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Game and Media Technology Master Thesis

Investigating the User Experience of Simulated Reality in Museums

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Abstract

In an increasingly fast-paced society, museums are facing the challenge of engaging visitors who crave immersive and interactive experiences. The conventional stations and technologies used in museums often fail to captivate the modern audience, leading to a less impactful museum visit due to the lack of a user-centered design approach. This study investigates the effectiveness of touchscreen kiosks and Simulated Reality technology in delivering user-centered design experiences for museum visitors. Through a user study involving museum visitors and workers, the advantages and disadvantages of each technology were assessed. Our findings revealed several advantages and disadvantages between the two technologies, which can be used differently to enhance the museum experience depending on the museum station's purpose. To aid museum station designers in making informed decisions, I proposed a decision tree recommendation model, considering factors such as museum content, visitor demographics, and exhibit goals. Embracing user-centered design principles and adopting innovative technologies can empower museums to meet modern visitor expectations and create compelling and memorable interactive exhibits.

Contents

1. Introduction

Our contemporary society, along with the rapid development of technology has generated museum visitors that are in a constant search for sensations, experiences, and multimodal interaction [1] [2]. As a result, it is needless to say that ordinary museums become victims of this development since fewer and fewer individuals are willing to enter the museum in order to read or see artifacts they cannot touch or interact with at all.

It is highly essential that museums keep up with the technology to spike and maintain individuals' interest. Prior studies[2] have shown that museums are trying to find the balance between the best user experience interaction with technology in museums with the use of Augmented Reality (AR) or Virtual Reality (VR), but unfortunately, the VR / AR experiences do not reflect the value of the real artifacts in the museum, since they cannot be 100% reproduced virtually (e.g. paintings [2]). Moreover, Augmented Reality and Virtual Reality technologies risk disrupting visitors' experience in the museum because museums are generally seen as places where one can go back in time [2].

Another step that museums have taken is the implementation of touchscreen kiosks. While walking past the artifacts in the museum, visitors are able to stop at the touchscreen kiosks and learn more about the context of the artifacts in the exhibition, how they were created, generated, or invented, and so on. However, the COVID-19 pandemic has influenced the museum experience as well, making the use of touchscreen kiosks almost impossible to use due to the high hygienic risk. Moreover, the higher chance of spreading germs and infections could be also questioned in non-pandemic circumstances in the greater museums with a considerably higher flow of visitors, since interaction with touchscreen kiosks implies hands touching surfaces that are not cleaned after each visitor use.

Since museums have been lately focusing more on communicating with the visitors and less on their collection, more emphasis has been placed on making 2D videos available. Unfortunately, large texts do not seem to encourage visitors to read them, and too long 2D videos can make visitors lose their patience [2]]. As a result, most visitors are unable to leverage their experience in the museum since they are discouraged to interact with the information channel. This happens due to a lack of engagement – which is a key concept - of the visitor with the information medium, mostly because a multimodal interaction is not provided in any way.

In order to solve the problem of hygiene, and disruption and to increase visitors' experience in the museum, this paper proposes an investigation of the use of technology from a slightly different perspective: using autostereoscopic monitors with eye-tracking and hand-tracking. Autostereoscopic monitors (glasses-free 3D monitors) have been around for some time and the human-computer interaction regarding them has been significantly improved due to the accuracy of the latest sensors and computer graphics; since they do not require any other equipment to be set up, they could provide a better visitor experience without any distractions.

This paper proposes a comparison of the visitors' experience and engagement between 2D touchscreen kiosks and autostereoscopic monitors. This way, the displays will be used not to present or recreate museum artifacts, but present - in an interactive, practical manner - the procedures, usages, or other similar aspects relevant to the museum visit. Sense of presence and agency and engagement rate of the participants' performance (and opinions) will be measured and investigated in the experiment to check if the user experience gained from performing on a specific device is better than the other one in the museum context and later, in broader circumstances.

The research questions for this study are:

RQ1. *Which device enhances better the user experience in museums based on visitors' perspective and their sense of presence, control, and engagement?*

RQ2. *What are participants' opinions on touchscreen kiosks vs SR monitors in Museums?*

RQ3. *Is there potential for (increasing) learning outcomes with SR monitors?*

We are very interested in answering RQ1 and hypothesizing if the museum visitors' experience for each specific device can be generalized to broader circumstances. In order to be able to respond to the main research question (RQ1), an exhaustive investigation and overview of museum visitors' behavior, senses, and technology was critical. Additionally, an overview of technologies already used in the museum was necessary with regard to making a relevant device comparison. On the same note, controllers were reviewed in order to find the most natural and suggestive way of interacting with technology.

As far as qualitative measures are concerned, several psychological frameworks were reviewed along with popular theories generally used in this area of research.

2. Previous Work

2.1 Sensory Museology

In this chapter, an overview upon the objectives of museums and the emphasis of sense inclusion in the museum experience from early ages up to present is presented.

The perception of museum visits has changed over the last centuries. While the twentieth-century museums are seen by scholars as places where visitors become spectators of glass-covered artifacts [1], the first museums of the seventeenth and eighteenth centuries were sites where visitors were permitted to handle artifacts [3] to leverage their engagement. It was believed that handling objects lead to faster learning, aesthetic appreciation of forms and beauty unavailable to the eye [4], and intimacy with the original creators of the objects. Moreover, touching artifacts was considered a method of healing, giving visitors a sense of well-being. Unfortunately, according to Niquette[5], by the end of the nineteenth century, the practice of handling museum artifacts has been removed due to the assumption that collections must be seen, not handled by public. This change can be a result of the "exhibitionary context" and the birth of public museums that happened in the nineteenth century. As a consequence of museums being opened to the worldwide public, handling artifacts was considered too damaging[1].

Although the transformation of museum visitors from artifact handlers to spectators has been seen as a "progress of civilization", the most salient trend in the contemporary museology is the rehabilitation of touch[1]. Since museums open to the hands-off trend are still not permitting any tactile contact with objects deemed to be collectables, reintroduction of touch has been facilitated by haptic interfaces using digital technology [6]. Additionally, the technologization of the senses has developed a plethora of possibilities for museums to offer their visitors a multimodal experience, by providing not only haptic channels, but also visual and auditory channels, with video screens, speaker systems and others.

Finally, the twenty-first century acknowledges a sense comeback, adding didactic multimodal approaches and higher affective participation to the museum visit [1]. As a result, it is primary important to investigate the best multimodal interaction for visitors' experience and learning in contemporary museums, hence this current study.

2.2 Museum Visitors

In order to deliver appropriate installations that can leverage visitors' experience in the museum environment, it is crucial to perform an analysis over the types of people that visit museums. A handful number of studies conclude that culture exposure from an early age can lead to adult individuals with culturally shaped mind that are more likely to participate in museum visits due to the influence of cultural childhood experiences and parental modeling[7][8].

An interesting aspect that often influences museum visits is the environmental factor, meaning that individuals are more likely to participate in a museum due to word-of-mouth (friends, family, neighbors, coworkers), advertising or promotional campaigns [9]. Moreover, Falk [10] concluded that more than 80% of first-time visitors have heard about the institution from either friends or family, while publicity managed to attract less than 20% of the visitors.

In their study[11], Booth outlines three types of museum visitors:

- *General visitors*
- *Educational visitors*
- *Specialist visitors*

According to Booth, general visitors are the visitors that require general information, such as museum opening times, important exhibitions and other museum facilities [12] [11]. Educational visitors are visitors that ask for more in-depth information in the scope of visit planning or project creation. Finally, specialist visitors are the visitors that need information regarding specific museum collections and expertise, and online access to detailed information about the collections. Falk proposes five general personas that can be met in museum environments[13]:

- *Explorers*

Explorers are visitors that seek museum content that is captivating and with which they can engage

- *Facilitators*
  Facilitators are visitors who are focused on enabling others to experience the museum experience at its full potential (e.g. parents bringing children to the museum)
- *Hobbyists & Professionals*
  These visitors are oriented on achieving or studying a specific content-related objective in the museum environment (e.g. painters that want to see a specific work of art)
- *Experience Seekers* // Experience seekers are visitors that are satisfied by visiting a museum as they believe that it is an important destination. Thus, their satisfaction comes from ticking their "bucket list"
- *Rechargers* Rechargers are visitors that seek a restorative, contemplative experience. They see the museum as a way of relaxation from the work hustle or a reaffirmation of their religious beliefs.

Additionally, Falk & Dierking [14] advise a multiple-level representation of information for time-constrained visitors and visitors that are satisfied by investing time in interacting with digital stations in the museum.

Another study [15] outlined several design issues and suggestions for museum multimedia interactive exhibitions usage and visitor experience improvement:

- *Effective use of technology*
- *Limited contact time*
- *High traffic/use*
- *Visitors travel in groups*
- *Need for revisit desire generation*
- *Exhibitions must work without supervision*
- *Educational content presented in an engaging, accessible manner*

However, their recommendations are vague and do not offer concrete guidance on how to meet users' needs. The current research is nevertheless building on these provided suggestions, aiming to delivering a user-centered game design for the experiment setup.

2.3 Technology in Museums

The following section provides exhaustive insight over the usage, benefits and/or drawbacks of technology currently used in museum contexts. Thus, the analysis starts with touchscreen kiosks, due to their high popularity in museum environments and continues with audio tours, Virtual Reality, Augmented Reality, and finally, Simulated Reality.

2.3.1 Touchscreen Kiosks

Touchscreen kiosks are one of the most common interaction devices in the twenty first century museums. According to Burmistrov[12], the reason behind using touchscreen kiosks is to provide involvement and increase the visitor rate. Since contemporary society is most familiar to touch gestures and since technologies are considered a brilliant method of attracting visitors to museums, touchscreen kiosks become the most feasible tool in museum environments [16] [17].

In their study, Economou suggests [18] five different touchscreen kiosks use cases for museum environments:

- *Conceptual pre-organizers and museum directories:*
  These kiosks are placed at a key location at the beginning of the museum experience, aiming to convey introductory information helping the visitors to familiarize themselves with the exhibitions
- *Advanced electronic labeling system for museum specimens:*
  These kiosks aid museum curator to present avoid information overload on the museum exhibition labels. A great deal of information can be found navigating through the kiosk, the visitor being offered the freedom of choice to go deeper into the exhibition details
- *Basic background information about the exhibition themes and their general*

context:

These kiosks present the background and perspective of the exhibition. They illustrate the critics, the culture or explain the peculiarities of specific movements that influenced the exhibition

- *Reference point after visiting part of the exhibition and before continuing the visit:*

  These kiosks offer more in-depth information about specific exhibitions as in Figure 2.1.

- *Post-visit resource:*

  These kiosks offer takeaways in the form of digital content that can be scanned or emailed to the visitors' email address and are generally placed at the end of the exhibitions.

Figure 2.1: Museum visitor using a touchscreen kiosk

However, as good as they may seem for the museum environment, touch-screen kiosks do have several constraints and accessibility issues, according to [12]:

- *Physical access:*

  Disabled visitors should be able to move and place themselves in front of the touchscreen kiosk. Thus, the kiosk should be strategically placed in locations with enough clear space paths for wheelchairs. Overall, these paths should not constrain visitor flow by any means.

- *Reach and visibility:*

  The design of the touchscreen kiosk should be created with ergonomics in mind so that they are easy to reach, be seen, and interact with. Additionally, the angle of the screen should be also taken into consideration in order to avoid gorilla arm development.

- *Display interfaces:*

  Display materials and kiosk positioning should be chosen in such a way that the kiosks will not be prone to glare from reasonable viewing angles. Moreover, text, icon size, parallax, and other similar details should be considered.

- *Touchscreen interfaces:*

  While visitors in wheelchairs should be able to reach and interact with the touchscreen kiosk, blind or low vision users should be facilitated with other alternatives of interaction, such as alternative haptic controls or voice interfaces.

- *Feedback:*

  The kiosk should be able to provide comprehensible feedback for users. This includes disabled users as well. The reason for this aspect is that visitors should be provided with responses to their actions to avoid confusion.

Touchscreen kiosks are a significant tool in creating the best visitor experience in museum environments. However, limitations must be mitigated in order to keep the experience at a high level.

With respect to this current research, touchscreen kiosks were considered as worth investigating devices with a focus on museum interaction and user experience, due to their popularity. Additionally, novel technology such as SR could be a valuable asset in mitigating the limitations of touchscreen kiosks.

2.3.2 Smartphones

In contemporary museums, the use of smartphones as information facilitators, guides, or audio guides is more and more common. However, a first-sight analysis of smartphones in museum environments from visitors' perspectives can reveal unexpected results.

First and foremost, while having your own museum guide in your pocket might be convenient, the constant need to check the smartphone for choosing different options in the guide or searching for specific information about the exhibits can disrupt the visitor from the actual exhibition. Additionally, the screen size difference between any smartphone and museum panels, touchscreen kiosks, or other installations is considerably significant [19].

