by visual stimuli. That being said, this has yet to be officially researched, so it is still important to keep in mind when developing virtual reality applications for the visually impaired.

2.4 Potential of VR

Virtual reality has been used a lot in both the educational, health, and rehabilitation industry. The technologies that virtual reality brings are extremely effective at simulating complex real-world scenarios. As such, surgeons and psychologists have been using virtual reality for virtual training [63]. Due to the similarity of VR to real life, skills that are learned in VR are directly transferable to the real world [34]. VR has been effective for treating mental health issues as well. By being able to simulate previous traumas, or in contrast, uplifting scenarios, VR has been revolutionary in various areas of care management, such as treating PTSD [64], assisted living and depression therapy [63]. In the healthcare industry, VR is also often used as a distraction method for patients who experience unbearable pain. It has been especially effective for children with severe burn injuries [64].

Physical therapy

VR has also been used as an innovative tool for motivating patients during physical therapy. By adding game-like elements to virtual exercise applications, patients get more engaged and make more progress in their rehabilitation [65]. Adding game-like elements to non-game contexts is called *gamification*. These game-like elements should make users more engaged, which improves the overall user experience [66]. A lot of interactive VR museums are essentially gamified versions of the physical museum, where the focus is to make the user as engaged as possible using interactive virtual objects.

Besides applications that focus on exercising, VR is also used for physical rehabilitation. Patients that had a stroke can use this rehabilitation method to learn how to walk again. The implementations vary from having patients watch other virtual characters walk, to individual virtually simulated walking, gait and balance training, or muscle strengthening. Virtual reality training yields slightly greater results than standard rehabilitation [67]. VR combined with haptic feedback for rehabilitation showed some promising, although varied results [68].

Future of VR

Most VR applications take place in a single standalone environment. Recent trends however are trying to convert this into an integrated network of sophisticated three-dimensional (3D) environments, also known as the MetaVerse. In order to realize this Metaverse, the realism, ubiquity, interoperability, and scalability of virtual reality and its environments need to be improved [69].

2.5 Visually impaired Navigation

Several mobility-assistance electronic devices exist to support or supplant traditional visual aids [70]. These devices can be categorized as either micro-navigation or macro-navigation. Micro-navigation focuses on detecting the location of nearby obstacles, whereas macro-navigation almost exclusively uses the Global Positioning System (GPS) for navigating larger-scale routes [71]. The main limitation of GPS is the precision, which is often not accurate and precise enough for micro navigation [33]. Micro-navigation devices can make use of several technologies for detecting and communicating the location of nearby obstacles. Examples are camera-based vision, remote speakers, haptics, Wi-Fi, and Bluetooth.

Individuals with a moderate visual impairment, as opposed to full blindness, rely less on non-visual cues, since they often still use their vision for navigating [72]. That is why navigation assistance applications for people with low vision often use Augmented Reality instead. Zhao et al. used bright-colored holograms to highlight where and how steep individual stair steps are, as well as where the railing can be held [72]. Angelopoulos et al. focused on outside navigation, where the goal was to improve depth perception for individuals with low vision. Using Microsoft's HoloLens [73], holograms of nearby objects were placed directly on top of the user's normal vision. The colors of these holograms would change based on their real-world distance to the user [70].

The aforementioned solutions are not applicable when a person is unable to rely on their vision at all. To help navigate (nearly) fully blind individuals, other senses are used for communicating information. One of the earliest studies used micro cameras for detecting nearby objects, which would then play a different indicative sound, relative to the user's head position and rotation. This allows the VI user to know which objects are nearby, and where exactly they are. What sound is being played depends on the object's color, texture, and purpose. [74]. Section 2.7.1: Sonification for VI discusses other similar implementations.

M. Avila et al. created a quadcopter that would lead the way for a VI individual. Because of the rotating propellers, VI are able to hear the position of the drone. By leashing the quadcopter, its traveling range can be restricted to the point where it is similar to traditional white canes [75]. Alongside auditory feedback, haptic feedback is also commonly used. Both Miesenberger et al. [54] and Bennet et al. [55] combined virtual reality equipment with spatial audio and a vibrating walking cane in order to train VI individuals with spatial navigation. The cane from Bennet et al., called Canetroller, was also able to provide physical resistance when colliding with virtual objects. Canetroller was tested with VI participants, all of whom use canes in real life. They were able to successfully identify the location of a variety of objects. Participants also mentioned how they felt like they really were in the virtual world, despite not being able to physically see the virtual world. These findings suggest that combining haptic and auditory feedback in virtual reality can make virtual reality environments immersive, despite the lack of vision.

Miesenberg et al.'s implementation seemed promising but was only tested with sighted users, despite the target group being the visually impaired. Using sighted individuals to test implementations that are specifically designed for the visually impaired is fairly common, due to the difficulty of gathering VI participants [76]. Sighted participants testing a design targeted toward VI are referred to as *blindfolded* participants. Depending on the implementation, the participants are not necessarily physically blindfolded. VI individuals tend to use their senses differently than those with full vision, especially their hearing, and they usually have a better sense of rhythm [31]. To test whether this affects player performance, Wagensveld and Zaal used VI, SI, and blindfolded (BF) participants for their rhythm audio-based game [25]. The difference in performance between VI and BF participants was minimal. This suggests that in general, results from the BF group can be expected to be similar to VI users.

2.6 Interactive Virtual Museums

2.6.1 Physical museums

Museums have typically been used to present the most precious artifacts of history in chronological order. Later on, museums developed into service facilities that contribute to the progress of society instead of settings that only collect and store objects. For example, since the 16th-century museums have been used for educational purposes as well [77]. In the current day and age, museums are used to install humanitarian values and a sense of self-worth in students. Museums motivate them to value the lives of others equally as high as their own while learning to differentiate right from wrong and good from vice [78].

Getting involved in art activities from an early age helps develop the aesthetical sensitivity and viewpoints of children. Supervised art learning allows students to gain skills such as observation and manual dexterity. Museums can also play a role in improving the integration of various groups in multicultural societies. This helps individuals who are sensitive to the community and to the world with the development of their personality, self-confidence, and citizenship [77].

Besides regular physical museums, there are also virtual, touchable, and mobile museums. Different audiences are targeted with each type, in an attempt to make learning as accessible and catered as possible. Museums have several collections or exhibitions on display. These exhibitions are usually organized as a structure that combines the displayed objects into one coherent narrative [79].

Different museum types have different purposes. For example, mobile exhibitions travel around to make them accessible regardless of where visitors are located. Touchable museums are especially useful for those with special needs. Adding the sense of touch can help them connect with an art piece. In the 70s, museums started to experiment with touching tours for the visually impaired, where they would be allowed to touch the art while wearing protective gloves [77]. Museums to this day still often host special tours for the visually impaired, where they are allowed to touch artifacts while listening to music and a narration about the exhibition [80, 81]. These tours can often only be done by making a reservation, or on very specific days or events. The visitors are only allowed to touch a few artifacts, meaning they cannot fully experience the entire collection. Although museums often have information about the exhibition written in braille, this does not provide the same experience for

VI as being able to touch the art.

2.6.2 Virtual museums

The main benefits of virtual museums are how they can be exploited to have virtual tours and events. By having a virtual exhibition, the art objects, historical displays, collections, and exhibits can be specifically tailored for educational purposes. Having exhibitions on a website or any other virtual medium also makes maintaining and securing the exhibitions easier compared to traditional physical museums [78]. The primary aim of virtual museums is to allow users to explore the real purpose and conceptual orientation of the physical museum, by looking at the virtual models and objects [82]. Virtual exhibitions are often an extension of the physical museum, rather than a replacement [82].

A popular variation of virtual museums is the circular panorama, where the user can look around from a static point as if they were really there. These 360 degrees panoramas can also be viewed in VR, making it even more immersive. What really makes virtual museums stand apart from physical museums is the potential of adding simulated content. The art and objects that are placed in the virtual exhibition are all 3D models, which can be manipulated and animated to the creator's liking.

Reconstructed 3D objects are not always scientifically accurate, and can be deemed subjective. This is because reconstructions sometimes add content based on the scientists' imagination or ethnohistorical information. When only one reconstruction is offered, it contradicts the fact that there are many ways to examine the past. This can cause the past to be misinterpreted and misrepresented. Reconstructions can be made scientifically accurate when museologists and computer experts work together [82]. The designers of the virtual museum can make the decision to allow users to interact with these reconstructed objects, which can improve the user experience [78].

Animated virtual objects, multimedia displays, and audible information are all types of virtual travel, which is a type of motivational education. Virtual travel provides the learner with extra stimulation and curiosity for the subject through audiovisual material [83].

2.6.3 Gamified virtual museums

The concept of virtual travel, where the user experience is made more immersive to improve engagement and learning, is also referred to as gamification. The goal of gamification is to increase user engagement by adding game-like elements to non-game contexts. Examples of these game-like elements include points, leaderboards, achievements, levels, story progression, and other rewards. Gamification is mainly used in educational contexts, but it is also popular for intra-organizational systems [66]. Nicholson mentions how museums and other leisure settings like zoos and libraries have a lot of potential for meaningful gamification, which refers to adding an overlay of play elements to a real-life setting. This allows users to explore, engage, interact and reflect however they like at their own pace. Nichelson's approach to gamification aims to replace game elements, such as badges and achievements, with engaging play in a ludic learning space. This means it is focused on the user's intrinsic motivation, rather than extrinsic motivation. By providing the user with opportunities of play, they are able to explore and engage on their own terms [84].

The majority of gamified museums however do focus on extrinsic motivation through the aforementioned game elements [85]. Madsen refers to this category of museums as *Add-on Games* [86]. Here, most of the learning is often done by having the user follow a historically accurate story. In order to progress through this story, the user has to perform game-like tasks. Most of the user engagement comes from having well-thought-out gameplay, where enjoyability is key. Good design can maximize content understanding [85].

2.6.4 Virtual reality museums

A late trend amongst virtual museums is the ability to experience them in virtual or augmented reality (AR) [85]. Wei Wei reviewed 60 VR and AR tourism and hospitality applications from the last decade. The virtual museums that used VR showed promising results, whereas the AR museums had mixed results, mainly due to the infancy of the technology [87].

VR can help create very immersive and experiential opportunities for the user [88]. When comparing VR exhibitions using HMDs to virtual exhibitions using a projector, both acquired similar levels of usability [89]. Where there are no real alternatives when using projectors or computer screens, VR sets often come with their own controllers, which likely improves the user experience over using a keyboard and mouse. Several more arguments, such as low resolution, were made against VR. However, most of these issues have been resolved with modern VR equipment.

Benefits of VR

Virtual reality has been used to draw in and engage the youth since their attendance at museums has been low in the past couple of years [90]. Regardless of whether a VR museum is non-, semi, or fully immersive, it is capable of positively influencing the individual motivation to actually visit a place [91]. At the same time, immersive VR museums do allow the user to have more control when viewing or interacting with virtual artifacts, which can help emulate the social experience of visiting a physical museum [92]. Intuitive VR experiences improve the user's enjoyability and involvement, which can lead to higher levels of presence. The positive effects of presence, such as an increase in the perceived usefulness, also apply to VR museums and other tourism VR applications [91].

Studies have looked at the differences between screen-based and virtual reality virtual museums. M. Hayashi created an exploratory virtual museum that could be traversed using regular computer input or using VR equipment accompanied by an Xbox One controller. Each method its user experience was graded based on four topics: "*Comfort of play*", "*Picture quality*", "*Freedom of operation*" and "*Immersion*".

The screen-based museum scored high on "Comfort of play" and "Picture quality", likely due to the 8K resolution of the display screen and the smooth camera motion. The VR-based museum scored better on "Freedom of operation" and "Immersion" since it allowed users to have a lot of control of their camera rotation and position while having more intuitive controls than the screen-based counterpart. Issues of the VR-based museum that were mentioned include motion sickness, low resolution, eye strain, and no tracking of the user's hands [93]. Some of these issues can be resolved by using new equipment. The quality of VR displays is improving rapidly, with current commercial HMDs having resolutions up to 5k pixels [94]. Issues such as motion sickness can be tackled by adjusting the implementation, which is exactly what was done in a follow-up paper by the authors, where VR controllers were used instead for selecting artworks and moving the player. The results of this study are comparable to the aforementioned study, with the main difference being a smaller difference in the perceived "realness" of the virtual world between the two versions. In the prior study, the screen-based version had a higher perceived realness, due to the high resolution. Due to the upgraded equipment, the difference in resolution is smaller. Motion sickness was also not mentioned by the participants in the follow-up study, which could be due to the different implementation and controls [95]. With VR equipment improving over time, it will likely be the preferred option for virtual experiences in the future.

Interactivity

In the early 2000s, museums started to shift from having static collections to providing active learning environments, where educational purposes are central [96]. Interactivity during tours is an example of providing active learning opportunities for the visitors [18]. This can also be applied to virtual experiences, where interactivity implies that the user can directly influence their experience by interacting with the virtual environment [17]. Falk and Dierking came up with the Interactive Experience Model (IEM), which can be used for analyzing the commonality and the complexity of museum experiences [97]. These experiences can be conceptualized in three contexts: *personal*, *social* and *physical* (see Figure 2.2). The visitors' experiences can be greatly influenced by these contexts [96].

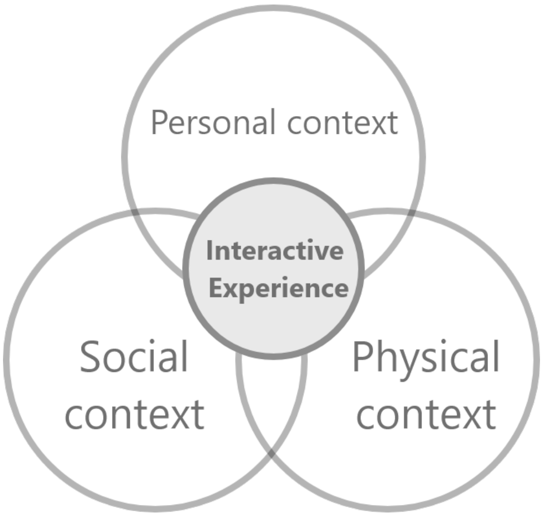

FIGURE 2.2: Interactive Experience Model, by Falk and Dierking (1992) [97]

The personal context refers to the individuality of the visitor, which includes their motivations, expectations, interests, beliefs, knowledge, and experience. The social context includes social interactions between the visitors. Lastly, the physical context includes the architecture, layout, activities, rules, decorations, collections, and facilities [97]. Ideally, museum experiences should consider all three contexts with respect to each other. The Interactive Experience Model can help create targeted exhibits with meaningful interaction by emphasizing that people create their own experiences and meanings; they select what to focus on and how it affects their experience [96].

Where early virtual museums would often only be navigable using a mouse and keyboard, recent trends focus on creative interface systems that focus on sensual involvement. Besides VR, another example is the tabletop exhibit, where visitors can interact with (projected) virtual objects on a large flat horizontal surface. These creative interfaces are more approachable than the standard keyboard-and-screen computer, while still allowing visitors to view and interact with virtual exhibitions [98]. Haptic stimulus also improves the visitor's capability of achieving presence, compared to visual-only stimuli [99].

2.7 Audio in museums

In museums, sound is used in a variety of modes of cultural communication. Audio can be used for determining the atmosphere of an environment. Museums used to have an acoustic culture of silence, likely due to the visual predominance. Recently, museums have started to use audio to enhance the narrative of the exhibitions [100]. This audio can be either diegetic or non-diegetic, and can either be part of the foreground or background layering of the acoustic experience. Diegetic sound refers to audio from within the world of the story that is presented, such as the voice of one of the characters. Non-diegetic audio, such as composed film music, is added afterward to 'color' the diegetic sounds or visuals [101]. The distinction between background and foreground sound can be used to direct the visitors' attention to the audio source. Moving audio is often used to transport visitors to focal points, to prevent pauses, immobility, and silence. This creates a sense of action for the visitors while also enlivening the art at these focal points [100].

When sound bounces around by reflecting off of surfaces, it is called *reverberation*. In museums, it is *cultural practice* to prevent as much reverberation as possible. This means the audio should not move through reflection to ensure the visitors can hear with optimal clarity [100]. Reverberation can negatively influence a person's ability to detect the origin and direction of audio, but with enough experience, it can improve distance perception [102]. With careful sound design, audio clarity can be maintained while also accentuating the room's architectural design. The sensation and meaning of specific objects can also be highlighted by allowing the audio of these objects to have distinguishable acoustics. For example, a muffled echo of a heavy door being shut can emphasize its size and weight. Traditionally, there is often a distance between the visitor and the exhibit, where audio is mainly used to help create an atmosphere. Recently, however, more museums have started experimenting with using audio to create immersive multi-sensory experiences, where the audio and visuals are synchronized [100].

In traditional exhibitions, background music is often used to help associate the artifacts and art pieces with certain historic eras. For example, classical music is often linked to the Renaissance [103]. On the other side of the spectrum are museums that are experimenting with audio-only exhibitions, where narrators, ambient sounds, and background music are used to set the mood and educate the listeners [104]. The main benefits of these museums are that they are inclusive toward the visually impaired, and can even be hosted online, making them easily accessible.

2.7.1 Sonification

Since visual data is often incomprehensible for a visually impaired person, this data needs to be represented so that it can be interpreted without the use of sight. This process is called *sonification*. Sonification is used to communicate data relations into a non-speech acoustic signal for the listener to interpret. This works well because of the perceptual abilities of human beings, allowing us to translate these auditory relations back into comprehensible data [105]. Humans are capable of grouping perceived sounds based on their similarities. This process is called 'primitive processes of auditory grouping', and can be exploited to help users find similarities between objects [106].

There are a variety of ways to map data to sound. Pauletto and Hunt categorized different sonification types into five perceptually distinguishable categories [107]:

1. Data mapped onto *clearly recognizable perceptual parameters*, such as pitch, loudness, and duration.
2. Data mapped so that the *overall timbre* represents the evolution of data.
3. When combining many channels of data, a *mix of perceivable sounds* can be made, such as assigning left/right ear data to certain values.
4. Data mapped as a *single sound with a complex timbre*
5. *One* channel of data is mapped onto *more than one sound variable*.

Different implementations can then be made based on these categories. The authors of the paper mention how they implemented eleven different variations, two of which are used for comparing the evolution of two data sets. What kind of data is used for sonification also varies a lot. In most use cases for the visually impaired, the input data is related to sight. For example, one prior study has used pitch sonification in order to successfully communicate visible colors [108]. Others used navigational maps as input data [109]. Sonification is also often used for helping the visually impaired with their spatial awareness. A variety of visual data can be used for creating audio cues that communicate the player's surroundings.

Spatial audio

To convey spatial information through the use of audio, the system must first know where the user is in the 3D environment, and where the other objects are in relation to the user. Playing audio based on the position and orientation of the user is done using *Head-Related Transfer Functions (HRTF)*. This is done by adjusting the frequency response of the sound for each ear individually, to replicate as if it had been heard by a human in real life [110]. This can be used to create a sense of direction for the audio cues. When the user moves and rotates around, the audio will stay at the same position in 3D world space, but depending on the relative position of the player it might shift from the left to the right ear. Prioritizing one ear over the other in this context is referred to as lateralization [111]. Most game engines have built-in support for this, allowing audio to be played anywhere in the 3D environment, which is then automatically adjusted based on the player's position and orientation. These systems often only support horizontal cues, meaning differences in vertical positions are hard to distinguish [110]. If audio is being played without taking (player) positions and orientation in mind, it is called 2D stereo audio. In these cases, audio will be played in both ears at an equal volume.

Sonification for VI

A variety of visual data can be used for generating the sounds. For example, depth information allows users to visualize objects at their corresponding location in 3D space [112]. One of the earliest papers about sonification for VI used depth for locating landmarks and objects, where every object has a distinct sound [113]. These distinct sounds are based on the object's purpose, colors, and texture. These objects are present in both the virtual as well as the physical world, where the virtual world's purpose is to alert the user of the objects in the physical space. Rays are used for the detection of these objects, where a Gaussian-like bias causes rays to be more clustered in the center of the field of view. This is in line with how humans use vision for detecting objects. The authors mention how some VI that still have a functional visual cortex were able to feel visual sensations when stimulated with adequately designed sounds. This implementation allowed VI to perceive spatial shapes and their physical distribution.

Gonzailez-Mora et al. used a similar approach, where depth maps are used to find and store potential collision points with nearby objects [114]. These nearby points would then each play a small continuously emitting acoustic sound. By auralizing (pre-processing in such a way that it appears to come from a certain position in the environment) this audio, users can be informed of all nearby points in 3D space. Every 153ms a random point plays its indicative sound. The results confirm the author's hypothesis that users are able to successfully differentiate the location of objects inside the perception field, using these stimuli. Several more variations were made within the same research project [115]. More complex environments were tested, as well as different methods of calculating nearby obstacles. Several prototypes were made using newer equipment and additional functionalities, such as the ability to read text. In the end, this 15-year-long research project showed that sonification can be very effective for perceiving the location and shapes of objects, which can be especially valuable for VI.