Second, using smartphone applications for additional information or guides for exhibitions is a smart solution with regard to hygiene problems, since smartphones are generally used by only one person. However, prior research[19] mentions visitors complaining about installing the application through mobile data which can become expensive. Despite museums providing free wifi network for application installations, the problem of smartphone local storage prospective issues remains critical.

Taking all these aspects into consideration, smartphones still remain a great tool for everyday use, however, they are not feasible for everyone in the museum environment. With regard to this study, phones were not selected to be part in the comparative evaluation.

2.3.3 Audio Tours

Audio Tours are common devices that are broadly used in museums. While in the past they were handheld devices that used radio waves, nowadays audio tours are hands-free devices (radio waves technology) or applications that can be installed on mobile phones [20]. Thus, visitors can install the application on their mobile phones, use headphones for the best audio tour experience, and scan exhibits' QR codes for information with their cameras.

Figure 2.2: Visitors using audio tour guides in Van Gogh Museum, Amsterdam, the Netherlands

For a better user experience, a study ran by Vallez et al. [20] has developed several applications for museum environments, among which EoT-based headset applications stood out. Figure 2.3 presents a depiction of the EoT-based headset hands-free audio guide scenario.

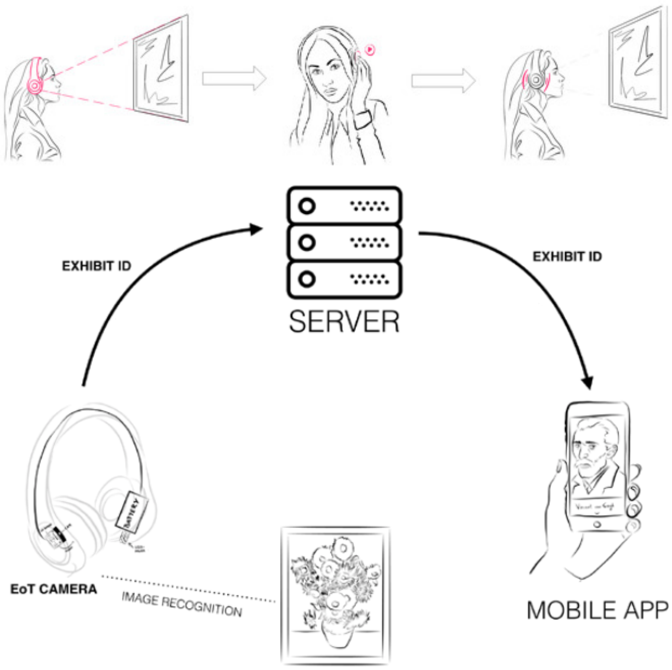


Figure 2.3: Hands-free museum audio-guide use case

The EoT-based headset application offers a hands-free experience for the visitors. They can explore the exhibition with the headset on being notified about available audio interpretations of recognized exhibits. However, the use of headsets in general raises the problem of hygiene, especially in public place such as a museum and post-pandemic days. Because of this reason and their lower rate of popularity in comparison with touchscreen kiosks, audio tours were not included in the current comparative study.

2.3.4 Virtual Reality

There has been a substantial increase in museum environments that adopted virtual reality technology in order to embrace technological innovation and match the younger generation's expectations. Certainly, the use of VR has created new content and storytelling dynamics [21], providing multiple ways in which visitors can interact with the museum environment [22]. According to [23], VR can be used for reconstructing historical events, for experiencing the enhancement on-side [24] and off-side [25], education purposes [26], and lastly for creating interactive, engaging and immersive experiences for museum visitors [27].

Figure 2.4: VR performance in the Museum of Nature in Berlin, Germany

Although VR is seen to be a significant tool for museums, scholars have shown concerns when VR opportunities are overemphasized while VR drawbacks are overlooked [19] [28]. A study [2] conducted by Maria Sheshade and Theopisti Stylianou-Lambert aimed to explore the advantages and disadvantages of Virtual Reality and Augmented Reality technologies and the museum professionals' vision for future museum technologies. Thus, after investigating 15 museums from diverse countries, data has shown that museums use technology to "remain relevant" in a world where visitors and younger generations are in a constant search for technology interactions and sensations, while seeking interactions that do not diminish the content [2]. With regard to virtual reality advantages, participants have stressed seven categories of advantages, namely:

- *Engagement with collections*
- *Visitor attraction*
- *Education*
- *Customised experiences*
- *Immersion*
- *Technology reliability*

- *Accessibility*

After being asked about the disadvantages of virtual reality, participants stressed the following:

- *Lack of social interaction*
- *Distraction*
- *Staffing & training*
- *Technology acceptance*
- *Accessibility*
- *Cost*
- *Graphics quality*
- *Practical & technical*
- *Exhibition flow*

Although some of the aspects mentioned above were highlighted both as an advantage and disadvantage, the same features can become limitations if seen from a different point of view. Thus, VR can provide powerful experiences through immersive storytelling and content, yet participants identified a strong disadvantage as an offset: since VR is mostly designed for only one user, there is a lack of social interaction. Moreover, being cut off from the rest of the museum environment creates a social rupture and distraction from the group the visitor belongs. As a result, group visitors or families will encounter a so-called "antisocial experience" [2].

While VR can bring new learning concepts into the educational field by also offering customized experiences (being combined with other technologies), the graphics quality makes the world appear unrealistic. Additionally, VR can be considered quite reliable, malfunctions may occur and the exhibition flow could be influenced negatively [2]. As for accessibility, VR can facilitate virtual explorations such as inaccessible ships, being considered a great marketing tool for attracting visitors. However, VR still remains inaccessible to deaf or blind individuals or children under 12 (the bottom-line age for VR use), and some visitors do not fully accept technology in museum environments [29] [2]. Therefore, participants belonging to these categories will be exposed to the experience of being left out [2]. Lastly, VR controllers and head mounted displays (HMDs) might consist in an expensive investment for museums, especially since cultural funds are generally short on budget [2]. As some visitors are not generally exposed to technology and VR specifically, staff and training should be provided at VR stations, meaning even more financial investments.

Another negative aspect regarding VR that participants have stated was hygiene and health concerns. VR headsets and controllers should be cleaned and disinfected after each use due to the large number of users per day. Moreover, it is important that visitors acknowledge the risk of headaches, cyber-sickness and eye strain that can occur during or after using VR.

In summary, although VR can represent an innovative tool for museums, museum professionals presented more challenges than advantages for using VR technology in museums. With regard to the current research, it is hypothetically believed that SR monitors can still offer the benefits VR can offer without the disadvantages presented above. Thus, VR was not included to the current research.

2.3.5 Augmented Reality

Despite the fact that museums have experimented Augmented Reality (AR) since the early 2000s, the museum community continues to be skeptical towards AR's efficiency since most of the AR softwares on the market have been unstable [19]. However, museums still embrace AR technology since it supports audience participation [30].

Figure 2.5 illustrates a common method of how AR technology can be used in museums.

Since museum environments are generally crowded areas, with a great deal of information already presented in a non-augmented reality, cognitive overload may occur when AR applications are used. The aspect of visitors being absorbed more by the AR devices than the museum exhibition creates also a concern, let alone the fact that visitors should also use their own device to download the AR application, process which should be clear enough and self-explanatory. Additionally, if visitors are internationals, a side issue would be the nonexistent WiFi network [31], due to the fact that roaming data fees can be expensive.

Figure 2.5: Visitor using AR during "The Private Life of Rembrandt" exhibition in 2019, the Netherlands

AR technology can be dependent on other technologies, in the matter of indoor or outdoor use. Thus, GPS signals are needed for AR outdoor applications, but they become inadequate when the application is used indoor (e.g. change of floor levels) [32]. Another known issue for indoor use is the incompatibility between the higher light conditions for object detection and low light presented in the museum for conservation purposes [33].

Crowds represent a strong obstacle in using AR applications, especially in museums with a larger visitor flow, as they can interfere with the physical space needed for AR, thus downgrading users' experience. Moreover, they can restrict visitors' AR itinerary choices [34]. Crowds generate a considerable amount of noise levels, meaning that the quality of the auditory narrative or explanations of AR applications will be negatively affected, especially if users must move or hover their device.

The study conducted by Diana Marques and Robert Costello presented a few solutions to the issues priorly presented. They developed an AR application on iPads for a specific, appropriately-lighted exhibition room in the National Museum of Natural History (NMNH) [19]. Since the museum was crowded, they designed the application to last for approximately 2 minutes to avoid a rupture in the visitor flow. Although there was no need for the visitors to download and install the AR app, they complained about not being able to hear the narrative. This led to the loss of engagement during the exhibition visit. Moreover, some visitors confronted an overwhelming thought that they were supposed to use all provided content in the application.

Finally, it is believed that AR technology can improve the museum experience among visitors, however, it is of high importance that the design of the software should be well thought, whereas the environmental constraints should be removed as much as possible. Therefore, in the current research, AR was excluded since touchscreen kiosks were still preferred in terms of design and use case scenarios.

2.3.6 Simulated Reality

Simulated Reality (SR) is the perception of a truly believable interactive 'Reality', without the need for unnatural peripherals such as headsets and controllers[35]. The concept has been created by Dimenco, a company that creates autostereoscopic 3D monitors with hand and eye tracking. Their 3D technology is based on creating unique parallel images due to motion parallax. Thus, the company managed to provide users with the possibility of interaction with the 3D content on the screen without additional devices, such as glasses or controls in a more eye-comfortable way.

Figure 2.6: Advertisement of Dimenco's Simulated Reality technology

2.3.6.1 Autostereoscopy

Autostereoscopy is a type of technology that displays stereoscopic images without the use of special headgear, glasses, or anything for the eyes on the part of the viewer. The peculiar, attractive aspect of autostereoscopy is that it provides the viewer with perceiving depth image[36], making the image appear more realistic. Because headgear is not required, it is also called "glassesless 3D" or "glasses-free 3D". There are two broad approaches currently used to accommodate motion parallax and wider viewing angles: eye-tracking, and multiple views so that the display does not need to sense where the viewer's eyes are located[36]. Examples of autostereoscopic display technology include lenticular lens, and parallax barrier, and may include Integral imaging, but notably do not include volumetric display or holographic displays.

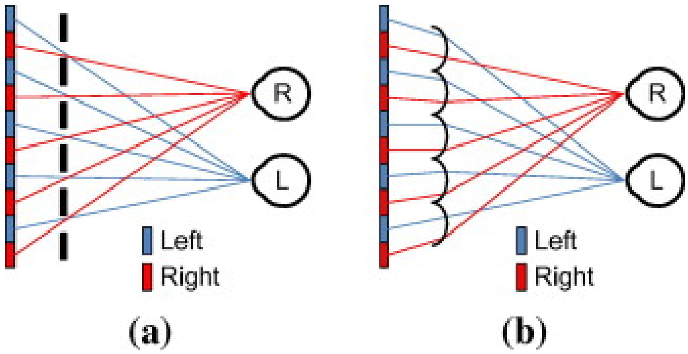


Figure 2.7: Autostereoscopic phenomenon

In figure 2.7 the autostereoscopic phenomenon was depicted. Thus, in scheme *a)*, the discontinued black vertical line represents the parallax. The Right eye (Red color) can only see the red portions of the screen, and the left eye (Blue color) can only see the blue portions of the screen. Thus, each eye sees a different image. In scheme *b)*, each screen portion belonging to the right eye and left eye is paired. This generates new combined images for the eyes. Lastly, the parallax also helps in generating new images at each viewing angle, all these providing the depth perception of the image.

What makes this technology stand out from the trivial 3D monitors is the implementation of the Ultraleap hand tracker, which provides a natural, intuitive interaction with the monitor by using hand gestures without any other type of controllers.

This technology is currently used by Beeld en Geluid Media Museum in Hilversum, The Netherlands.

Taken all this into consideration, it is believed that museum environments benefit from a plethora of technological devices that can leverage visitors' experience in this specific context. While common, classical stations, such as touchscreen kiosks are a valuable asset, designing more appropriate user-centered stations is needed since touchscreen kiosks, audio tours, smartphones, VR, and AR present diverse limitations and drawbacks. SR aims to bridge touchscreen kiosks and VR technology by covering the limitations of both technologies while offering additional benefits at the same time. Hence, this paper endeavours to present, test, and compare the benefits of SR technology and touchscreen kiosks and build a future base of research in user experience with regard to SR.

2.3.7 Standard 2D monitors vs. 3D monitors

Technology development has triggered the rapid design and development of 3D monitors as a replacement for 2D monitors. Although there surely are a plethora of benefits when using 3D monitors, researchers paid increased attention in the past years to reviewing the psychology, advantages, and disadvantages of 2D and 3D displays.