Sonification has also been applied to artworks, where the visuals are directly converted into auditory cues. This process can be done by extracting layers of visual data, such as color [116]. Other examples include genre, art-style, emotional message, mood, etc [117]. When these features are stored as a data structure, they can directly be converted into an audio file. The other option is to create the audio files by hand, keeping all of the important object features in mind. Here the most important part is for listeners to be able to associate the created sound with the object, which can often be achieved by replicating the real-world sounds of the object. For both the manual and automated methods of creating the audio, the developers choose which features to extract. Studies have also experimented with using machine learning, which both extracts and classifies features of the artworks automatically based on previous learning experience [118]. The extracted features can then be converted into audio files through a similar reinforced learning process. Although this method seems promising, the produced results are often hard to differentiate from each other and lack musical cohesion [119]. Some artists have also used sonification for inspirational purposes, where the sonified audio of a space or architecture serves as the main inspiration for their yet-to-be-created artworks [120].

2.8 Virtual Reality Entertainment for Visually Impaired

Since VR exhibitions follow a design philosophy similar to VR entertainment games, it can be useful to look at VR games, and how they were adjusted/designed for the visually impaired. In general, few VR games exist that were designed for the visually impaired. This inspired Wedoff et al. to create a VR replica of the game Showdown, which is an accessible game where blindfolded players use their hearing to locate and hit a ball towards their opponent [111]. The non-visual aspect allowed the developers to use audio as the primary cue for communicating gameplay information to the player. The game was tested with over 30 visually impaired participants, causing it to be one of the only VI VR games that was well-tested and successful among the target audience. As such, it is useful to thoroughly analyze the implementation, and discuss which features worked well, and for what reasons.

All gameplay events played a distinct sound when they occurred. To convey the location of an event, such as a ball being hit by a player, lateralized spatial audio was used. Lateralization is the most important cue for localizing the origin of the audio source since it produces different sound waves between the left and right ear of the player, based on the relative position. The distance of the object was communicated by using the Inverse Square Law to decrease the volume and intensity. The game engine's generic HRTF settings were also used for communicating the location. Over-ear headphones were used in order to properly differentiate audio source positions.

Virtual reality head-tracking was especially useful to prevent audio barriers, which is confusion where the player cannot distinguish sound between their ears. By allowing the user to look around, the relative positions of the objects change, causing a shift in which ear receives which sound waves. This allows the user to more accurately figure out the audio's origin inside the 3D virtual environment.

Alongside the sound effects, voice-over instructions and vibrating controllers were used for communicating information to the player. Three different complexities were used for the voice-over lines, ranging from long grammatically correct sentences, to short 3-word descriptions, such as "left to right". These voice lines would be played in the ear of the corresponding direction, meaning "the ball is starting from the left" would be played in the left ear, while "the far right" would be played in the right ear. This was used to further emphasize the trajectory of the incoming ball. Upon missing the ball, the player would also hear how and by how much they missed the ball. The controllers would vibrate increasingly stronger when the player moved it closer to the ball. During the first levels, where elaborate voice lines would also play, the vibrations were turned off to prevent players from being overwhelmed by all the cues. Although conceptually the vibrations could work well, most players performed worse compared to when they only relied on the auditory cues. This can be caused by players having prior Showdown experience, in which they also exclusively rely on their hearing abilities. The authors recommend exclusively using audio for communication.

2.9 VR museums for VI

Virtual reality more easily allows multiple senses to be stimulated at once, which makes it stand apart from web-based virtual museums. Although VR systems are capable of including all five senses, most VR museum experiences are still largely limited to vision [91]. Some virtual museums are adding complementary audio to their experiences, but vision is often still required to be able to experience the virtual exhibition. The visually impaired thus cannot successfully experience the majority of existing exhibitions.

A few virtual museums exist that were designed with VI in mind. Robotics lab Percro designed an exoskeleton arm that provides haptic feedback upon collision with virtual artifacts [121]. A similar project was done in Prague, where haptic gloves were used in combination with VR equipment, allowing users to walk around and 'touch' the virtual objects [122]. Haptic gloves for VI were first experimented with in 2004 when the CyberGlove made its first appearance [123]. Kreimeier et al. used a VR treadmill and haptic feedback to allow users to walk around in a virtual environment and feel nearby objects [124]. A VR controller would vibrate upon collision with a nearby virtual object, allowing users to 'feel' its shape and exact location. Although the study focuses more on the navigation aspect, it showed that simple haptic feedback can be useful for communicating the location of nearby objects. Equipment such as the aforementioned examples allows users to 'feel' virtual objects, which is a lot more stimulating than reading or hearing about the objects.

Although these additional VR-compatible devices seem promising, they are often not available for commercial purchase, or very expensive. This makes the created experiences less accessible since the (financial) entry barrier is so high. The goal of this thesis is to create an inclusive and easily accessible virtual reality museum. As such, the used equipment will be limited to equipment that is included in commercial VR sets.

2.10 Literature review conclusions

The literature review highlighted a few research topics that influenced the actual implementation. By going over the research sub-questions, and what the literature stated regarding these topics, concrete implementation decisions can be made.

The first question, *"How can virtual reality spatial awareness be facilitated for the visually impaired?"*, has been discussed in Section 2.1.1: Spatial awareness and Section 2.7.1: Spatial audio. The visually impaired tend to use their hearing for most of their spatial recognition. Virtual reality spatial awareness tends to be very similar to real-life awareness, meaning the training of one's hearing skills is transferable both ways. By adjusting audio direction and volume using the HRTF, audio can be perceived to come from an origin point inside the virtual environment. By using 'reference' sounds, VI are able to recognize nearby objects and are encouraged to interact with them. For presenting information, speech/narration tends to be preferred by VI.

When using spatial audio, it can be difficult to differentiate audio coming from similar directions. In most game engines, spatial audio works best when used on the horizontal axis, since vertical differences tend to be harder to differentiate. As such, the virtual environment needs to be designed in a way to ensure all objects are horizontally well spaced out, and that the interaction with these objects does not require (precise) vertical aiming. When trying to answer the sub-question: *"How can the controls be adjusted so that the visually impaired can successfully interact with the environment?"*, Section 2.3.3: Haptics concludes how simple haptic feedback can be great for indicative cues. Haptics can even be used as anticipatory cues in order to alert and guide VI players. Games for VI, such as the one mentioned in Section 2.8: Virtual Reality Entertainment for Visually Impaired, often use handheld controllers for their interactions, due to their ease of use and accessibility.

Advanced haptic devices, such as haptic gloves, have been used to allow VI to 'feel' virtual objects. Although these technologies seem very promising, they are often not available for commercial purchases, or very expensive. Simple vibrational feedback in handheld controllers has been successfully used in a variety of contexts, as mentioned in Section 2.9: VR museums for VI. Another way of representing (virtual) objects for the visually impaired, is through sonification, which is discussed in Section 2.7.1: Sonification for VI. A variety of methods can be used to convert the visual data into a playable audio file. The created/generated audio should represent some of the prominent features of the object, such as the color, purpose, or texture. The aforementioned examples of haptic and auditory cues can be used for representing artworks and artifacts in a non-visual way, and as such are the answer to the research sub-question: *"How can historic figures and artifacts of a virtual museum be represented for the visually impaired?"*.

3 Thesis Setup

3.1 Existing VR museum

An existing interactive VR museum will be used as a baseline. This is a virtual museum focused on The Night Watch, which was painted by Rembrandt. Most of the content is about the painting and the people that are depicted in it. Five of the historic figures eventually 'jump out' of the painting, appearing as 3D characters in the environment. The player can then interact with them, prompting the figures to walk forward. Here, the player has the option to select one of several audio cues, which will trigger a voice-over providing in-depth information about the historic figure and why they are on the painting. A signature item of each of the historic figures is also put on display on the opposite side of the room. These can also be interacted with, which will trigger a short animation or sound effect.

FIGURE 3.1: The Night's Watch in VR

3.2 Implementation concept

Several issues with the existing version arise when removing all vision. These will be discussed in Section 4.2: Experience adjustments. In order to compensate for the sight of VI, emphasis will be placed on the use of audio and haptics. Although bright colors can help low vision people with detecting objects, this will not work for fully blind people. As such, constantly emitting indicative audio will be played at the location of the historic figures and the artifacts instead. This draws attention to them and encourages the players to interact with the figures and artifacts. Handheld controllers will start vibrating when the player is looking in the direction of a nearby virtual object. Different vibration magnitudes of the two controllers can be exploited to steer the player in certain directions, which will be activated after 20 seconds of non-interaction. This method is henceforth referred to as the 'steering' method. The aforementioned combination of haptic and auditory feedback is an example of multi-sensory stimuli. Once the player is looking in the right direction, they can use the trigger button on the handheld controller to interact with the object. For the objects, this will start a short animation. For the historic figures, it will queue a narrative story.

3.3 Pilot experiment

This method of locating and interacting with nearby objects will first be tested in a pilot experiment before being implemented in the VR museum. A small audio-only game is created with the aforementioned controls, where the goal is to interact with nearby objects while looking directly at them. The initial data and the feedback of the test participants is then used to further tweak the implementation.

The participant will be wearing the VR HMD, as well as using both handheld controllers. To ensure the focus of the experiment is on the auditory and haptic cues, the display of the HMD will be turned off. The participants will still need to wear the HMD for the head tracking functionality. Aiming at the virtual objects is done using the player's head gaze direction, instead of the common use of controllers. This is to reduce potential discomfort and difficulty that some visually impaired individuals might experience when trying to control their limbs.

Several objects are placed in the virtual environment, surrounding the player. These objects will be spaced apart far enough to ensure differences in distance and position can be heard when playing spatial audio at the origin of these objects. A constantly emitting indicative sound will play at the location of a randomly chosen object. The participant will attempt to gaze directly at it, after which they will press the 'trigger' button. After a few seconds, a new object will be picked, repeating this cycle.

In an attempt to make the pilot experiment as similar as the VR museum as possible, the rectangular shape of the virtual environment will be replicated. Similar object scaling and distances will also be applied. Figure 3.2 shows the original layout of the Rijksmuseum exhibit. Figure 3.3 shows where the virtual objects reside in the pilot experiment.

A total of five different objects, each with their own unique audio cues, are present in the virtual environment:

1. Drums
2. Flags
3. Guns
4. Spears
5. Swords

At the start of the experiment, a random object is picked to play its indicative cue sound. This will repeat for a certain amount of times, after which a new object is picked. If the player interacts with the object before a new object is picked, the accuracy of interaction is measured using the angle between the player's gaze direction and the direction to the object. The object will then play a unique audio sequence, such as the sound of swords clashing in a fight, after which a new object is picked to play its indicative sound. This loop continues until all objects have been interacted with.