2.3.8 Advantages and Disadvantages

While understanding the benefits and drawbacks of technologies in museums is highly relevant for this current study, this section outlines the advantages and disadvantages of 2D and 3D monitors specifically, without controllers, in order to facilitate a better perspective upon the proposed comparison.

As stated previously, 2D and 3D monitors have a great deal of benefits and drawbacks, however, the opinions of researchers are divided because of the different use cases and purposes.

In their studies, [37][38], Taylor considers 2D monitors to be more efficient for model development due to higher performance, but nonetheless, other studies raise appraisal to 3D monitors for their 3D visualization, verification, and validation tasks[39][40].

Thus, Akpan and Shanker published a comparative evaluation [41] in which they analyze a great number of use cases for 2D and 3D monitors, using the Cognitive Fit Theoretical framework [42]. This framework explains the need for problem representations and task matching, resulting in better problem-solving performance. However, the absence of matching between the problem representation and the task results in absent choice guidance for the problem user and a worse performance[42].

Akpan's and Shanker's results prove that 3D monitors offer greater benefits than 2D monitors for the presentation of 3D models, simulations, or validation and verification tasks. Moreover, presentations shown on 3D displays were proven to have a greater impact on users than when presented on 2D displays. However, the creation process of 3D models can be time-consuming and may take longer times when used in development use cases, therefore 2D is considered more effective when it comes to performance.

Another comparative study [43] between 2D and 3D displays aimed to examine the tasks 3D displays are suited for.

Thus, results unveiled that 3D displays offer high benefits to spatial manipulations of objects. This was not a surprise, since a great amount of research has proven the benefits of binocular vision when grasping, reaching or controlling objects [44] [45] [46] [47] [48] [49] [50]. Another aspect that resulted from the review was that 3D is overall better for spatial understanding and recall tasks, with significant results in more complex tasks. As for positions and distances, 3D displays offered provided better accuracy and reduced times of completion for these types of tasks. However, this is not always true, since Reising and Mazur [51] found 3D displays to be beneficial only when there were no monocular depth cues. Opinions are split when search and identification tasks are concerned. A great deal of research was performed and the generated results are mixed, therefore, one cannot say the 3D display is always better for performing searching or identification tasks. Another use case that generated split opinions is navigation. While some studies show the benefits of using 3d displays for navigation [52], other studies prove that navigation on 3D monitors have no benefits [53][54], [55]. This means that 3D displays can sometimes be beneficial for navigational tasks only depending on task requirements ("when used in conjunction with other informational displays regarding hovering performance" [43]). Lastly, the medical domain has performed a great amount of research regarding learning and training tasks on 3D displays [52] [56] for training medical students and teaching.

Overall, 3D displays offer very select benefits on specific, complex tasks, especially if they are depth-related, hence the reason of investigating the user experience between (2D) touchscreen kiosks and SR (3D) monitors.

2.3.9 Human-Computer Interaction Controllers

In the current section, an overview of the most used controllers is presented.

2.3.9.1 Mouse & Keyboard

Mouse controllers have been aiding computer display control since 1965[57]. Up to this point, various types of computer mice have been used for diverse human-computer interaction (HCI) purposes, mostly:

- *Standard use (e.g. optical mouse, track-ball mouse, laser mouse, etc)*
- *Entertainment (e.g. gaming mouse, ergonomic mouse etc)*
- *3D Modelling (e.g. ergonomic mouse, 3D mouse, 6-DOF mouse, laser mouse etc)*

Keyboards, however, were introduced in 1955 and have been mainly used for computers. Although mouse and keyboard are the most common input HCI controllers, due to the rapid development of technology it is considered that these input devices are restricting the opportunities of HCI to a bare minimum[58].

As far as the museum environment is concerned, I decided not to use a mouse and keyboard for this study owing to hygiene concerns and spatial constraints. Furthermore, the use of mouse and keyboard are not commonly used in museums and integrating them into the current study might lead to disruptions in the visitors' experience, engagement, and flow.

2.3.9.2 Entertainment controllers

Entertainment as a purpose has strongly influenced HCI controller development. Therefore, joysticks, steering wheels, PlayStation and Nintendo Switch controllers, along with VR controllers have dominated the gaming domain.

However, these controllers have several constraints. Joysticks and steering wheels are generally used at a desk, implying that users must be seated while playing.

PlayStation and Nintendo Switch controllers offer more freedom to users, but the haptics and ergonomics of these controllers are not quite natural. VR controllers appear to solve both problems, giving the user endless freedom in the game and a natural ergonomic controller design. However, VR controllers can be used for VR games only.

As an overall, although entertainment has increased user opportunities - and user experience concomitantly, marketing reasons most probably have constrained controllers from offering users full freedom. Additionally, although these controllers might have fewer spatial constraints, they still need extra instruction personnel in museums and the hygiene problem is not solved. Thus, I decided not to use these controllers either.

2.3.9.3 Hands

With regards to user experience and especially HCI, a strong key concept is characterized by naturality [59]. Thus, using hands as controllers has become one of the biggest research targets due to the natural, common sense and suggestive way of control. As a result, tactile and gesture gloves, touchscreen and have appeared on the market to revolutionize HCI.

2.3.9.3.1 Touch With the introduction of touchscreen phones, touch has most probably become the most common way of interaction with screens [60]. Although different methods of tracking touch were implemented, they all share the same purpose: serving users with intuitive, natural and precise HCI, for handling, pointing or accessing information. Since this method implies physical touch, hygiene concerns may be raised. Touch input technology started in the late 1960's, 1980s for multi-touch device development respectively [58]. According to Wan-Chen, most commercial touchscreens split into two large categories:

- *Resistive touch screens*
- *Capacitive touch screens*

Resistive touchscreens consist of multiple layers. When the outside layer is pressed, it will activate the inside layers. This will cause an electrical resistance which will alter be identified as a "touch event".

Capacitive touchscreens are usually made of glass and have a transparent conductor layer. Unlike resistive touchscreens, capacitive touchscreens do not need pressure to identify touch events. This aspect comes with advantages and disadvantages. An advantage is that capacitive touchscreens are more precise, sensitive and allow multi-touch, unlike resistive touchscreens. However, they are more expensive and less reliable in unstable environments. Additionally, resistive touchscreens allow users to wear gloves, while capacitive touchscreen have several limitations (e.g. touchscreen gloves, etc). Since touchscreen displays are easier to clean and disinfect compared to keyboards or entertainment controllers (fat surface vs. ergonomic surface), they are cheap and do not require extra staff in a museum environment, I decided to use this type of interaction in my study.

2.3.9.3.2 Gestures: Gestures, however, have been used for handling object from distance, without physical touch [59]. According to Cadoz, there are three types of hand gesture functions[61]:

- *Ergotic*
- *Epistemic*
- *Semiotic*

Ergotic function transforms the environment by energy transfer. Epistemic function is used to acquire perception of the environment. This functions is always related to the ergotic function and requires contact with an object. Semiotic function is used to communicate information towards the environment (e.g sign language, gesticulations, etc).

2.3.9.4 Microsoft Kinect:

Microsoft Kinect is a motion sensor add-on for the Xbox360 gaming console, that senses mid-air gestures and speech. Unfortunately, Microsoft discontinued the manufacturing of Kinect in 2017.

Figure 2.8 presents an Xbox 360 with Kinect sensor. The Kinect consists of three important pieces that work together to track motion and create a screen image: an RGB color VGA video camera, a depth sensor, and a multi-array microphone.

Figure 2.8: Xbox360 with Kinect add-on

2.3.9.5 UltraLeap Sensors:

The Leap Motion Controller is an optical hand tracking module that captures hand movements and gestures with unparalleled accuracy. From XR to touchless kiosks, the Leap Motion Controller makes interaction with digital content natural and effortless.

Figure 2.9 presents the Leap Motion Controller from Ultraleap. After connecting

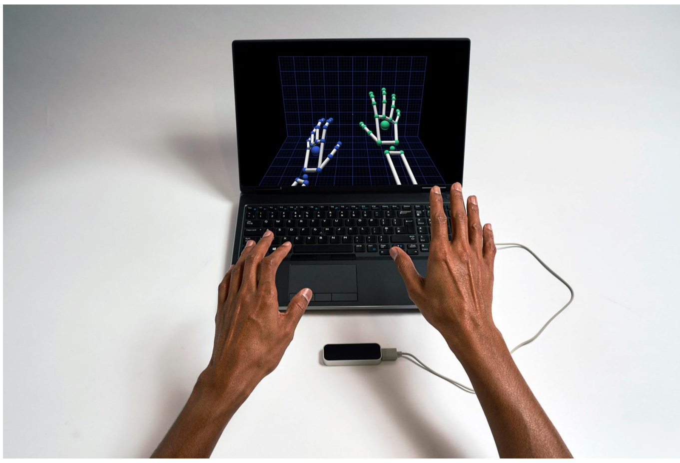


Figure 2.9: UltraLeap Controller Technology

the sensor to a laptop, the screen shows the hand tracking of the sensor.

So far, the leap Motion Controller detects several types of handposes with specific points:

- *Palm Direction Detector*
- *Proximity Detector*
- *Pinch Detector*
- *Finger Direction Detector, with bones:*
  - *Metacarpal*
  - *Proximal*
  - *Distal*

Most applications of hand gestures are found in entertainment (games), education, and healthcare (muscle memory reinforcement) [62]. The Leap Motion controller is currently included in the SR monitor hardware. Hand gestures can be used for muscle memory reinforcement applications, entertainment and others, and solve the problem of hygiene.

Similarly to touch, hand gestures are suggestive, do not require extra personnel, and solve the problem of hygiene at a higher extent. As a result, I decided to use this interaction in my study.

2.3.9.6 Eye-Gazing

Since eye-tracker-based applications have known a great success (e.g VR, AR), researchers and developers are investigating new eye-tracking possibilities in a more contemporary way: eye-gazing. In his study[63], Duchowski proposes a taxonomy for categorizing eye-gaze which can be seen in Figure 2.10. Therefore, there are 4 types of eye-gaze:

- *Active*
- *Passive*
- *Expressive*
- *Diagnostic*

Active eye-gazing depicts the power of real-time signal produced by eye trackers

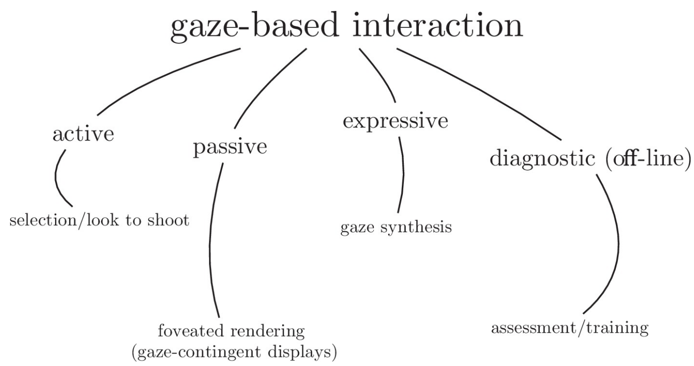


Figure 2.10: Eye gaze interaction taxonomy

in order to trigger an "action event" (e.g. Selection). Passive eye-gazing is generally used for gaze-contingent displays (GCD). According to [64], GCDs balance the information load displayed against the visual information processing capacity of the user with eye-trackers. Expressive eye-gazing applications revolve around eye-movement modeling with the most realistic eye-motion [65]. This is crucial since there is a strong interaction between character realism and their gaze[65]. Lastly, diagnostic eye-gazing refers to the analysis of eye movements during specific tasks. An example is shown in [66], where virtual laparoscopic training was held with novices and experts. The results between the novices' and the experts' gaze proved to be significantly different.

Certainly, eye-gazing can become an important way of HCI, however, Zhai suggests that eyes should not be used for interactive motor devices (that generally use hands), but more as a perceptual organ [67]. A strong reason for this aspect might be that eye-gazing is still prone to eye jittering or eye tracking errors, that can lead to inaccuracy and inadvert manipulations an a daily basis [68]. In their study [68], Moiz, Weber, and Lutteroth investigated alternative clicking scenarios for hypertext with eye-gazing. Mouse was still considered better than eye-gazing interaction methods.

Another study aimed to use eye-gazing for more complex interaction with displays [69]. However, due to the complexity of the interaction, touch was needed to complete the tasks, using the eye-gazing interaction still only for locating purposes.

Microsoft HoloLens: One worth-mentioning device that uses eye gazing is Microsoft's HoloLens [70]. HoloLens is similar to HMDs with holographic lenses that lay HoloLens in the AR technology domain.

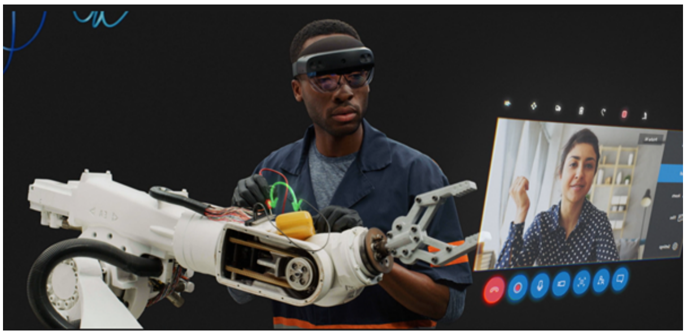


Figure 2.11: Person using HoloLens while working

Moreover, since the current study aims to compare the user experience in museums on touchscreens and SR monitors, the use of eye-gazing might interfere with the eye-tracking signals and the 3D optical phenomenon, leading to an unpleasant experience eventually. Subsequently, eye-gazing interaction was not considered in the current study.

	Naturality	*Price*	*Personnel*	*Space Constraints*	*Accuracy*
Mouse	No	3-180€	No	Yes	High
Keyboard	No	10-97€	No	Yes	?
Joystick /Wheel	No	53-549€	Maybe?	Yes	Medium
PS/Switch	No	30-87€	Maybe	None	?
VR controls	Maybe	19-60€	Yes	Yes	High
Touch	Yes	229-13,390€	No	No	High
Gesture sensor	Yes	105€	No	No	High
Eye-gaze	Yes	259€	No	No	Medium(-Low)

Table 2.1: HCI Controllers Overview with regards to this study

In Table 2.1, an exhaustive overview on the discussed HCI controllers is presented. As the table shows, the most convenient and similar interactions are touch and hand gestures.

Taking into account the features presented above, this study focuses mainly on hand interaction in museums: hand gestures and touchscreen.

2.4 Game Experience in Museum Environments

In order to understand the outcomes and factors of visitors' experience in museum environments and their information retetion potential, it is critical to analyze and comprehend their engagement, sense of presence and control from a psychological perspective. Thus, this section focuses on presenting popular frameworks used to measure, follow and/or investigate the cognitive processes that take place during museum station performances.

2.4.1 CAMIL theoretical framework

The Cognitive Affective Model of Immersive Learning (CAMIL) is a theoretical research-based model of learning in Immersive Virtual Reality (IVR) which summarizes all the research that was conducted in the immersive educational direction in order to explain and present the learning process in IVR[71].

Since most research studies have concluded that media interacts with method[71], CAMIL builds on this base and enhances presence and agency as the main psychological affordances of learning in IVR and describes how these two affordances are triggered by immersion, sense of control and representational fidelity. Furthermore, the framework presents six cognitive-affective factors that facilitate learning outcomes in IVR. These are interest, motivation, embodiment, self-efficacy, cognitive load and self-regulation.

CAMIL finally portrays the way the cognitive affective factors stimulate factual, conceptual, and procedural knowledge acquisition and knowledge transfer.

2.4.1.1 Immersive Virtual Reality

Virtual Reality can be defined as a simulated experience that can be similar or completely different from the real world. The technology behind it generally includes augmented reality or mixed reality and the person using the virtual reality technology makes use of specific equipment to leverage the virtual experience, such as monitors, multi-projected environments, controls for interaction with the artificial world and head-mounted displays (HMD)[72].

Immersion is defined by previous studies as a "description of overall fidelity in relation to physical reality provided by the display and interaction systems" [73][74][75]. This means that immersion can be differentiated by presence since presence is defined as a successfully supported action in the environment [76].

Immersive virtual reality emphasizes the efforts of designers and developers of leveraging the sense of presence and interaction with the artificial world in the VR environment[71]. Thus, IVR distinguishes itself by being accessed through HMD or cave virtual environment (CAVE); the user can easily see themselves in the virtual environment, with almost all distractions from the real world being minimalized[77]. The VR experience via HMD or CAVE is labeled as high immersion[71], whereas VR experiences via desktop computer is considered of low immersion[71].

2.4.1.1.1 Presence and triggering factors: The sense of presence can be described as the sense of being in a particular place or time period, or the awareness of one's current existence. According to prior studies, presence can be illustrated as the feeling of "being there"[78]. CAMIL synthesizes the previous research[79] regarding the determinants of presence in the following factors that are also shown in Fig. 2.12 : immersion, control factors and representational fidelity [71].

Therefore, immersion can be seen as a measure of vividness a system can provide, and also an extent to which the system can mitigate the real world[80]; control factors are measured by the extent of control, the mode and the rapidity of control[81], while representational fidelity encompasses visual realism and the consistency of object behaviour[82]. Based on prior studies[83][84], authors of CAMIL define three dimensions of presence, which are physical presence - one can experience virtual objects as real, social presence - virtual social actors are perceived as real social actors, and self presence - the virtual self is perceived as the real self.

2.4.1.1.2 Agency: Prior studies have described agency to be a feeling of generating and controlling actions[85], meaning that users of IVR environments have control over their actions in the virtual world. Therefore, a high sense of agency would mean that users can interact with the virtual world and change its narrative[86]. Since control factors consist of mode, immediacy and degree of control, it is needless to mention that there is a natural correlation between control factors

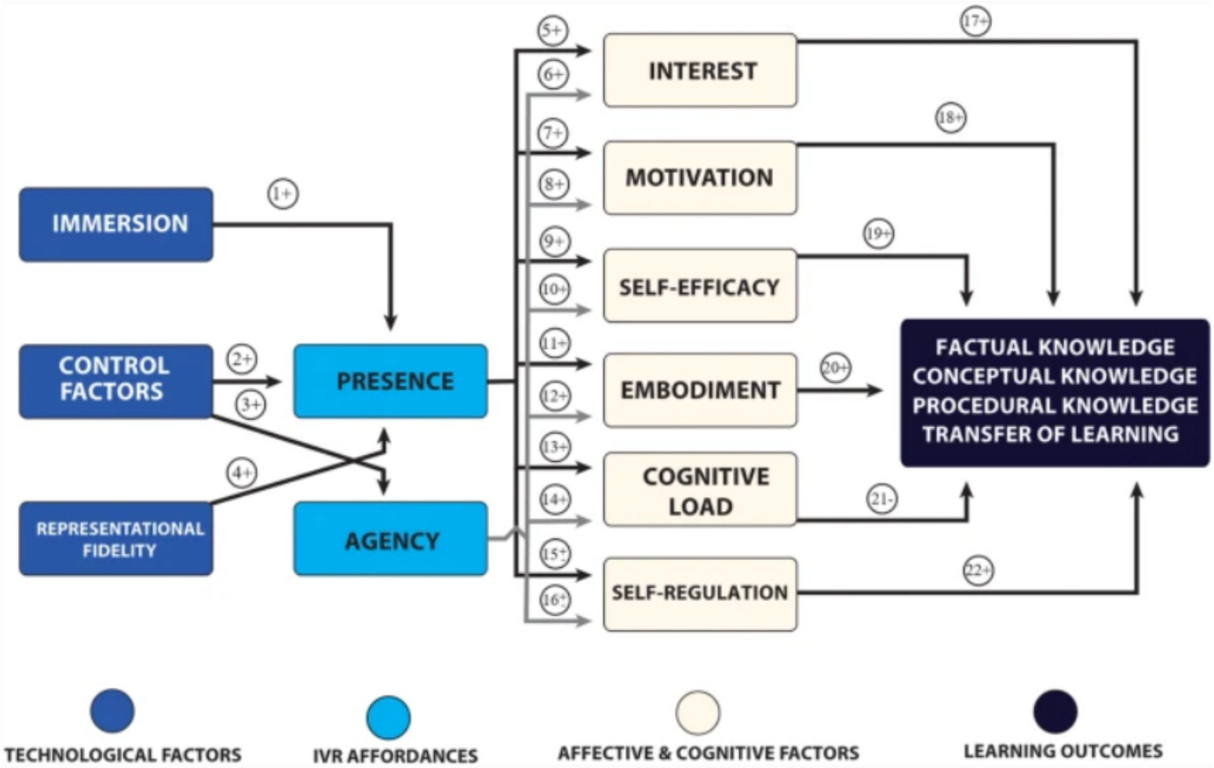


Figure 2.12: Overview of the theoretical framework CAMIL

and agency[87]. However, this study focuses only on the effects of presence on the learning curve.

2.4.1.1.3 Cognitive affective factors: According to Fig. 2.2, presence influence six cognitive affective factors, which are: interest, motivation, self-efficacy, embodiment, cognitive load and self regulation. Starting with interest, CAMIL focuses on situational interest, since feeling a high sense of presence can trigger one's interest in the moment[88]. However, this can also develop individual interest, as the user may want to know more and therefore presents a knowledge-seeking behavior[89].

Motivation, especially intrinsic motivation is shown to be higher measured, along with sense of enjoyment according to prior empirical studies[90][91]. Moreover, in accordance with Self-Determination Theory (SDT), intrinsic motivation is enhanced by internal perspective that is stimulated when users are provided with choice and acknowledgement[92].

Since self-efficacy describes the extent of individuals perceiving their capabilities for performing specific tasks[93], experiencing a high sense of presence in the virtual experience can make learners associate and feel that the tasks they are performing with/to performance experiences[71].

As stated in prior studies, the sense of presence - especially self-presence - is associated with the sense of embodiment, because the way one thinks is dependent on how their body interacts with the environment[94][71].

The last two cognitive affective factors are capable of negatively influence the learner's experience, since cognitive load illustrates the extent of information to be processed while learning that surpass the memory[95][96] and self-regulation is dependent on the extent to which one can manipulate their' behavior so that they withstand impulses, maintain focus and undertake tasks[97]. Thus, high levels of presence might also overwhelm the individual and minimalize the learning outcomes. Moreover, if individuals can treat the learning environment more superficially, serving their motivation and self-fulfillment rather than see the IVR environment as an instrumental value[98]. However, CAMIL presents a positive relation between extraneous cognitive load (how information is presented to the learner) and presence, with the explanation that the design of the learning task and the way the information is presented to the learner have a high impact on their learning curve[71].

With respect to the current study, where the main focus is put on the whole visitor experience, it was decided to investigate affordances only, along with the affective and cognitive factors. However, it is indeed possible that the experiment content setup might lead to learning outcomes, an aspect that can be investigated in future research.

2.4.2 Game Flow

Game flow is a relevant aspect of game design that will be further discussed in this subsection regarding game design for museum environments.

According to Sweetser and Wyeth[99], game flow is an experience that makes the user immersed and focused on fame, with the power to control it while facing clear goals. The game flow state appears when a proper fit of difficulty and player skills is present. In order to impact both effectiveness and attractiveness, Sinclair [100] proposes a new concept of dual flow. Dual flow can be obtained by maintaining a balance between level difficulty and player skills, as depicted in Figure 2.13. Therefore, in order to reach the dual flow, the game, and the environment must provide the appropriate medium so that individuals can fully focus their attention on the game tasks. This, eventually provides a sense of engagement since engagement has been defined as being "present" in thoughts and activities, according to [101].

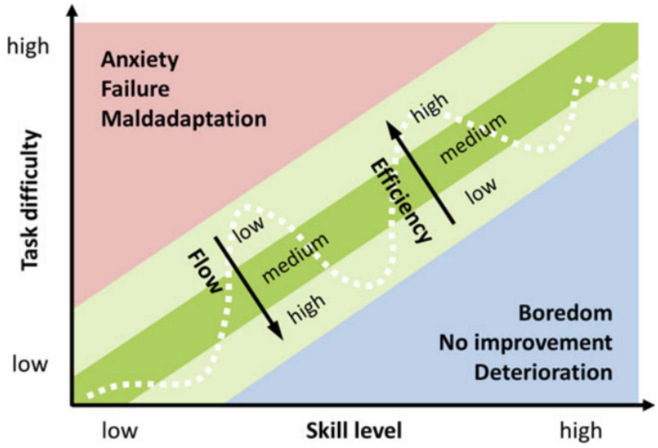


Figure 2.13: Dual flow as a balance of task difficulty and skill level

An interesting discovery has been presented by Michailidis and his team [102]. They showed that despite presence and immersion being seen and described almost identical due to the fact that presence is enveloped in immersion[102], the relation to each of them with regards to flow has different outcomes. Thus, the dimensions of flow are nearly identical with the dimensions of immersion, while presence appears as a considerably distinct state from flow, especially on a neural level. However, there is a lack of literature evidence for such neural patterns.

Due to the fact that the current study has specific limitations imposed with regards to the time spent at the museum stations, dual game flow is acknowledged to be of high importance, however not to a high extent. This is because museum visitors are not offered extended time to get fully immersed into the game presented at the museum installation.

2.4.3 Narrative

Narrative is another relevant aspect of game design that is critical to a leveraged gameplay experience. Thus, the following section provides a review upon related work findings and narrative frameworks essential for game design, that construct the base for the current research.

2.4.3.1 Story Scaffolding Dashboard (SSD)

Since game immersion is shown to be provided also by consistent storylines[103][104], it is highly salient that a monitorization on the relation between storyline and gameplay must be kept. In this sense, Chris Ferguson proposes a novel tool that fills the gap between the gameplay and storyline[105], based on prior research[106][107][108][109].