3.4 Expert interview

After the pilot experiment, a short interview was held with an expert. The history teacher of a school for VI was interviewed to gain insights into how the visually

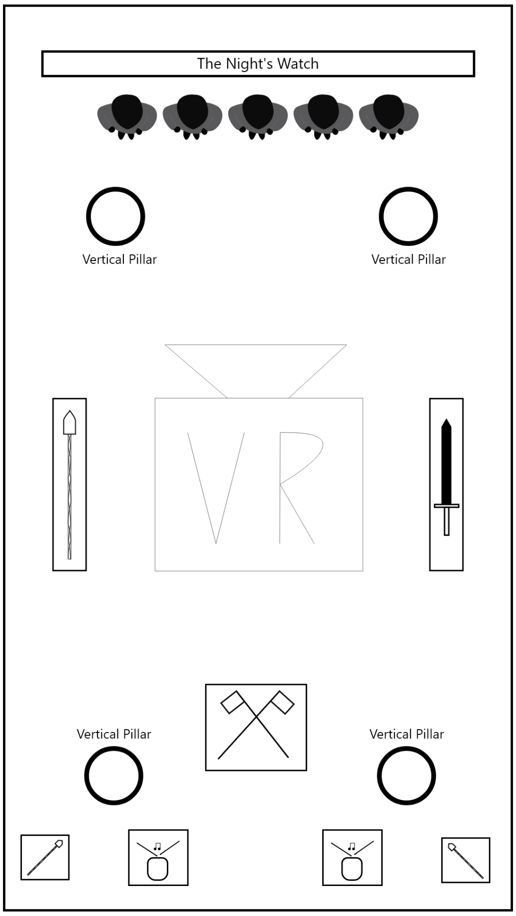

FIGURE 3.2: The Night's Watch in VR - Room Layout

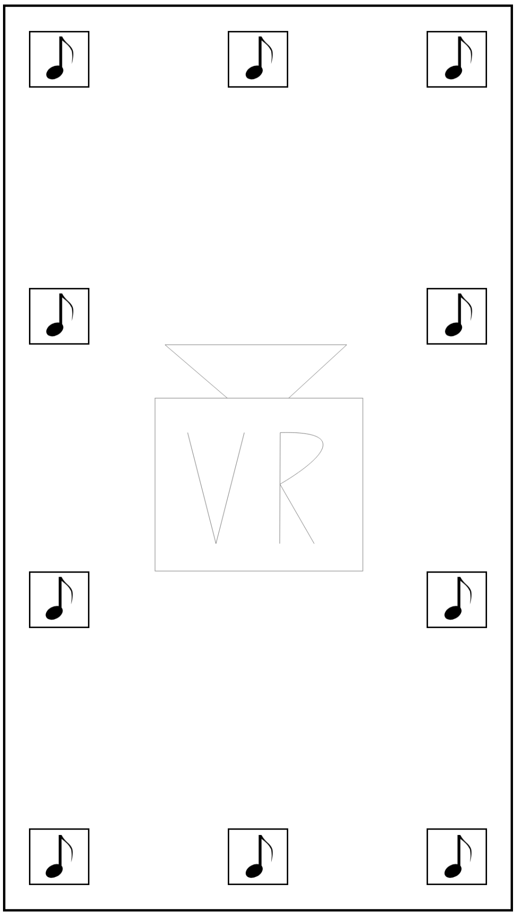

FIGURE 3.3: Pilot Experiment - Room Layout

impaired usually learn about history. This person also has experience with making physical museums more accessible for the visually and physically impaired. The interview questions can be found in Section A.2: Interview questions.

The main focus of the interview was discussing the importance of understanding the full picture when it comes to historic events or people. For example, knowing who Hitler was and what he did might not provide you with all the necessary context as to why his story was the way it is. Documentaries and films can help with this, as they allow viewers to experience similar emotions as the people from that time period. Even though these documentaries provide mainly visual stimuli, the audio that is accompanied by the visuals is often capable of carrying the same weight. This is because teaching history is essentially storytelling, which is inherently auditory. Alongside auditory teaching, touchable objects are also sometimes used. One example that the teacher provided was how exclusively talking about wigs from the 17th century might not stimulate the senses enough for the students to remember. As such, replicates of these wigs were brought in for the students to touch. This allowed them to feel the difference between the wigs and modern hair(styles).

For the VR museum, the teacher advised changing the experience from audio-only to audio-based, since some VI people still rely on their sight for navigating. Haptic feedback should also not be overlooked, as it can be a great alternative for communicating cues. Existing physical exhibitions sometimes contain haptic/braille versions of the art pieces, allowing VI to feel the art. Although this can be used for communicating shapes, other visual aspects such as colors are more difficult to communicate. Thoroughly narrating additional visual aspects is thus recommended by the teacher.

4 Experience design

4.1 Pilot results

The pilot was held to measure how well visually impaired teenagers were able to detect the origin point of spatialized audio in a virtual environment. Accuracy and speed are key variables for measuring how well the implementation worked. The accuracy is measured by taking the angle between the user's gaze direction and the direction to the target object, where a difference of 45 degrees results in an accuracy of exactly 0 percent. The median *accuracy* of the pilot experiments is 74.4%, and the average *accuracy* is 65.1%. This suggests that participants were able to consistently precisely locate the audio origin point. However, the few times they did make a mistake, they were off by a large margin. The average *time between interactions* was 4.2 seconds, and the median *time between interactions* is 2.9 seconds. Considering the participants had a maximum of 15 seconds to locate the new object and perform the interaction, they were fairly fast with initiating new interactions.

Figure 4.1 contains top-down heatmaps of the room, where the red lines indicate where the user was looking when they interacted with the virtual object. The camera icon is rotated towards the actual position of the target, meaning this is the expected gaze direction of the users. In general, these heatmaps show that most users were able to successfully detect the origin point of the virtual objects, and directly look at them. Another interesting detail is that some of the errors that were made, were because the user looked in the exact opposite direction of the actual origin point. This can be explained by the fact that audio that is played right in front of you will sound similar to audio that is played right behind you. The aforementioned difference in average and median accuracy are likely caused by these occurrences.

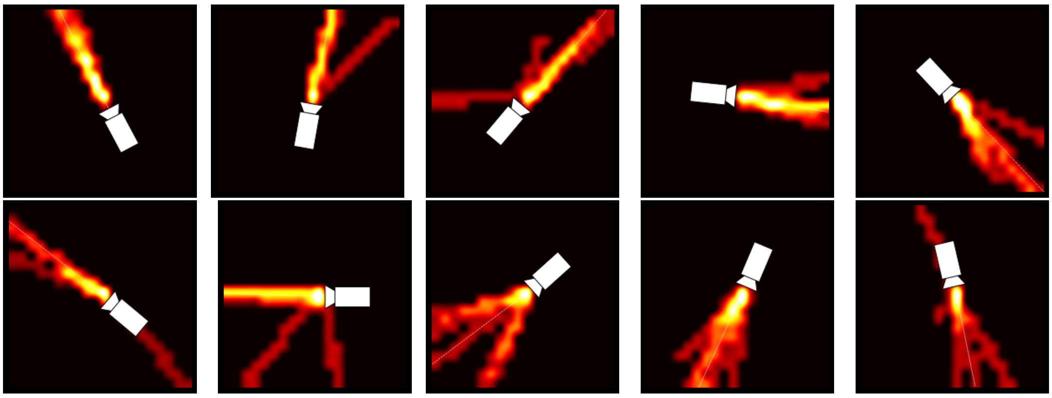

FIGURE 4.1: Top-down gaze directions heatmap of each target

4.2 Experience adjustments

When combining the results of the pilot with the advice from the expert, a few alterations will be made to the controls before finalizing them in the full-scale project. First, the experience will be audio-based, allowing users to use their sight. The pilot version also continuously played indicative audio cues. This will be changed to only happen when the user has not interacted with anything for a certain amount of time. The feature should be there to help users find objects to interact with, rather than to force a sequence of expected interactions onto the player. By making this change, users have more control over what they want to interact with, while also having control over the pace. This also means that the collision sound effect and haptic feedback will play when directly looking at **any** of the interactable objects. When this occurs, the indicative audio cue will also play to entice the player to interact with this object. Figure 4.2 shows the updated flow of the experience.

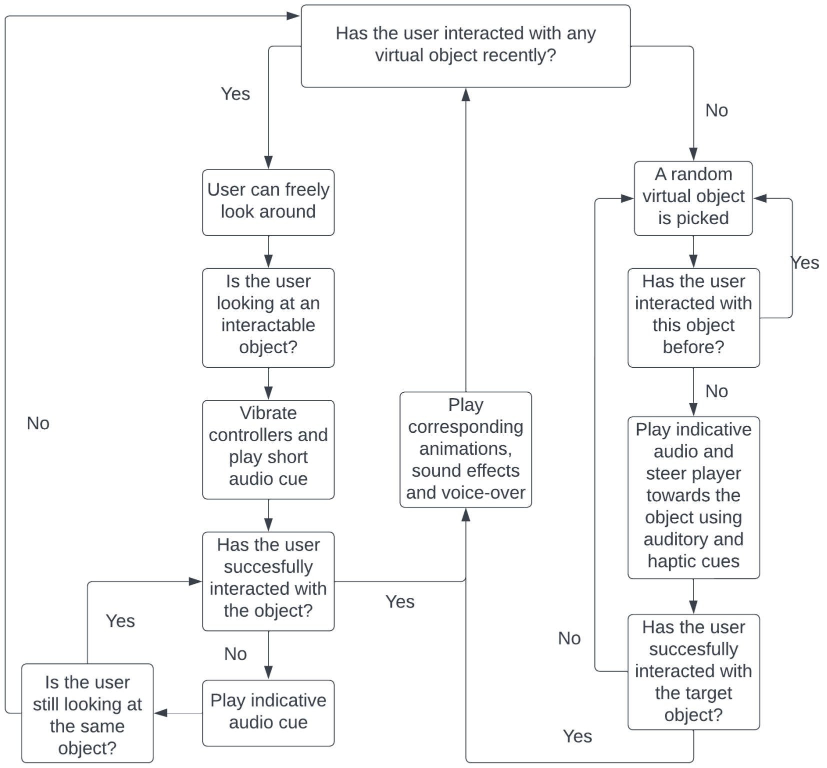

FIGURE 4.2: Flow of the experience

4.2.1 Existing problems

Several issues arise for the existing version of the museum when removing sight as the primary sense. Although the application has a variety of narration voice lines, none exist that clearly explain what can be seen on The Night Watch. Besides this, some sentences are too complicated for children to understand. As such, several voice lines need to be rewritten or added. Another issue is how precise aiming is required for selecting individual voice lines about one of the historic figures in the painting (see the **(i)**s on Figure 3.1). This can be resolved by combining the voice lines into one, which will then be played upon interaction.

The pilot study revealed that users can consistently precisely aim at virtual objects based on audio clues alone. In some cases, however, users aimed slightly more to the sides of the object. To ensure that this does not lead to unwanted interactions, all objects in the room should be spaced apart. Interacting with objects will also be temporarily disabled when a user is already interacting with another virtual object. The historic figures from The Night Watch will be placed following a similar layout to the static objects in the pilot. Figure 4.3 contains a screenshot of the virtual room with its updated layout.