The Story Scaffolding Dashboard approach consists of node tree graphs with explicit encoding in order to offer an exhaustive documentation for games. By creating a more visualized documentation of the game, game developers and educators can easily use the documentation to track the players through the game. A visual representation of SSD use case can be seen in figure 2.14.

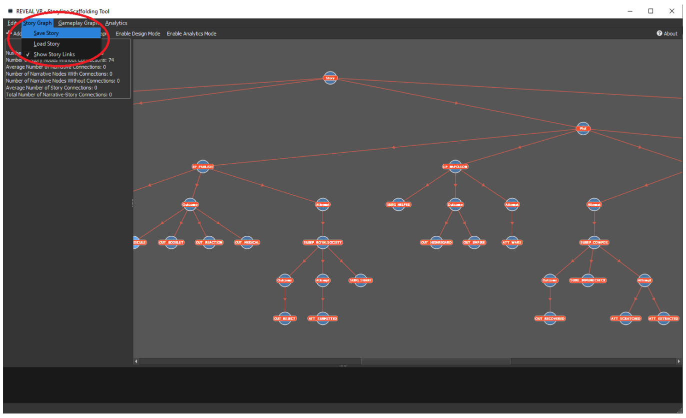


Figure 2.14: Story Scaffolding Dashboard interface

2.4.3.2 String of pearls

While SSD seems to be a reliable and effective approach for covering the gap between the gameplay and the storyline, the current research is time-constrained. This means that the game as a whole and the storyline should be kept less complex, leading us to integrating a more common approach to game designers: the string of pearls approach[110].

According to Schell, the string from the string of pearls represent the non-interactive story, where the gameplay proceeds from level to level in a pre-given direction. The pearl represents the interactive frame-period in which the player is given free movement and choice on their own actions within the fixed goal in the game. When the goal is achieved, players move forward in the string of pearls until they reach the end of the game. A visual depiction of this approach is shown in Figure 2.15.

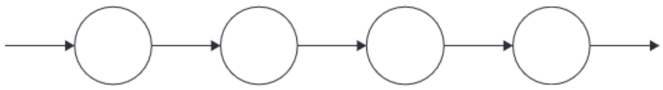


Figure 2.15: String of pearls approach visualization

2.4.3.3 Narrative storylines

Narrative persuasion has been a field of research many endeavored to explore since it triggers and influences individuals' beliefs regarding the consumed topic on displays[111]. Thus, being absorbed into a narrative becomes a problem of transportation[112]. In previous studies [112], this is defined as "being lost in a story with no regard or recognition of their « real world » surroundings". By doing this, most of the individuals' cognitive and emotional resources are influenced by the narrative and desire to enjoy the storyline, having their beliefs shaped by the story at a certain extent[113][114][115]. In their transportation imagery model, Green and Brock [113] explain that individuals can construct mental models of the narrative through imagery. These models consist not only of storyline but also related beliefs and attitudes, leading to a more assimilated and activated storyline eventually.

In order to obtain transportation and emotional arousal[112][116], research has presented the need of perceived realism and identification[116][117][118][119]. In other words, the more realistic the content, the more transportation will occur[116][117].

In their study[111], Janicke and Ellis investigated the power of narrative persuasion for both 2D and 3D environments. Their results have shown no significant difference between the influence of 2D content and 3D environments, due to the finicky nature of the 3D environment, since the conversion of 2D content to autostereoscopic displays was considered difficult. However, they proved that the type of content shown on the 2D or 3D displays matters, since it leads to emotional arousal that is related to transportation[112], and that can lead to increased attention and enjoyment. Therefore, they suggest that added realism to 3D gameplay can offer a higher enjoyment rate, as it increases players' sense of presence, immersion, involvement, and attention. Furthermore, results showed that optical discomfort perceived from 3D displays did not affect participants' enjoyment. This means that the finicky nature of 3D environments allows influence only for ideal cases (e.g. gaming). Hence, it is important to take this aspect into consideration while developing applications for 3D monitors - with regards to this study, games for touchscreen and SR monitors, specifically.

2.4.4 Learning

Since museums are environments where a large amount of information is presented, and some individuals visit museums in order to learn with respect to their own agendas, it is intriguing to investigate or at least consider the learning outcomes potential on a secondary facet with respect to current research. Therefore, an in-depth overview of learning was necessary for such an investigation.

2.4.4.1 Contextual Learning

The concept of learning leads back to museum visitors analysis. While a growing number of studies are investigating the meaning-making of the museum experience, researchers remain aware of the fact that museum visitors come from different socio-cultural backgrounds, with different mindsets, expectations, perceptions and own agendas[9]. Thus, they create their own meanings within the museum environment. Taking this into consideration, EunJung Chang proposes a Contextual Learning Model based on Falk's and Dierking's Interactive Experience Model[8] [120] introduced in 1992. Figure 2.16 illustrates the Contextual Learning Model proposed by Chang.

The Contextual Learning Model consists of 3 main contexts: personal context, physical context, and socio-cultural context. Since museums are learning settings where visitors can have the freedom of choice when it comes to exhibitions[9], the personal context encapsulates the following facets:

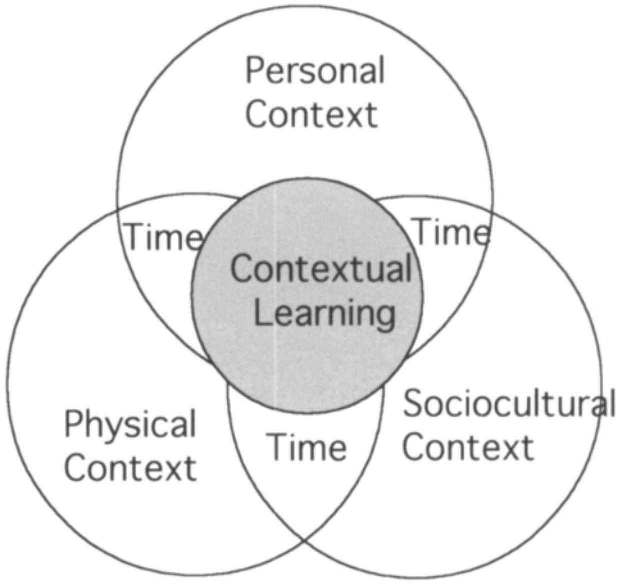


Figure 2.16: Contextual Learning Model

- *Motivation and expectation*
- *Prior knowledge*
- *Choice and control*

In a practical matter, Chang recommends museum educators to reach and frame a positive motivation and expectation for the prospective visitors, by providing opportunities to construct connections between their lives and museum experiences that offer freedom of choice of learning [9].

While some visitors participate individually, most of the museum visits are made by groups. The socio-cultural context, therefore, is focused more on the interaction with performers and collaborative learning, encapsulating the following facets:

- *Within group*
- *Socio-cultural mediation*
- *Content of facilitated mediation by others*

Proposed applications with respect to social learning experiences, according to Chang, would be the ability to share experiences socially and physically through activities or offering visitors the opportunity to build their knowledge by conversating with an expert.

Lastly, physical context focuses on the administrative and organizational parts of the museum, encapsulating:

- *Advanced organizers and orientation*
- *Exhibitions, programs, websites*
- *Reinforcing events or experiences outside the museum*

Practical aspects regarding the physical context can be summarized to smart environment learning design so that visitors can benefit from more comfort and safety while navigating spontaneously among the exhibitions.

By refining Falk's and Dierking's model[8][120], Chang outlines new possibilities for museum educators to leverage visitors' experience and learning.

2.4.4.2 Optimized Learning

A consistently occurring issue in museums is cognitive overload [121]. This happens mostly due to the fact that museums present a great amount of information through numerous and different exhibitions. Additionally, depending on visitors - especially if they are parents, the amount of information that has to be read and then explained to others (children) in a more comprehensive way or language, without losing their attention span can lead to the so-called "museum fatigue"[122]. Studies[123] have shown that people prefer reading short labels to long labels, without complaining about the lack of information[124].

In order to mitigate "museum-fatigue" and cognitive overload, after running research for Exploratorium, Sue Allen[121] proposes several methods through which museum educators can optimize visitors' learning:

- *User-centered design*
- *Multimodal exhibitions*
- *Physical interaction*

The user-centered design is a crucial method for optimizing learning since visitors must feel that they interact with the exhibitions in a natural, suggestive way. This aspect can be analyzed and implemented only through a user-centered design.

In the past years, research has proven that interactivity leads to engagement, understanding, and recall of exhibitions [125]. As a result, Sue Allen recommends using multimodal exhibitions and physical interaction as they can increase engagement and understanding of the exhibitions.

2.4.4.3 Learning in Museums

Museums are generally informal environments where visitors from different backgrounds can wander among exhibits, learn or fulfill other satisfaction. Due to a serious lack of research aiming game-based learning exhibition design in museum environments, a recent study [126] proposed six design principles for a specific exhibition at the North Carolina Museum of Natural Sciences, taking into consideration that visitors only spend a few minutes for each exhibition which can limit deep knowledge gains:

- *Low barrier to entry*
  This aspect is crucial since visitors do not spend too much time interacting with exhibitions, meaning that the game interaction and mechanics should be easy to learn for quicker interaction.
- *Exploration and curiosity*
  With regards to improving the learning experience for visitors, game exhibits should be focused on the learner's manipulation of the game, putting the accent on cause and effect and avoiding long instructional texts.
- *Immediate and dramatic feedback*
  Feedback is another critical aspect of game-based learning design and goes hand in hand with exploration and curiosity since visitors should be able to comprehend the effects of their input in the virtual world. Thus, colors, animations and other multimodal effects are used to seal visitors' decisions.
- *Inviting visual aesthetics with broad appeal*
  There is no secret that individuals are attracted to friendly, appealing aesthetics. In fact, prior research suggests adopting visually appealing styles with respect to educational game design [127].
- *Novel hardware platforms*
  Similarly to the visual aesthetics aspect, new, innovative hardware manages

to attract individuals.

- *Providing flexible user experiences*
  The facilitation of flexible user experiences is the last critical aspect of game-based learning design for the museum environment. As mentioned above, visitors with different backgrounds, agendas, and expectations visit and interact with the exhibitions. It is up to the museum educators and designers to provide a broad range of interactions for different types of visitors.

2.4.4.4 Personal Meaning Mapping

Personal Meaning Mapping (PMM) is a method used for museum visitor learning assessment in prior research[10]. This method was created to measure the impact of educational experiences on individuals with respect to conceptual, attitudinal and emotional understanding. Thus, Falk states that PMM is "a versatile and reliable tool for assessing learning".

PMM consists of two parts. First, participants are asked to write words, phrases or ideas related to the assessed field. In the second part, they will explain their inputs in an interview.

A more recent study[128] conducted by Hartmeyer, Bolling and Bentsen has proven that PMM can be used for students' self-knowledge also as a foundation for their personal reflection on own depth of knowledge. However, the authors argue that PMM is accurate for unidimensional understanding of knowledge forms and should not be used as a standalone measure with regard to multidimensional knowledge forms understanding. Since PMM does not measure learning outcomes on long terms, the "meaning" individuals create while engaging with the museum station is difficult to separate from what is described as short-term memory.

To summarize, the current study mainly focuses on visitors' experience with regard to interaction, engagement, presence, and control. On a secondary level, we would like to investigate whether there is potential in increasing learning outcomes through SR monitors. Thus, a user-centered design approach with respect to learning outcomes was also taken into account.

2.4.4.5 Self-Determination Theory

With regards to measuring player experience (PX) while gaming, it is highly salient to measure not only the feelings and players' psychological assets but to dive deeper into users' motivation. This leads us to involve self-determination theory (SDT) [129] in the measurements, fact that is not quite surprising.

With respect to the three universal needs supporting intrinsic motivation, autonomy represents the sense of willingness while performing a task[130][131]. Thus, it is highly important that the user does not feel obliged or pushed to perform specific tasks, especially with regard of this current study setting. Competence is described as the need for challenge or sense of effectance [132][130]. Games should be able to provide optimal feedback and challenges to players in order to acquire new skills that lead to the sense of competence and intrinsic motivation [133]. Finally, the need of relatedness is presented as a motivation enhancer when individuals connect with each other[134][135]. This aspect occurs in multiplayer games[133] more frequently.

Since SDT is highly considered in questionnaires for measuring PX, the current study decided to include this aspect into the research.

2.4.4.6 M-Dimensions Framework

As far as installations in museum environments as a whole are concerned, it is critical to acquire a better perspective with respect to interaction-focused exhibition design. The following subsection provides insight regarding dimension designs for exhibitions.

Since learning by exploration and the need for new methods of entertaining visitors have made interactive museums increasingly popular [136] [137] [138], numerous investigations towards the matter of interactivity have been performed. However, little attention has been paid on the interactivity level among museum installations.

As a result, Goncalves, Campos, and Souse have proposed a framework for evaluating and comparing interactive installations in museums[136] that is based on the design principles[139][140], frameworks[141] that have been adapted to the museum environment with focus on previous studies[142] [143] [144] [145], exhibitions[146], learning and education[147][148][149], entertainment[150] and lastly, collaboration[151].

M-Dimension framework consists of ten dimensions to be taken into consideration when developing museum interactive installations, namely: *interaction style adequacy, area integration, visibility, feedback, structure, reuse, simplicity, learning, entertainment"* and *collaboration*. Figure 2.17 represents an exhaustive overview of the M-dimensions framework, facilitated by Burmistrov [12]. However, though their framework contains the most consistent criteria for museum station design, the authors of the M-Dimension framework did not back up the validity and reliability of the scales with psychometric analysis, and thus, the framework was only consulted in this study, but not included in the questionnaire.

2.4.5 Measuring Game Experience in Museums

2.4.5.1 Related Work Overview

All related work has been consulted with regard of proposing a solution for leveraging the user experience in museums. Therefore, a user-centered design approach is desired, as we learned that there are several types of museum visitors and that the experience and interaction range should be broad and flexible. As previously mentioned, in relation to technology in the museum environment, the current study includes a touchscreen tablet and an SR monitor. Implicitly, touch and hand gestures were considered appropriate for the current comparative study as controllers for the above-mentioned devices. This is due to the similarity range and the extent of naturality and common sense they have globally. As seen earlier, the need for innovative technology is critical, hence the use of SR monitors despite their less common use case among museum environments. Moreover, it is considered that SR monitors can bring the benefits of VR and AR technologies closer to the users, without the great amount of disadvantages that was covered in the earlier sections. Lastly, since visitors are moving in a rather fast manner through the exhibitions in the museum, the installation design should be as friendly, attractive, and inviting to interaction as it can possibly be.

A plethora of models and frameworks were discussed in this study. As far as the learning curve is concerned, it would be nearly impossible to apply the frame-

Dimension	Description
Interaction style adequacy	How adequate is the interaction style of an interactive installation with regard to its goal. Ease of use: the installation may be more or less difficult to use, and the visitor feels more or less tired when using it. If the style of interaction is related with the information content and the museum atmosphere, improving or not the engagement of the visitor with the module.
Area integration	The installation's degree of isolation regarding the subject matter and whether the narrative of the exhibition is maintained or fragmented. The installation should perfectly fit the narrative and the spatial context, should be physically close to other related elements that complement and contextualize the interactive installation. The focus of the visitor will be the work of art/content and not the technology.
Visibility	Ability to show users what they need to complete a task without distracting them. The module must be in a visible place where all visitors can see it. Moreover, its disposition must encourage its usage and it must be identified with a title or labels to facilitate the interaction. Installations should provide immediate interaction capabilities and the visitor shouldn't show a hesitation, because all the elements needed are visible and available, without the presence of distracting objects, both physical (e. g. reflections on the screen because of high luminosity) and digital (e. g. difficulties in recognizing control buttons or difficulties in reading because of improper fonts). Physical location of the installation within the visitor's passway through a museum space.
Feedback	The system should always keep users informed about what is going on, through appropriate response within reasonable time. A museum installation must effectively inform the visitor of events, results, progress, state changes and the remaining information that the visitor needs to complete the desired task while interacting with installation. The user interface must show useful information recognizable and understandable through visitor language.
Structure	Organization that reflects the intrinsic or familiar organization of things: things that are similar or related are supposed to resemble each other. Element organization or arrangement inside the installation or between similar installations. Layout, format, visual associations and distinction of the installation's elements. Consistency within the module or between similar modules.
Reuse	Recycling visual elements and interaction patterns so that interfaces are not only consistent, but also contain fewer distinct things to understand and master. Reuse of elements and behaviors inside the installation or between similar installations.
Simplicity	Genuine elegance and parsimony rather than "simple-minded reductionism". Simplicity can be affected by many factors, such as lack of identification of the installation, lack of tips for using, unexpected behaviors, malfunctions and so on. The interaction with the module should be immediate and successful during the time of use by the most of the visitors (90% to 100%).
Learning	Giving visitors a choice depending on their attention span on what to display to them. Promoting critical thinking in visitors and have them reach their own conclusions on things. Free choice, addressing multiple points of view, enhancing visitor's curiosity.
Entertainment	Participatory experiences that promote fun and allow the visitor to see new and interesting things in a relaxing and aesthetically pleasing setting. Installations should be pleasant to use and interact with, increasing the level of engagement and time of use. Time spent on interaction as a measure of the level of engagement.
Collaboration	Being able to be used/viewed/enjoyed by multiple visitors simultaneously. An installation is considered collaboratively good if it can be directly used by up to 4 visitors at the same time and others visitors can easily see the interaction and discuss its results among them.

Figure 2.17: Burmistrov's explanation over the M-Dimension framework:

works appropriately without adapting them first to the museum environment and the current study's circumstances. As a consequence, the CAMIL model [71] along with its proposed questionnaire [152] is mainly used for measuring the presence of technological, affective, and cognitive factors and immersive affordances. This is because of the short interaction time visitors generally offer while exploring the exhibitions. As far as the PMM approach is concerned, it will not be applied in the experiment, due to its lack of reliability. While dual flow is critical to serious game design, the measuring expectations for dual game flow in the particular case of a media museum environment where visitors will not be able to spend a significant amount of time to check for a considerable flow state are rather low, but not insignificant. The contextual learning model supports the idea of the need for three different leveraged contexts that will overall lead to learning with a museum environment at the base. However, since the comparative study takes place only in a specific area in the museum, the current study design will take into consideration only the recommendations from the authors on the design and use case notes. Another set of user-centered design regulations is offered for optimized learning, which were also took into consideration when designing the setup, applications, and study design.

For data collection and qualitative measurements, the CAMIL questionnaire proposed by [152] is used to measure the sense of presence and agency. For the rest of the museum game experience, an overview of the most popular game experience questionnaires is presented below.

2.4.5.2 Player Experience of Need Satisfaction (PENS) Questionnaire

PENS questionnaire[133] successfully integrates SDT into the measurements, as its main focus is to measure the three universal needs described by SDT [129] - autonomy, competence, relatedness - along with presence/immersion and intuitive controls. This popular questionnaire was purposely designed for players since research has shown that people play games because they offer intrinsic satisfaction [153] and a sense of "fun"[154].

Therefore, PENS has been used in diverse settings with regards to motivation[155], identity[156] and well-being [157]([158]). Moreover, research has also outlined the relation between the need of satisfaction to emotional, psychological and social well-being[159][160]. While presence/immersion depict an aspect of PENS that was already described earlier in this study, intuitive controls represent the last facet of PENS. Intuitive controls describe the degree to which game controls are suggestive and self-explanatory. Thus, using these game controls should feel natural, intuitive and easy to master.

On another note, although PENS is considered a great tool for PX in both recreational and non-recreational game play scenarios, some researchers consider it to have a high constraint rate due to its focus that targets mainly game evaluation[161], suggesting how to develop engaging, satisfactory games [162]. Thus, this questionnaire was not included in the current experiment.

2.4.5.3 Game Engagement Questionnaire (GEQ)

The purpose of the Game Engagement Questionnaire (GEQ)[163] is to measure the potential impact of playing video games that is generated by engagement. Unlike PENS, GEQ is not constructed on the basis of a psychological theory, but rather on a conceptual accounts of PX and group group-gaming experiments[163] [158]. GEQ measurements consists of the following factors:

- *Immersion*
- *Presence*
- *Flow*
- *Psychological absorption*
- *Psychological dissociation*

As mentioned above, immersion and presence are terms that were described previously in this study. The sense of flow is represents the game state in which the ratio between skill and challenge is balanced, leading to a rewarding activity [164][165][166]. This means that the player also feels that they are in control, becoming immersed in the activity [163]. Psychological absorption is differentiated from immersion, presence and flow through its power to alter the state of consciousness [167]. This can generate two types of affects: positive (absorption) and negative affect (frustration, anxiety). everyday experiences of psychological absorption, however, lead to "non-pathological dissociations". Thus, dissociation has been described as "the lack of normal integration of thoughts, feelings, and experiences into the steam of consciousness and memory"[168]. In their study [163], Brockmyer, Fox, Curtiss and Broom give an example on non-pathological dissociations: "highway hypnosis", meaning that the individual is absorbed by an unrelated cognitive activity.

GEQ focuses mainly on individual's feelings while playing. As a result of its design, GEQ manages to measure enjoyment as a multidimensional construct, however with scales appropriate for adults only. Since the current study's setup is taking place in the museum environment, it relevant to mention that younger participants should have the possibility to completely understand and comprehend GEQ scale. Thus, excluding GEQ entirely or merging it with other measurement tools is considered.

2.4.5.4 Ubisoft Perceived Experience Questionnaire (UPEQ)

While PENS and GEQ have been largely used in the past years, it is important to acknowledge their limitations of availability, validation sample, semantic overlap of constructs and subject orientation, tenuous and overlapping theory, and ad hoc development[169], respectively, and aim to complement them.

On this note, Azadvar and Canossa propose another questionnaire entitled "Ubisoft Perceived Experience Questionnaire" (UPEQ)[169], with SDT at base to measure to which extent the player's gratification and universal needs are satisfied. As a result, the questionnaire consists of 21 questions while simply based on the SDT 3 factors: Autonomy, Competence and Relatedness, leading to subtle nuance of player experience capturings, like enjoyment. However, studies have questioned the reliability of UPEQ due to its semantic overlap of constructs [169] and complication of the data interpretation provided by it[170]. As a result, this questionnaire was not included in the current research.

2.4.5.5 FunQ Questionnaire

Fun is an important characteristic of gameplay that should be experimented by all players. That is because fun is proven to have an inviting effect[171] that also increases engagement with learning technologies [172][171]. In their research, Tisza and Markopoulos describe the FunQ Questionnaire [161] and its focus on measuring "fun" in learning contexts. Being built on a theoretical foundation with regards to gamification education [173][174], intrinsic motivation[175][153][176], flow[177][178] and attention span[179][180], FunQ has been created to handle "fun" in a multidimensional construct scale that is appropriate for adolescents, an aspect that is crucial for the current study measurements. The factors measured by FunQ are as follows:

- *Autonomy*
- *Challenge*
- *Delight*
- *Immersion*
- *Loss of social barriers*
- *Stress*

As outlined previously in this study, autonomy and immersion terms have already been described. Challenge is a variable that points to whether the participant felt challenged during the activity while delight represents the positive emotions the participant experiences while performing the activity. Lastly, the loss of social borders factor and stress factor illustrates the social connectivity of the participant and the negative emotions experienced respectively. This questionnaire was not included to the current study due to its similarity to GEQ and PENS questionnaires in terms of constructs and reliability.

2.4.5.6 Means-End Theory and Player Experience Inventory (PXI)

2.4.5.6.1 Means-End Theory: The Means-End Theory was proposed by Jonathan Gutman[181] with an aim to emphasize the linkage between the values important to customers and specific attributes of products. By doing this, Gutman shows that customers choose products not because of their attributes -or means, but because they see the products as tools that can help them achieve specific "consequences" - the so-called end. Thus, Means-End theory opened a new door to researchers in the field of marketing and many others with regards to usage behavior experience, consumer perception and preferences[181][182]. The shape of the Means-end Theory can be consulted at Figure 5.6. Consumers do not have a relation with product attributes but rather with their values. However, product attributes can generate functional and psychological desires in consumers that will align eventually with their values. Exhaustively, functional consequences are linked to immediate usage, while psychological consequences are related to more emotional experiences that go beyond usage, reaching social and psychological facets. Therefore, it is salient to understand the impact and the interaction extent consequences exert on consumers[183].

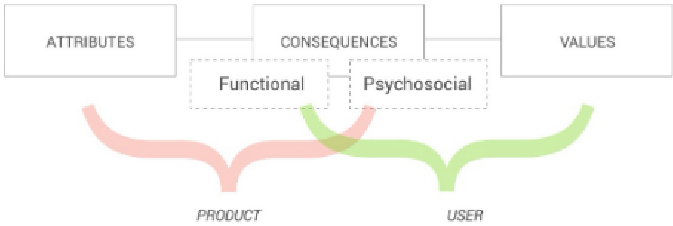


Figure 2.18: Means-End Chain

2.4.5.6.2 Player Experience Inventory (PXI): With respect to game development, functional and psychological consequence measurements are encapsulated in a questionnaire proposed by Vero Vanden Abeele and her colleagues - the Player Experience Inventory (PXI) questionnaire[184]. The questionnaire was built on the Means-End Theory and consists of 30 questions formed from functional and psychological consequence constructs. The overview of the PXI can be seen in Fig 2.19.