FIGURE 4.3: The Night's Watch in VR - Room screenshot

4.2.2 Audio design

Unity's AudioSource component was used for spatializing and playing the audio files. All diegetic audio is no longer 2D stereo audio. Instead, the sound plays at the location of the corresponding virtual object. For example, the footsteps of the historic figures walking around now originate from the actual feet of the historic figures. Non-diegetic audio, such as the narration and background audio, has also been adjusted. An ambisonic effect has been applied to the audio files, creating a 'skybox' effect. This makes it appear as though it does not have one origin point while being less static than 2D stereo audio. This change makes it sounds as though it is present in the virtual world, while still being distinguishable from the diegetic audio. Lastly, Unity's Reverb Zones were used to simulate realistic acoustics. Different settings affect the distances, pitch, and reverb of all audio in the room.

4.3 Experience versions

An overview of all the key differences between the sighted and the visually impaired version can be seen below. Most of the differences affect the interaction aspect of the experience.

Sighted version:

- Aim using controllers
- All three dimensions are used when aiming
- Voicelines can be selected individually
- Colliders are used to determine hits
- There is no additional support for helping find targets

Visually impaired version:

- Aim using HMD
- Vertical axis is disregarded when aiming
- Voicelines are combined into one, which is played upon interaction
- Angle between target and the aiming point is used to determine hits
- Vibrations and spatial audio are used to help find targets

5 Methodology

This section will elaborate on the target audience, participant groups, and the recorded measures. Ethical considerations and the research design will also be discussed.

5.1 Participants

Similar to existing VI studies, some sighted individuals were asked to play the *visually impaired* version of the experience instead. These participants will henceforth be referred to as the *blindfolded* participant group. The other two participant groups are the *sighted*, and the *visually impaired*. In total 34 people participated in the experiments, of which 18 identified as male, and 16 identified as female. Of the participants, 10 were visually impaired, 10 were blindfolded and 13 were sighted. All participants were (high school) students between 12 and 20 years old (M = 15.52, SD = 2.71). The experiment group was purposely restricted to young students, because of the benefits of experiencing art and history at a young age, as mentioned in Section 1: Introduction. One 28-year-old visually impaired employee of the high school was asked to participate as well since this person is an expert in the field of games and digital experiences for the visually impaired. The visually impaired group consisted of participants with a variety of visual impairments, ranging from low vision to being fully blind.

5.2 Ethical considerations

An information and consent document was created to inform the parents/guardians of the children and ask permission for their kid to partake in the experiments. This document can be found in Appendix Section A.1: Information and consent form. It includes information about the testing procedure, and what happens to the collected data. If the parent gave active consent, their child was invited to participate in the experiments.

5.3 Research design

On the day of the experiments, students were called in one by one to try out the VR museum. They would first be explained what the study is about, and what actions they can perform in the virtual environment. After this, the researcher helped the student with equipping the equipment. When everything is set up, the player first goes through a tutorial explaining all the controls. When all is understood, they could freely explore the VR museum. When the student was done with the experience, the equipment was removed and the student was asked to fill out an online survey. For the VI participants, an uninvolved sighted person asked the questions aloud and filled in the answers for the VI participant. Since every participant only tries one version, the study follows a between-subjects design.

5.4 Measures

This thesis aims to investigate how haptic cues combined with spatial audio compare to traditional vision-based interaction in a VR museum. The independent variable is the *experience version* since three different versions are compared against each other (VI, SI, BF). Dependent variables include *accuracy*, *time between interactions* and *total playtime*.

Both quantitative and qualitative data were recorded during the experiments. The quantitative data include:

1. Which objects were interacted with
2. How long the entire session lasted
3. How accurately the user used the controls
4. Heatmap of where the player looked

The qualitative data mainly focused on demographic information, and the user experience, which includes Likert-scale questions about:

1. Easy of use
2. Enjoyability
3. Feeling of presence
4. Understanding of the auditory cues
5. Understanding of the environment

Spatial awareness	**Controls**	**Represent art and artifacts**
Accuracy	Ease of use	Audio cues meaning
Audio cues meaning	Time between interactions	Understanding of environment
Presence	Total playtime	

TABLE 5.1: Research sub-question topics and their relevant measures

Table 5.1 contains an overview of the research questions and which measures can be used to answer them. A full list of all the survey questions, and the logic behind the question conditions can be found in Section B.1: Qualitative survey questions.

The survey questions are inspired by the Virtual Experience Text (VET), which is a survey instrument used to measure five dimensions of Experience Design (ED) [125]. Virtual experiences are often designed around five different dimensions: sensory, cognitive, affective, active, and relational. By including qualitative questions regarding these dimensions, presence can be measured more in-depth compared to standard presence theory. Table 5.2 contains descriptions for each of the Experience Design Dimensions (EDD). An overview of all survey questions and their respective EDDs can be found in Appendix Section B.2: Survey design dimensions.

5.5 Materials

The VR experience was made entirely in Unity. SteamVR, which is a VR library made by Valve, was used additionally, as it has built-in support for most commercially available VR devices. For the experiments, the HTC Vive and its controllers were used. To ensure spatial audio could be heard, all participants wore high-quality over-ear headphones, namely the HyperX Cloud II.

The survey, which was hosted on Qualtrics, was filled out by the participants on the laptop that was connected to the VR equipment. For the visually impaired students, a sighted individual would ask the questions instead and enter the answers for them.

Experiential Design Dimension	**Description**
Sensory	Sensory input (auditory, haptic, visual), as well as how these are perceived. Sensations are created through sensory hardware and software.
Cognitive	Task engagement in an experience, performed using mental engagement.
Affective	The user's emotional state. Refers to how well the user's emotions can be translated to similar real-world scenarios.
Active	How much of a connection (empathy, identification, and personal relation) the user feels to the virtual environment and the experience.
Relational	The social aspect of an experience, such as the user's perception of collaborative experiences.

TABLE 5.2: Experiential Design Dimensions and their description [125]

6 Results

In this section, the results obtained from the experiment will be analyzed. Both quantitative and qualitative data from the three participant groups will be compared.

6.1 Interaction quality

How well the user was able to interact with the environment can be analyzed by looking at a variety of variables. The *accuracy* of each interaction tells how close the player aimed to the middle of the target. How long it took the player to find and precisely aim at the target is measured using the *time between interactions*. The *total playtime* shows how long it took the user to go through the entire experience. When combining these quantitative measures with the survey questions regarding spatial awareness, the controls, and environmental understanding, conclusions can be drawn in order to answer the research sub-questions.

6.2 Comparing group data

Existing research often makes use of blindfolded sighted individuals as a replacement or supplementary group to the visually impaired participants. In order to estimate how applicable this is within the context of virtual exhibitions, and to estimate how similar their data is to the existing version, data from all three groups should be compared. Equivalence Tests are used to look for statistical equivalence between several groups. This serves as an indication of inclusiveness, where equivalence means that users have similar experiences or performances. These tests will be done for all three participant groups and their distributions of the quantitative measures. By looking for statistically significant differences, the potential influence of qualitative factors, such as age, experience, or interests, can be investigated. The results are split up into different sections based on which research question they tackle.

6.3 Spatial awareness

The first research sub-question focuses on improving spatial awareness when eliminating vision. Spatial audio and haptic cues were added to help with locating objects. In order to analyze the effectiveness of this implementation, the interaction accuracies should be investigated.

Figure 6.1 shows how the visually impaired participants significantly improved their accuracy compared to the results of the pilot. When comparing the accuracies of all three groups, the blindfolded group has the highest mean, whereas the sighted group is the most consistent. This is visualized in Figure 6.2. The mean and standard deviation per group can be seen in Table 6.1. All three experience versions were compared in a one-way ANOVA test in order to try and reject the following null hypothesis:

H0.1: *The mean accuracy is the same for all three experience versions.*

The test resulted in statistically significant differences between the accuracies ($p = 0.005$), meaning the null hypothesis can be rejected. An equivalence test was also done in order to reject the presence of the smallest effect size of interest (SESOI). The equivalence bounds were set to a standardized effect size (ES) of 0.5 [126], also known as Cohen's medium-sized effect [127]. These bounds are used to determine the range in which differences are smaller than what is considered meaningful. The test found statistical equivalence with a 90% confidence interval (CI) between the means of the blindfolded and the sighted version (-0.34 - 0.093), but none between other combinations of experience versions.

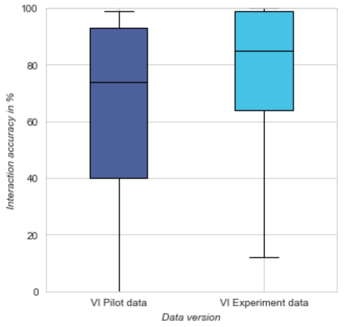

FIGURE 6.1: VI accuracies comparison

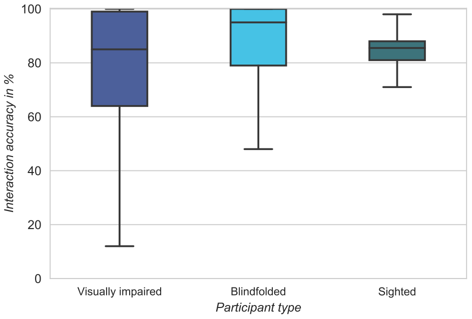

FIGURE 6.2: Accuracies per version

Experience version	Mean	Standard deviation
Visually impaired	77.22%	23.97
Blindfolded	85.20%	20.51
Sighted	83.36%	8.79

TABLE 6.1: *Accuracy* distribution per version

Most participants mentioned that they could properly understand the audio cues during the experiment. They also mentioned how when the game tried to steer them towards a specific object, they were able to locate the spatialized audio. The mean of the survey question regarding their understanding of the audio cues is 4.30, and 4.10 for the self-reported feeling of presence, on a scale of 1-5. The standard deviation for these survey questions is 0.88 and 1.13 respectively. There were statistically significant differences between the mean feeling of presence ($p < 0.001$), and no statistical equivalence was found between any of the three versions.

Figure 6.3 shows how well the participant groups were able to understand the audio cues. This will be further discussed in Section 6.5: Understanding of the environment. Figure 6.4 shows the feeling of presence for each participant group, with the blindfolded group scoring the lowest. Although the accuracy is not equivalent across all three groups, the results do show that the VI group had a positive experience overall in terms of spatial awareness and presence.

6.4 Controls

The total playtime and the time between interactions can be used in order to analyze how effective the controls were. Combining these with quantitative data regarding the ease of use can provide insights into the usability of the controls.

The distributions of the time spent between interactions can be found in Figure 6.5. All three participant groups performed similarly, with the visually impaired group being the fastest on average. Table 6.2 shows the differences in the mean and standard deviation between the three versions. The total playtime for each group is visualized in Figure 6.6. On average, the visually impaired participants took ten seconds longer to go through the entire experience compared to the other groups. Table 6.3 shows the distributions of the total playtime of each experience version.