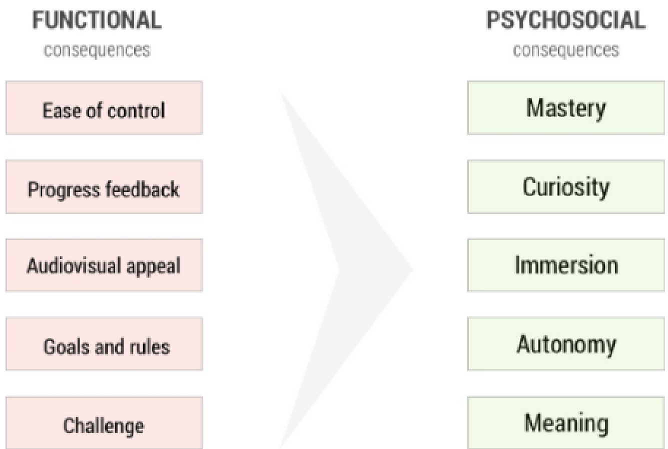


Figure 2.19: PXI overview

Although the PXI questionnaire seems to be more reliable in the light of game research and development, authors admit that the questionnaire might have a number of limitations since the constructs have been created to suit a broad genre of games and audiences. This means that additional questions might be needed in order to address narrative, relatedness, and other aspects that are relevant to other researchers' topics. However, due to limited time constraints in interaction with museum stations, authors of PXI have proposed a single-item-per-construct questionnaire - a so-called "miniPXI" questionnaire - based on the same model in order to aid time-constrained experiments that investigate engagement and game experience [185]. The questionnaire contains 11 constructs that cover several facets of visitors' experience. In this sense, the current research benefits the most from using the miniPXI questionnaire out of all the other reviewed questionnaires.

2.5 Summary

This section provided an overview of museums, visitors, technology in museums, controllers, and different frameworks for user-centered design approaches, and learning outcomes through technology and game-based museum stations. These are all factors that contribute to the enhancement of engagement in the museum context. Thus, the museum context has been affected by the fast pace of technological development and needs new user-centered design approaches to be implemented in the museum stations with novel technology that will help visitors make the most out of their experience[9][2][19]. On the same note, visitors come to the museum with different agendas and expectations, demanding a suitable user-centered design for a broad audience in terms of personas, age, and background [12][13][11]. While technology has been included in museums lately, existing technologies fail to meet all criteria for a suitable museum station that is built around a user-centered approach[2][19]. Simulated Reality[35] is a novel technology that provides interaction with glasses-free 3D monitors by using bare hands, without any controllers. A comparison between the SR monitors and different existing controllers has been performed. After analysing the benefits and the drawback of each technology used in the museum, along with the controllers, touchscreen kiosks and SR monitors stand out for a fair comparison in terms of the impact on the visitor experience. Thus, the current study aims to respond to the research questions, with the scope of finding which of the two devices (touchscreen kiosk or SR monitors) is able to provide museum visitors with a better experience, in terms of presence, controls, and engagement. Visitors' opinions are also analysed, along with their information retention to check for a learning outcome potential. In this regard, we propose the following three hypotheses:

H1. *There is a difference in the ways SR technology and touchscreen kiosks enhance visitors' experience.*

H2. *SR technology is a better museum experience enhancer than touchscreen kiosks.*

H3. *There is potential for a learning curve and information retention when using SR technology.*

Thus, cognitive-affective frameworks[71] are consulted in order to draw a clear investigation direction. Moreover, user-centered frameworks[9][142][136] and game-based learning frameworks[126] have been also researched and consulted in this regard.

3. Method

3.1 Serious Games design & development

This chapter presents an overview of the frameworks and the pipeline used in the current study. Additionally, it provides additional insights regarding open-question surveys and questionnaires used in the experiment, along with information concerning the museum station design and encountered constraints.

With regard to serious games, one cannot argue against the complex process of designing and developing serious games that are engaging and educational. In his book [186], Stefan Göbel establishes three processes in the cycle of designing and developing a serious game, namely:

- *Preparation*
- *Development*
- *Deployment*

Since serious games are described as "a promising mechanism or “tool” to fulfill a specific goal in the different application areas"[186], the preparation phase encapsulates different origins of games - public-funded or industry-driven. The second phase is checking the market for existing serious games, or performing research. Then, a development team of different specialists is formed.

The development phase represents the core section of the whole cycle. It implies a user-centered design approach involving users that provide feedback for the development team. The prototypes delivered by the development team are then iteratively tested till the room for improvement is highly mitigated.

The deployment phase consists in a roll-out session where the serious game is sent to numerous end users and distribution channels such as Steam.

The serious game design and development cycle can be visually consulted in

Figure 3.1.

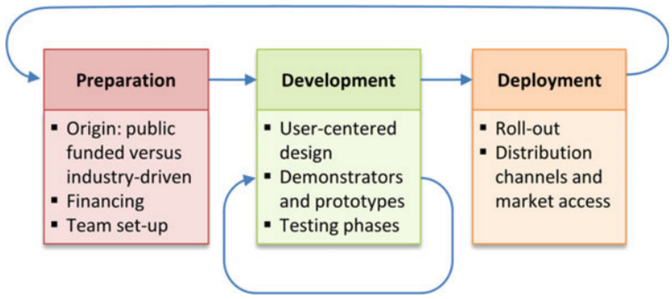


Figure 3.1: Game design process

The current study has followed a similar cycle. The content delivery (SR & Android application) for this paper has been checked on the serious games market, and the design approach involved a UX product designer consultant during the prototypes and testing phases. The usage of the applications in the experiment setup serves as a deployment phase.

3.2 Double Diamond Model Framework

With regards to the current study approach concretely, the double diamond model has been applied. The Double Diamond model framework is a non linear process entailing problem analysis as a basis for creating solutions and it has been introduced by Design Council [187]. It is formed of four important facets, namely:

- *Discover*
- *Define*
- *Develop*
- *Deliver*

The Discover phase represents the understanding of the existing problem by performing research and identifying it. The Define phase takes the insight built by the discovery phase and generates a definition of a clear and concrete problem. The Development phase focuses on creating solutions for the clear problem. Finally, the Delivery phase represents the testing the prospective solutions at a small scale, rejecting those that fail and considering those that succeed.

Similar steps have been applied to the current study. Therefore, research has been performed in order to identify and clarify the problem of interactive museum installations that do not leverage visitors' experience. Afterwards, testable hypotheses have been created according to prior studies and actual technology opportunities. Lastly, an experiment has been set up and the results have been analyzed.

The Double Diamond Model framework can be visually consulted in Figure 3.2.

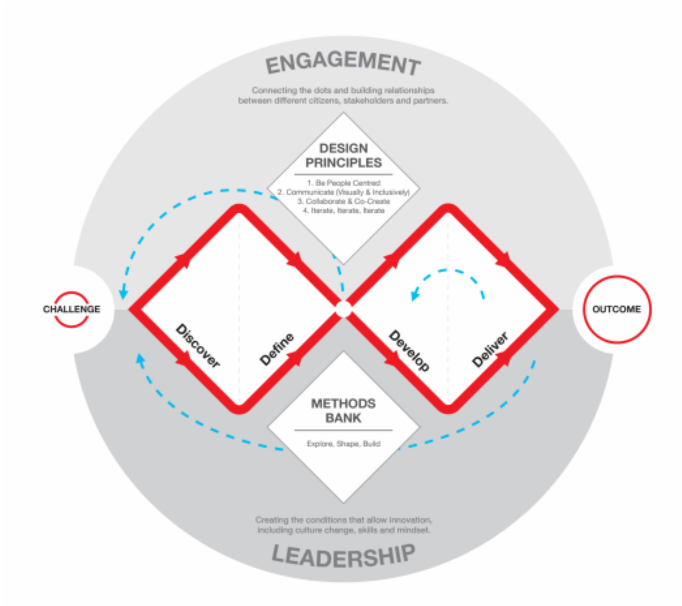


Figure 3.2: Double Diamond Model framework

Dan Nessler has proposed an updated version of the Double Diamond framework that aids design thinking and research design. The updated version of the Double Diamond framework can be consulted in Figure 4.6.

Thus, the Discover facet encompasses the research that has been done, first in brief and in specific fields important for the research question, then diving into these clustered research topics in order to gain more depth and perspective. Thus, this facet has been completed by gathering findings from previous research that focused on museums, visitors, technology, and psychological frameworks.

The Synthesis facet is reserved to mainly organise the findings and the insigths of the research topics and start defining hypotheses and research questions (or "how-might-we ..." [HMW] questions). Therefore, the first Diamond consisting in these two facets - Research and Synthesis - leads to the base of designing a suitable "solution" to the defined "problem". With respect to the current research, after narrowing the findings gathered in the Discovery phase to the current study's "problem", several research questions, along with hypotheses have been outlined.

The second Diamond consists of the Ideation and Implementation phases. These two phases are fundamental in finding the most suitable method to answer the research questions or to develop the right application to serve as a solution for the initial problem. The Ideation phase encapsulates the brainstorming phase for ideas and possible solutions to the problem, and the evaluation part, where all the prospective solutions have been evaluated. After the evaluation phase, one or a very small number of solutions should still remain feasible. This facet has been completed by the current research through open-question surveys sent to a 3D model artist to gain insights upon creating 3D model applications with full engagement potential. Additionally, based on the foreseen constraints, a short timeframe questionnaire was created to measure engagement, presence, agency and the sense of device utility. The last facet, the Implementation facet is reserved for applying an agile approach to develop the right solution or application to respond to the initial questions or solve the initial problem. Thus, three steps are implemented in this process: the prototype phase - where minimum viable product (or prototypes) are created for testing the solutions, the analysis phase - where the prototype gets tested, and the iteration phase - where the first two steps are repeated until the solution or the application are improved enough to respond to the initial questions or solve the initial solution. The current study respects these iteration phases: a prototype has been created for a pilot test. After gathering all the feedback from the pilot test, the prototype has been improved to its final state, which is used in the experiment. This final application serves as a tool for gathering experiment participants' feedback on the museum station experience.

As an end result, the updated Double Diamond framework delivers a final answer, product or solution for the initial question or problem. However, the updated version of the Double Diamond remains a personal approach that can be challenged, questioned, and iterated upon. In the current research case, the solution to the initial problem is a provision of insights regarding the advantages and disadvantages of touchscreen kiosks and SR technology in museums, followed by device choice recommendations for museum station designers in the shape of a decision tree. Moreover, further research directions are outlined in this sense.

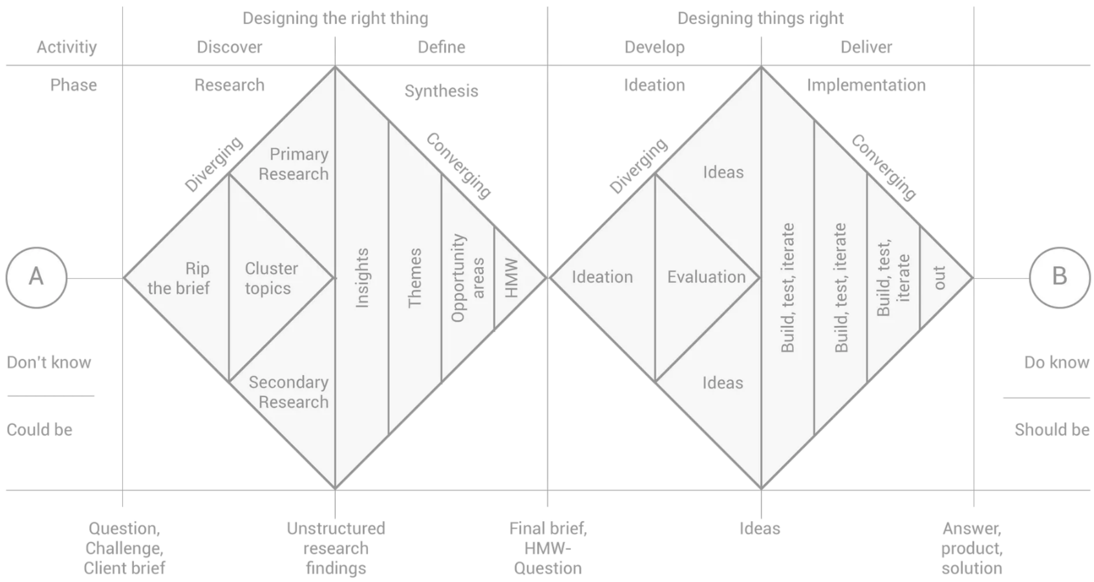


Figure 3.3: Dan Nessler's updated Double Diamond Model framework

3.3 Pipeline

This study follows the Serious Games Design and Development (SGDD) cycle [186] and the updated version of the Double Diamond design framework [187] with appropriate adaptations. The pipeline used for the software application in the current research can be consulted in Figure 3.4.