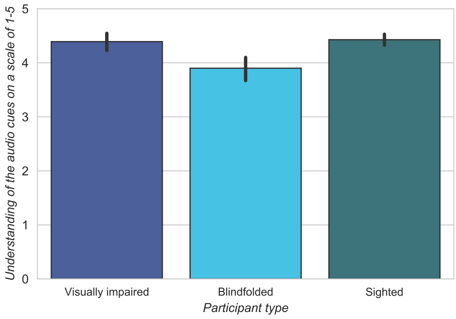

FIGURE 6.3: Audio cue understanding per group

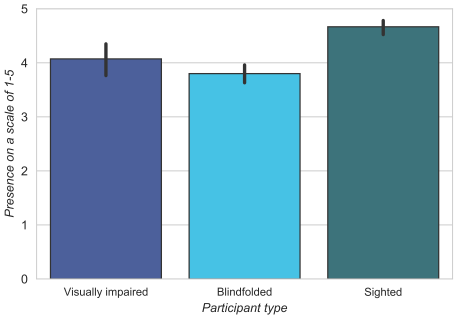

FIGURE 6.4: Presence per group

Although participants were instructed to go through the experience at their own pace, the data can still be insightful during comparisons, since it can also be linked to confusing or difficult controls.

A variety of external variables, such as art and history interests, experienced boredom, museum experience, and prior VR experience, were investigated to see whether they affected the total playtime. In the end, no statistically significant differences were found. Afterward, a one-way ANOVA test was used to try and reject the following null hypotheses:

H0.2: *the mean time between interactions is the same for all three experience versions*

and

H0.3: *the mean total playtime is the same for all three experience versions*.

The test resulted in statistically significant differences in the mean total playtime (p = < 0.001), but there were no statistically significant differences in the mean time between interactions (p = 0.589). This means only the null hypothesis regarding the total playtime can be rejected.

Statistical equivalence (CI = 90%, ES = 0.5) of the mean time between interactions of all experience versions was found. The smallest difference was present between the visually impaired and the blindfolded version (-0.349 - 0.12). The total playtime was only statistically equivalent (CI = 90%, ES = 0.5) between the blindfolded and sighted version (-0.437 - -0.004).

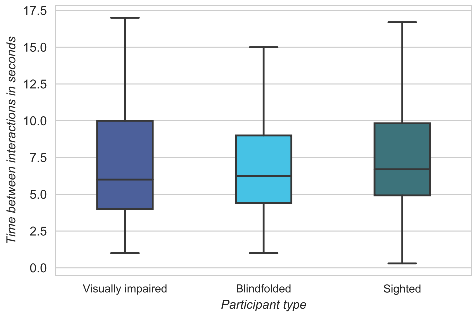

FIGURE 6.5: Time between interactions per version

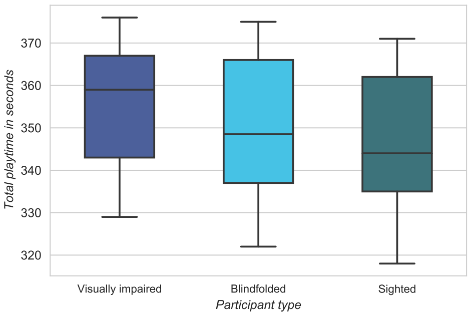

FIGURE 6.6: Total playtime per version

Experience version	Mean	Standard deviation
Visually impaired	8.24	6.77
Blindfolded	11.41	7.45
Sighted	9.25	5.20

TABLE 6.2: *Time between interactions* distribution per version

Experience version	Mean	Standard deviation
Visually impaired	355.45	14.835
Blindfolded	349.80	15.820
Sighted	346.18	16.858

TABLE 6.3: *Total playtime* distribution per version

The visually impaired version had the additional steering method. Figure 6.7 visualizes the occurrence of this method for both groups, with the visually impaired group using it more on average than the blindfolded group. When comparing the accuracy distribution of both methods, the exploring method consistently performs better than the steering method, as seen in Figure 6.8. On average, participants were able to find the target they were being steered towards in 4.31 seconds, with the regular exploring method taking an average of 7.15 seconds.

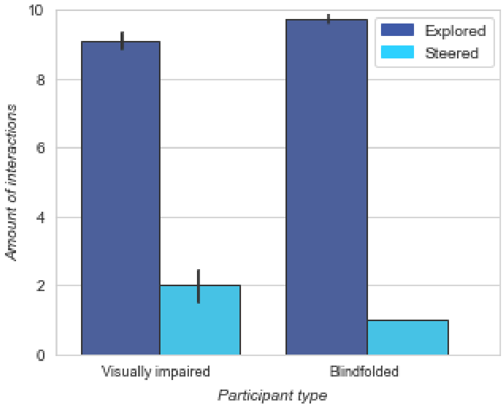

FIGURE 6.7: Interactions per version

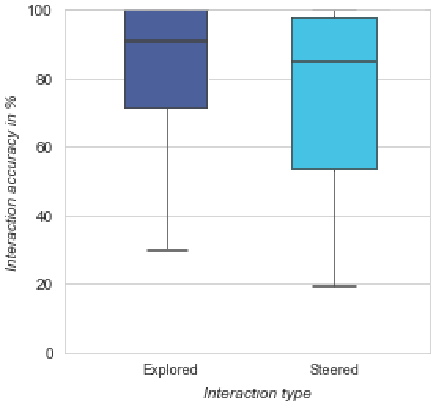

FIGURE 6.8: Accuracies per interaction type

When looking at the understanding of the controls in Figure 6.9, it can be seen that the sighted group picked up on the controls the best. The visually impaired rated the ease of controls the lowest. They also happened to have more steering interactions than participants who rated the ease of controls higher, as seen in Figure 6.10. Although the steering method allowed the users to have faster interactions, they also rated the understanding of the controls lower. Even though there were statistically significant differences ($p < 0.001$), and there was no statistical equivalence between the three groups, all groups were positive about being able to understand how and when to use which controls.

6.5 Understanding of the environment

In order to conclude how well the player understood the represented artifacts and historic figures, two survey questions need to be analyzed. Figure 6.3 shows how

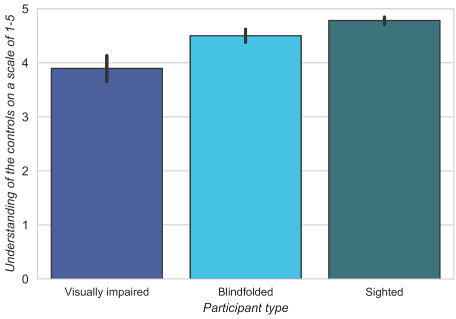

FIGURE 6.9: Controls understanding per version

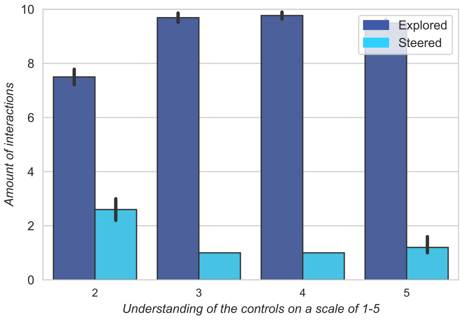

FIGURE 6.10: Controls interaction types per understanding rating

well the audio cues were picked up by the participants. The visually impaired and the sighted group have similar performances, with the blindfolded group following shortly behind. When testing for equivalence (CI = 90%, ES = 0.5), statistical equivalence was only found between the sighted and the visually impaired group (-0.162 - 0.274). No other equivalence was found, due to the blindfolded group scoring significantly lower. Despite this, all three groups were positive about being able to understand the audio cues. Section 6.7: Observations and additional feedback further elaborates on the participants their experience, and which audio cues were (un)clear.

Figure 6.11 shows that all three groups were able to understand their surroundings, with the blindfolded group scoring slightly lower than the other groups. That being said, there were statistically significant differences between all three versions ($p < 0.001$). There was also no statistical equivalence between any of the three groups. Although all three groups had a positive understanding of the environment, there was a big difference between the three groups regarding how well they understood what was happening around them and which virtual objects were in the room.

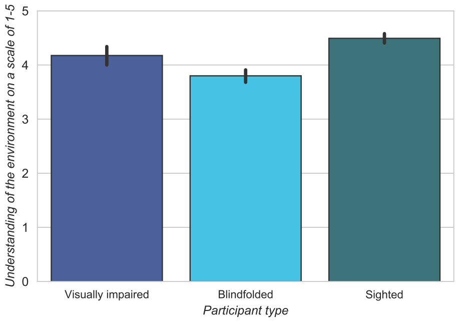

FIGURE 6.11: Understanding of environment per group

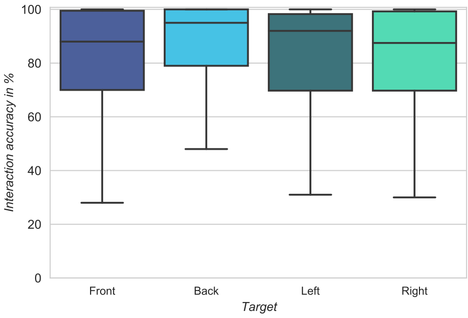

FIGURE 6.12: Accuracies per room direction

6.6 Supplementary data

The effect of external factors, such as age, gender, or experience has also been analyzed for the visually impaired and blindfolded versions. Figure 6.13 shows the relationship between age and the accuracies. A one-way ANOVA test showed statistically significant differences in mean accuracy between the age groups (p = 0.008). Similar to the age groups, statistically significant differences were also found based on the user's experience with virtual reality (p = 0.008).

Figure 6.14 shows how VR experience tends to positively influence accuracy. On a scale of 1-5, the sighted participants had the least VR experience on average (1.97), followed by the visually impaired (2.42). The blindfolded group had the most experience with VR, with an average score of 4.0 out of 5.

Figure 6.12 shows the relationship between the placement in the room and the interaction accuracy. With the exception of the objects in the back, all other directions have similar interaction accuracies. As seen in Figure 4.3, the back of the room has fewer objects than the front, causing inconsistent horizontal spacing.

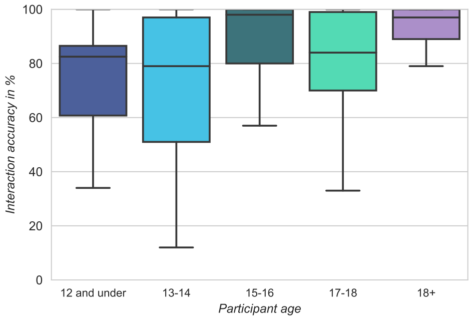

FIGURE 6.13:
Accuracy per
age group

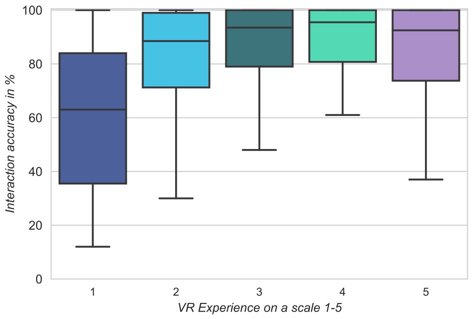

FIGURE 6.14:
Accuracy based
on user experience

Virtual reality can cause light nausea and dizziness. Figure 6.15 shows that within this experience, barely anyone experienced these symptoms. The few visually impaired who experienced nausea or dizziness had varying levels of visual impairments, ranging from legal blindness to stereo blindness (inability to perceive depth). The experienced boredom was also investigated. The participants that had prior experience with VR tended to experience more boredom than those who had never tried it. This can be seen in Figure 6.16.

6.7 Observations and additional feedback

A variety of feedback was mentioned by participants or observed during the experiments. The sighted participants enjoyed the additional haptic and auditory feedback they received when looking at an object, similar to the visually impaired version. All groups also mentioned that the added haptic feedback during the animations improved the enjoyability and made their experience more immersive.

Although the visually impaired were able to recognize most of the haptic and auditory feedback they received, some mentioned that it could have been amplified to make it less subtle. A few sound effects were confusing yet intriguing, such as the audio that played during the sword fight. Participants mentioned how some additional feedback would be appreciated to let them know when a previous interaction has officially ended, or when they successfully interacted with an object or historic

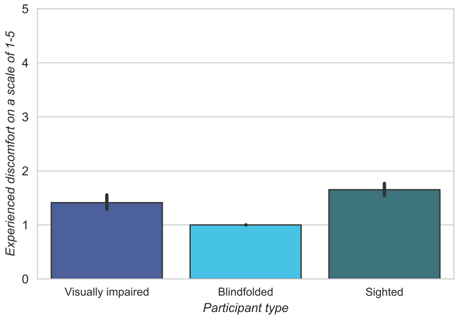

FIGURE 6.15: Discomfort per group

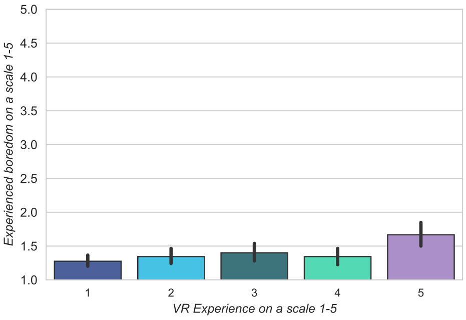

FIGURE 6.16: Boredom per version

figure. A voice line suggesting the player to follow the sound when they are being steered also would have been appreciated.

Some participants were also confused by the steering method since they expected the vibrations to increase in power the closer they were to the object, rather than the other way around. Due to the perceived subtlety of the auditory feedback when being steered, some participants thought the audio was simply ambient noise. Once they understood that they had to look for the object that was playing the audio, they were able to quickly find and interact with it.

When it came to the narrative voice lines, some visually impaired participants mentioned how some wording could have been more comprehensible. For example, mentioning the color of an item might not be understandable by some, especially if they were born with a visual impairment. Adding audio cues to redirect the user's vision to specific items was also a mentioned suggestion. This can be paired especially well with the narrative voice lines, which sometimes mention specific clothing or accessories of the historic figures. The visually impaired participants applauded the realism of the experience, with several participants mentioning how they completely forgot that they were actually in virtual reality.

7 Discussion

This section will elaborate upon the results from the previous section. Additionally, the limitations of this research and implications for future research will be discussed.

7.1 Analysis of the results

Through a thorough analysis of the results, conclusions can be drawn as to why certain features were successfully implemented. These can then be compared to the research goals and/or literature in order to answer the research sub-questions. As such, the results will be grouped by the research question they affect and will be discussed one by one.

7.1.1 Spatial awareness

When removing vision, it can be difficult to locate and differentiate objects from one another. Spatial audio is often used to help with locating objects, whereas unique sound effects can be used to differentiate virtual objects. By looking at the interaction accuracies and the users' understanding of the audio cues, a conclusion can be drawn as to how well the participants were able to locate and differentiate the virtual objects.

When looking at the mean accuracy of each of the three versions, there were statistically significant differences. This can be explained by the sighted group having a different interaction method, where interactions require the user to actually hit the collider of the target, without there being any leeway. This causes the range of possible accuracies to be smaller, hence the low standard deviation. Statistical equivalence was found between the mean accuracy of the BF and the SI group, which could be explained by the high level of VR experience of the BF participants since VR experience was shown to have a positive effect on accuracy.

Audio cue understanding and presence were fairly similar between all three groups, with the blindfolded group scoring those the worst. Statistical equivalence was found between the sighted and the visually impaired group, suggesting they had an equivalent experience. As for the blindfolded group, their lower rating can be explained by how the experience is likely the most distant from reality to them since they are not used to having no vision at all.

When trying to answer the research sub-question *"How can virtual reality spatial awareness be facilitated for the visually impaired?"*, it can be concluded that a combination of spatial audio playing at the origin of the virtual objects, and haptic feedback upon looking at the virtual objects can be used to successfully create a sense of spatial awareness.

7.1.2 Controls

The original version of the virtual reality museum had controls that were unsuitable for the visually impaired, due to the required precision and vertical aiming. A variety of variables can be analyzed in order to assess the quality of new controls, which only use the horizontal axis for aiming and the angle to the nearest virtual object to determine collisions.

When it comes to the time between interactions, there were no statistically significant differences between all three versions. The means were also statistically equivalent between all versions, suggesting the difference in interaction method does not affect the speed at which participants find and interact with the virtual objects. The total playtime was also statistically equivalent between the sighted and the blindfolded group. Although there were statistically significant differences in total playtime, the means and standard deviations were fairly similar across all three versions.

In terms of accuracy, the additional steering method that is added to the visually impaired version performed slightly worse than the standard exploring method. However, once activated it allowed users to find the designated object faster than with the exploring method. Because there was no clear indicator that the player was now being steered, some participants found the feature a bit confusing at first. Consequentially, the visually impaired participants, who used this feature the most, ended up giving the clarity of the controls a lower score than the blindfolded group. With additional auditory or haptic feedback, this feature could be a good addition in order to help users with their spatial awareness.

In the end, it can be concluded that by keeping interactions exclusively on the horizontal axis and using the user's head gaze direction, users can successfully and comfortably interact with virtual objects at varying places in the virtual environment. As such, the implementation successfully achieved the goal of the research sub-question: *"How can the controls be adjusted so that VI can successfully interact with the environment?"*.

7.1.3 Artifact and historic figures representation

Although some sonified representations were slightly confusing, most participants enjoyed the additional audio. It allowed them to successfully differentiate objects from one another. Although some visually impaired participants mentioned how more ambient noise could have been added, the sound design was regarded as realistic by most. This is reflected in the rating of the survey question regarding environment understanding, where the visually impaired group scored almost equal to the sighted group. Even though the differences in the understanding of the environment between the three groups were statistically significant, all three groups mentioned how they were still able to successfully understand what was happening around them. This suggests the manually-made 'reference' sounds as a form of auditory representations were a sufficient replacement, just not as good as vision was for the sighted individuals. The addition of manually-made 'reference' sounds, which complement the features of the object, can suffice as the answer to the research sub-question: *"How can historic figures and artifacts of a virtual museum be represented for the visually impaired?"*.

7.2 Blindfolded group

Existing research often makes use of blindfolded sighted participants as a replacement or supplementary group to the visually impaired group. Within this study, it was found that this is not always applicable, since the results of these two groups have not been consistently statistically equivalent. As such, future studies can still use this method to increase their sample size, but should always investigate (potential) differences between the two groups in order to fully assess the applicability for the visually impaired.

7.3 Evaluating inclusive play

The inclusiveness of the implementation can be analyzed by looking at the five guidelines for inclusive play by Sensory Trust [13]. Although these guidelines were originally created for outside play, they can be applied to virtual play as well.

The first inclusivity guideline *(Create a rich mix of play opportunities)* is achieved by allowing users to interact with the environment at their own pace and in their preferred order. This gives them the freedom to explore as they like, without following strict instructions. Because of the size of the room, participants also have the option to walk around, resulting in even more freedom in how they go through the experience.

By using multi-sensory stimulus to communicate gameplay events, the second guideline *(Engage the senses)* is achieved. Depending on the version, either the visual and haptic, or the visual sense is stimulated most. The guideline also explicitly mentions the importance of considering children with sensory impairments when designing the experience. Due to the addition of multiple types of sensory feedback, users with a variety of sensory impairments should be able to adequately experience the virtual museum.

The second guideline can be applied by heightening or lowering certain sensory stimuli in order to provide players with a choice. This could be especially interesting for friends of VI players, as they can choose between two different versions to play. They can lower visual stimuli and heighten touch stimuli, which could also give them some insight into what gaming for their VI friend is like. Additionally, this guideline stated that children with sensory impairments should be considered as well, which is done in the VI/BF version of the game, as they can explore through sound and vibration.

The virtual environment is split up into two parts. One side is for interacting with the historic figures, and one side is for interacting with the artifacts. Some parts of the room are also denser than others. This design was inspired by the third inclusivity guideline (*Make different types of space*), which allows users to choose which virtual objects they would rather interact with, without necessarily being exposed to the others. Because interactions with the artifacts do not require the user to actively listen to a narrator, it can be seen as a 'relaxing' time.

By using standard VR equipment in order to develop a VR museum especially designed for the visually impaired, the experience is as accessible as possible. Had advanced haptic equipment been used, the entry barrier for VR exhibitions would have been raised even more. As such, the fourth guideline *(Make it accessible)* is met, by allowing users with a visual impairment easy access to an experience that is similar to one that can be experienced by sighted individuals. By shifting the feedback method to focus on different senses, individuals with other sensory impairments can be given an opportunity to experience the museum as well.

At last, the fifth guideline *(Don't forget parents and families)* emphasizes inclusive play between disabled and non-disabled individuals. Since the experience is currently based on one player at a time, this is not yet relevant. Future iterations could play around with multiplayer, to see whether the social aspect of visiting exhibitions can be brought to virtual reality.

7.4 Limitations

Several limitations of the research should be acknowledged, as they could have influenced the results. Firstly, the total amount of participants could have been higher. Due to the difficulty of finding participants within this specific target audience, only 10 of the participants were actually visually impaired teenagers. Although some sighted participants were asked to play the visually impaired version instead, they did not always perform and score equivalent to the visually impaired group.

There was also a difference in age and VR experience between the participants. Participants also varied in education levels, ranging from the lowest levels to the highest levels. Although this can be useful to investigate the generalizability, it also makes it hard to draw conclusions when combined with such a small sample size.

This difference in experience is especially prevalent due to the sighted version having a built-in tutorial, whereas the visually impaired version only had an oral explanation. This could have caused a difference in the learning curve between the two versions.

Lastly, the VR equipment that was used is rather outdated. This means the visual quality is not on par with that of the latest equipment. This could have negatively affected the immersion and the discomfort of the sighted and potentially even the visually impaired group.

7.5 Future work

A variety of research directions can be investigated inspired by the findings of this thesis. With inclusivity and accessibility being the focus here, future work could look into optimizing the user experience of the sensory impaired. This can be done with the use of advanced haptic devices, or other advanced technologies, such as augmented or mixed reality. Different input methods can also be tested, such as eye tracking, hand gestures, or voice input.

Where the interaction in this implementation was adjusted to hopefully make it as easy as possible, others could look into keeping the interaction the exact same between different versions, and mainly focus on adding and adjusting the sensory feedback. As such, vertical differences in the interaction with the objects can be reintroduced and perhaps even highlighted. Lastly, the social aspect could be investigated through the use of multiplayer. This would allow users with a variety of sensory impairments to have a similar experience at the same time in the same room.

8 Conclusion

At last, the implementation as a response to the research problem will be analyzed, which was formulated as follows: *"Create an altered version of a virtual reality museum that can be adequately experienced by visually impaired teenagers"*. The main goal of the implementation was to create an inclusive and accessible version of a virtual reality museum, which could be adequately, and perhaps even equivalently experienced by visually impaired teenagers.

With the visually impaired being the main target group of this study, it is of utmost importance that they were able to successfully go through the virtual reality museum. To assess whether the implementation was successfully adapted, the three research sub-questions need to be answered. With the successful implementation of all three of the sub-questions, the virtual museum should be adequately experienceable by the visually impaired.

The adapted version successfully creates a sense of spatial awareness by using a combination of spatial audio and haptic feedback. This allowed the visually impaired participants to locate and differentiate virtual objects from one another. Although they were able to successfully locate the virtual objects, the visually impaired were slightly less accurate in doing so compared to the other groups. This can be explained by the sighted version having a slightly different collision detection method, where there is no leeway when barely missing the object. Experience with VR, which the visually impaired often lacked, tended to positively affect the interaction accuracies.

By changing the interactions to keep them exclusively on the horizontal axis, and using the user's head gaze direction for collision detection, the visually impaired participants were able to successfully interact with the environment while at a statistically equivalent pace as the sighted and the blindfolded group. Lastly, narrative audio and manually-made 'reference' sounds, which complement the features of the virtual objects, allowed users to understand what was happening around them, and which objects were in the room with them. Although the perceived understanding between the three groups was not statistically equivalent, the visually impaired group still rated their environment understanding really high, with there only being a slight difference to the sighted group.

Since all three research sub-questions were answered and successfully implemented into the virtual museum, it can be concluded that the main research problem of this thesis has been tackled. Although the user experiences were not always statistically equivalent, inclusive opportunities for play were present in the virtual museum, and the differences between versions were often small. The visually impaired were able to adequately experience the adapted version of the virtual museum, just not always to an equivalent degree as the sighted and the blindfolded group.

A Experiments appendix

A.1 Information and consent form

Virtual Reality Museum for the Visually Impaired

Consent and information sheet for the participants and their parents/guardians

A while back I created a rhythm game for visually impaired children, which was thoroughly enjoyed by those who tried it. This inspired me to continue this line of research for my thesis. For my thesis I look to improve accessibility of digital experiences such as games, this time focusing on virtual museums. In order to estimate the effectiveness of the implementation, I would like to try it out with a few students. During the experiments, the participant will wear a virtual reality headset to experience a gamified and interactive digital museum. Afterwards a few questions regarding their interests and the user experience will be asked. Some participants will be asked to try the 'normal' version, and some will be asked to try the version designed for the visually impaired, in which all visual elements are disabled to emulate having a visual impairment. Because the study focuses on (high school) students, parental consent is required.

In short, this will happen during the experiments, and with the data of the students.

- The following data will be gathered during the session: *how well the student can use the controls, the user experience of the virtual museum, generic demographic information, experience with virtual reality and gaming*
- All data will be anonymized and **cannot** be tracked back to an individual.
- If after or during the experiment the participant changes their mind, all data will be deleted, and the experiment will be stopped.
- The recorded data will **only** be used for research purposes and will **not** be used for commercial use
- Only current researchers and involved third parties (follow-up studies / supervisors) will have access to this anonymized data.
- Utrecht University has an agreement to protect all the data (EULA).

To give consent, the checkbox should be checked, and a signature should be placed in the text box below.

☐ *I read the document, understand what will happen during the experiments, and give consent for my child to partake in the study*

Signature

Thank you for reading the document! For additional questions, feel free to send an email to:
t.q.zaal@students.uu.nl

Best Regards,
Tycho Zaal

Universiteit Utrecht

A.2 Interview questions

1. How is teaching to VI different from teaching to SI
2. How important is it to know how something looks compared to knowing it exists? For example, kids that were born blind likely do not know how a dinosaur or a guillotine looks.
3. Do you use alternative methods of teaching that might be especially useful for VI, such as letting them feel objects instead?
4. It is quite common for history classes to occasionally watch documentaries, does this happen with your VI classes?
5. When a certain era is focused around art, how would you usually go about teaching these rather visually prominent things?
6. Does the school go on excursions to museums for example? And if so, which ones are prioritized and how is the experience different from with SI?
7. How familiar are the students with the Golden Age? Are there any specific historic figures or art pieces that they might know better than others?

B Survey appendix

B.1 Qualitative survey questions

Survey

Start of Block

Instructions: The game generated a random number + letter for you (example: 123A). Please enter your number below.

Question 1: What is your user ID?

____

Page Break

Question 2: What is your age?

○ 12 and under (4)

○ 13-14 (5)

○ 15-16 (6)

○ 17-18 (7)

○ 18+ (8)

Question 3: Do you have a visual impairment (defined as an issue with sight that can NOT be resolved by using glasses)?

○ No (1)

○ Yes: colorblind (2)

○ Yes: full/legal blindness (3)

○ Yes: low vision, or another similar impairment (4)

Question 4: What gender do you identify as?

○ Female (1)

○ Male (2)

○ Non-binary / other (3)

Page Break

Question 5: How often do you visit museums?

○ Never (1)

○ Up to once a year (2)

○ Between 1 and 5 times a year (3)

○ Over 5 times a year (4)

Skip To: Instructions If How often do you visit museums? = Never

Instructions: For the upcoming questions, please select the option that best represents how much you agree with the statement.

Question 6: "I enjoy visiting museums"

○ Disagree a lot (1)

○ Disagree a little (2)

○ Neutral (3)

○ Agree a little (4)

○ Agree a lot (5)

Display This Question:

If How often do you visit museums? = Never

Instructions: For the upcoming questions, please select the option that best represents how much you agree with the statement.

Display This Question:

If Do you have a visual impairment (defined as an issue with sight that can NOT be resolved by using... != No

Question 7: "I would visit museums more often if they were more accessible to me"

○ Disagree a lot (1)

○ Disagree a little (2)

○ Neutral (3)

○ Agree a little (4)

○ Agree a lot (5)

Question 8: "I have an interest in art"

○ Disagree a lot (1)

○ Disagree a little (2)

○ Neutral (3)

○ Agree a little (4)

○ Agree a lot (5)

Question 9: "I have an interest in history"

○ Disagree a lot (1)

○ Disagree a little (2)

○ Neutral (3)

○ Agree a little (4)

○ Agree a lot (5)

Question 10: "I have experience with Virtual Reality"

○ Disagree a lot (1)

○ Disagree a little (2)

○ Neutral (3)

○ Agree a little (4)

○ Agree a lot (5)

Page Break

Instructions: For the upcoming questions, please select the option that best represents how much you agree with the statement.

Question 11: "I learned something about the Night's Watch from this experience"

○ Disagree a lot (1)

○ Disagree a little (2)

○ Neutral (3)

○ Agree a little (4)

○ Agree a lot (5)

Question 12: "The virtual reality museum was boring"

○ Disagree a lot (1)

○ Disagree a little (2)

○ Neutral (3)

○ Agree a little (4)

○ Agree a lot (5)

Question 13: "I felt engaged during the experience, and wanted to continue playing"

- ○ Disagree a lot (1)
- ○ Disagree a little (2)
- ○ Neutral (3)
- ○ Agree a little (4)
- ○ Agree a lot (5)

Question 14: "It felt as though I really was there in the virtual environment"

- ○ Disagree a lot (1)
- ○ Disagree a little (2)
- ○ Neutral (3)
- ○ Agree a little (4)
- ○ Agree a lot (5)

Question 15: "I experienced nausea or dizziness during the experience"

- ○ Disagree a lot (1)
- ○ Disagree a little (2)
- ○ Neutral (3)
- ○ Agree a little (4)
- ○ Agree a lot (5)

Page Break

Instructions: For the upcoming questions, please select the option that best represents how much you agree with the statement.

Question 16: "The controls were easy to understand"

- ○ Disagree a lot (1)
- ○ Disagree a little (2)
- ○ Neutral (3)
- ○ Agree a little (4)
- ○ Agree a lot (5)

Question 17: "I understood what the audio cues meant"

- ○ Disagree a lot (1)
- ○ Disagree a little (2)
- ○ Neutral (3)
- ○ Agree a little (4)
- ○ Agree a lot (5)

Question 18: "I understood what was happening around me in the virtual environment"

- ○ Disagree a lot (1)
- ○ Disagree a little (2)
- ○ Neutral (3)
- ○ Agree a little (4)
- ○ Agree a lot (5)

Question 19: "I would like to try similar experiences in the future"

- ○ Disagree a lot (1)
- ○ Disagree a little (2)
- ○ Neutral (3)
- ○ Agree a little (4)
- ○ Agree a lot (5)

Question 20: "I would rather visit similar virtual (reality) museums than physical museums"

- ○ Disagree a lot (1)
- ○ Disagree a little (2)
- ○ Neutral (3)
- ○ Agree a little (4)
- ○ Agree a lot (5)

B.2 Survey design dimensions

Question	**Experiential Design Dimension**
1. What is your age	-
2. Do you have a visual impairment (defined as an issue with sight that can NOT be resolved by using glasses)?	-
3. What gender do you identify as?	-
4. How often do you visit museums?	-
5. I enjoy visiting museums	-
6. I would visit museums more often if they were more accessible to me	-
7. I have an interest in art	-
8. I have an interest in history	-
9. I have experience with Virtual Reality	-
10. I learned something about the Night's Watch from this experience	Active
11. The virtual reality museum was boring	Active
12. I felt engaged during the experience, and wanted to continue playing	Affective
13. It felt as though I really was there in the virtual environment	Affective
14. I experienced nausea or dizziness during the experience	Affective
15. The controls were easy to understand	Cognitive
16. I understood what the audio cues meant	Cognitive
17. I understood what was happening around me in the virtual environment	Sensory
18. I would like to try similar experiences in the future	Active
19. I would rather visit similar virtual (reality) museums than physical museums	Active

TABLE B.1: Survey questions and their respective Experiential Design Dimension

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