3.3.1 Preparation and Discovery phase

For the *Preparation* stage from the SGDD and the *Discovery* stage that belongs to the Double Diamond framework, exhaustive research in the museum field, psychology and technology use cases has been performed. After clustering these topics, we gained insights upon the problems that museums encounter due to the lack of a user-centered design approach regarding museum stations. As a conclusion, three hypotheses and three research questions were defined. Thus, the *Discovery* stage of the Double Diamond framework has been reached.

3.3.2 Development phase

The second stage of the pipeline encapsulated the solution brainstorming and evaluation, and lastly, the application guidelines development. Consulting the findings gathered from the research and synthesis phases, a comparison between touchscreen kiosks and SR technology has been proposed, and specific frameworks have been selected to measure the overall visitor experience for each of the devices. Thus, a cross-platform application created with a user-centered design approach must be developed in this regard.

An open-question survey has been sent to a 3D model expert in order to gain perspective upon what makes a 3D application engaging in museum environments, and how visitors react or need from museum stations. After analysing the survey, we could highlight important aspects that will aid in developing a user-centered design application.

The application has been developed while taking into account the highlights provided by the open-question survey from the 3D model expert. Overall, this stage is identical to the *Development* stages of both SGDD and Double Diamond frameworks.

However, with respect to the SGDD cycle, the *Development* stage is not complete without user testing. Therefore, a pilot study has been run to investigate if the audiovisual appeal of the application, the controls, and the rest of the content is still following the user-centered design approach established at the beginning.

3.3.3 Deployment and Deliver stage

Lastly, for the *Deployment* and *Deliver* stages from the SGDD and Double Diamond model respectively, the application has been revised. All users' perspectives and opinions towards the application collected from the pilot study have been taken into consideration, along with a visual analysis of their performance. Thus, specific controls or levels were either changed or fully omitted in order to improve users' experience.

The following subsection presents the answers from the open-question survey with the 3D model artist expert.

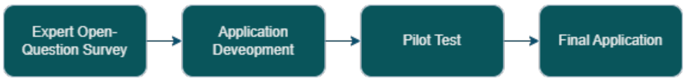


Figure 3.4: Application development pipeline

3.4 TijdLab Open Question Survey

Tijdlab is a Dutch company that creates cultural, archeological and historical 3D models in the form of games, mobile applications, hologram showcases, and presentations. We approached an artist working at Tijdlab to have an interview in order to learn more about the important aspects that need to be taken into consideration when developing an application for museum stations. The questions and the responses were as follows :

1. What is the specific problem that you've seen and wanted to solve by creating 3d models for museums? What are your strategy and target while creating the 3D models?

"Many museums and heritage institutions display objects that are partially or completely invisible. Think of potsherds or completely disappeared settlements. The 3D visualization of objects, landscapes, settlements or other cultural-historical relics makes it possible to take the visitor to long-gone worlds. In addition, 3D offers the possibility to show existing things to the public that are not presentable for whatever reason."

2. What is your approach to testing the 3D models? Which perspective are you more interested in (user experience, convenience, marketing)?

"Two things are very important in the museum sector: credibility and user experience, of which convenience is part. The user must believe the product, this does not mean that everything must be lifelike but must be in the same style and appropriate. The user should be able to orient themselves easily and the experience should feel natural."

3. From your experience, what are the most used methods(touch table, holo-

grams, 3D printing, VR, AR) for viewing your models or presentations in museums? Which one do you think is the most beneficial, first to your company purpose, and second, to the end user (museum visitors)?

"There is no unequivocal answer to this. Depending on the story to be told, one application lends itself better than the other. The best methods, therefore, depend entirely on the circumstances in which 3D is used."

4. On your website, you also mentioned gamification as a method of storytelling and 3D presentation. What is your primary focus while developing games - do you put more accent on the information, the 3D models(visual realism), gamification, or user experience?

"Again, there is no unequivocal answer. The focus depends on the objective of the product, the associated story, and the intended target group."

3.5 Museum station design

3.5.1 Setup

After analysing the accessibility constraints of touchscreen kiosks and the multimedia interactive station design suggestions proposed by [12] and [14], and taking into consideration the design dimensions presented by [136] and [12], we came up with the following setup in the museum. A map of this setup can be consulted in Figures 3.5 and 3.6. Thus, the current study's station is centrally placed at the "Wonderfloor" in the Beeld & Geluid Media Museum where the current research experiment takes place, between two other museum stations. Positioning the SR DevKit close to the wall, we ensured physical access. Moreover, in order to facilitate visitor flow, benches were positioned near the station to mitigate potential visitors that would stop to see other visitors performing and eventually block the walking aisle. A chair has been positioned in front of the SR DevKit in order to ensure accurate physical distance and height from the monitor. In the case of users using a wheelchair, the chair can be easily moved away.

Table 3.1 offers a hypothetical analysis of the touchscreen kiosks and SR monitor installations in the museum environment based on the M-Dimensions framework. The results were rated on the 5 point Likert scale, according to [136]. Based on this, there is already small evidence that the first two hypotheses of this current study may be inferred, which means that SR technology offers a higher interaction rate than touchscreen kiosks, and therefore, it can improve visitors' experience in museums.

Dimensions	***Touchscreen Kiosks***	***SR Monitor Station***
Interaction	5	5
Area Integration	4	5
Visibility	4	4
Feedback	4	4
Structure	4	4
Reuse	5	5
Simplicity	4	3
Learning	3	4
Entertainment	3	5
Collaboration	2	2
Total:	***3.8***	***4.2***

Table 3.1: Hypothetical interaction comparison between touchscreen kiosks and SR monitor installation based on M-Dimension framework

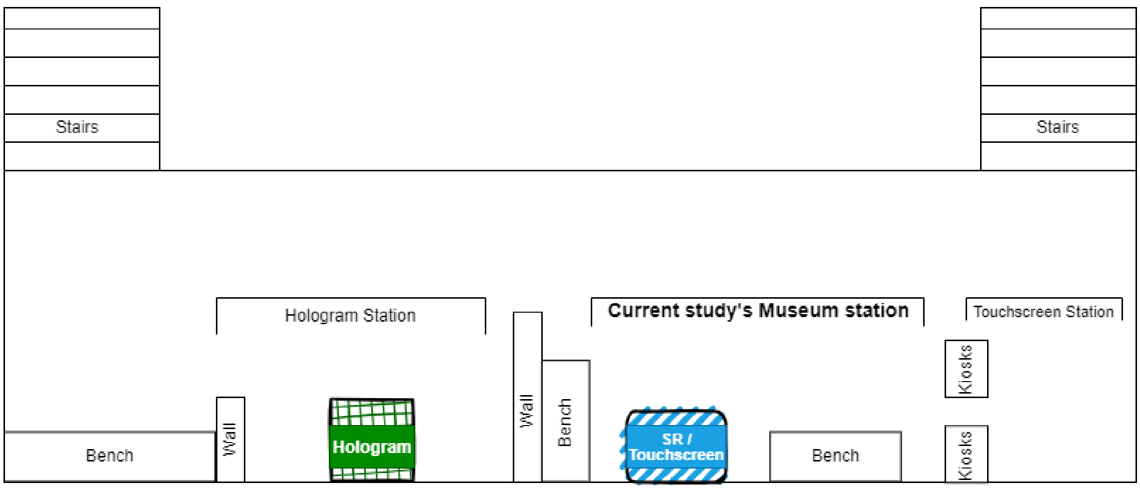


Figure 3.5: Map of the "Wonderfloor" inside Beeld & Geluid, showing the placement of the current study's experiment station

Figure 3.6: Picture of the station seen from the left side

3.6 Constraints

The current study was held in Beeld en Geluid Media Museum in Hilversum, The Netherlands, due to convenience reasons: the museum already had an SR monitor (SR DevKit) installed and the manager of the museum was receptive to this study setup.

The experiment has taken place at the "Wonder Floor", where the SR monitor was installed. As a result, visitors that explored this floor were informed about the experiment and had the freedom of choice to participate or not in this study. However, the museum manager required that the experiment will not take longer than 5 minutes participant, as they wanted to ensure that visitors will not be disrupted by any means from the whole museum experience, or experience increased fatigue after performing the experiment.

Figure 3.7: Beeld en Geluid Media Museum, Hilversum, The Netherlands

Figure 3.8: (Interior) Playing Zone in the Media Museum

3.7 Measures and Variables

In order to ensure the quality of data collection, the miniPXI questionnaire along with CAMIL questionnaire constructs and an additional Intuitive Controls construct were considered appropriate for use. Thus, the sense of presence and agency are measured by using the CAMIL questionnaire, and game experience and engagement are measured with the help of miniPXI questionnaire.

3.7.1 Mini-PXI

Player experience questionnaires are constantly improving in order to collect the most reliable data. However, an overlooked aspect of gameplay experience questionnaires is their increasing length, which can become an impediment in the light of experiment setups[185]. Thus, researchers have suggested a compressed version of the PXI questionnaire - The miniPXI. The miniPXI questionnaire adopts the method of single-item per construct. Thus, the questionnaire has been compressed from a 30-item questionnaire to an eleven-item questionnaire. Authors state that this shortened questionnaire comes with advantages such as less missing data, decreased frustration, and most important, offer the possibility of collecting data in a shorter time period per respondent in time-constrained field experiments[185]. These advantages come with respect to users not testing different games, but the same game. Authors raise awareness regarding the decreased validity of the miniPXI compared to the standard PXI.

Due to the fact that this current study implies a time-constrained field experiment, the miniPXI questionnaire was considered appropriate for usage. However, participants in this study will respond to additional questions regarding immersion in control according to CAMIL model, for reliability reasons.

For the practicality and user experience analysis, the following variables are measured:

- *Engagement (Visitor's opinion)*
- *Presence & Agency (Visitor's opinion)*
- *Sense of utility (Visitor's opinion)*

3.7.2 Open questions

In addition to the question constructs, we added four open questions to help us respond to the RQ2 and RQ3 in order to comprehend participants' perspectives towards SR technology and the prospective information retention potential. Thus, the first three open questions belong to RQ2 while the last question belongs to RQ3. The open questions used in this study's questionnaire are the following:

1. *What had the most impact on you in the experience?*
2. *In general, what do you think about technology in museums?*
3. *Would you recommend SR technology for museums? Why?*

4. *Write (educational/non-educational) things that you remember from the game.*

4. Game design

Overall , the interview with the artist from Tijdlab managed to emphasise three aspects that must be kept in mind when creating 3D applications for cultural environments. First, the objects to be presented in the application must be objects that one cannot see in everyday life, such as historical settlements, space, and so on. Then, the experience created for the user should feel natural and inviting to study or manipulate the objects. Lastly, a user-centered design approach is crucial in order to find the best information delivery medium.

Nevertheless, the SR and touchscreen applications are as important for the current research as the hardware station setup. At first glance, a cross-platform application on the topic of space, with some gamification elements (construction of a spacecraft, creation of a pulsar, and analysing a planet) has been created. The game can be played either in English or in Dutch so that the foreign language barrier is mitigated.

Based on this, in the current chapter, the main aspects of the cross-platform application design are overviewed. Additionally, this chapter presents the outcomes and insights of the pilot study performed before the experiment.

4.1 Theme

Based on the insights gathered from the interview with the 3D model expert from Tijdlab, and prior research with respect to interaction and user-centered design in museums[136][137][138], we implemented a cross-platform application that would meet all the user-centered criteria (Table 3.1) in order to enhance visitors' experience in the museum environment. Additionally, since the 3D model artist expert implied that it is important that the application should display objects that are partially or completely invisible, and that technology should present objects or places that are almost impossible to travel to, according to [2], the theme application has been established to revolve around outer space. Thus, visitors could see three different space objects in three different levels.

4.2 Goals, feedback and gamification elements

The three levels are interconnected with short animations that present the exit of the previous level and entrance to the next level to ensure a smooth, logical transition between the levels which is needed according to [110] to fill in the gap between the gameplay and storyline. The main goal of the game is to collect three spacecraft parts within the game and assemble the spacecraft to save the spatial mission.

The goal of the first level is to assemble a pulsar by connecting three parts of the star together. After each successful piece connection, an audiovisual effect is triggered in order to provide feedback to the user. When all pieces are put together, users can zoom in or out, and rotate the pulsar to study it better. These manipulations can be performed by using one hand in a fist position to drag and connect the pieces, and two hands to zoom in, out, or rotate the complete pulsar. The goal of the second level is to visualise and rotate the planet Saturn by moving a flat hand in the area of the hand tracker, and eventually "smash" it with the hand in a fist position, to be able to study the interior components of the planet. When the planet is "smashed", another audiovisual effect is triggered in order to provide feedback. The internal section of the planet can also be rotated for educational purposes with the same controls as previous state. The goal of the last level is to assemble a spacecraft by connecting its three pieces together by using identical hand gestures with the ones in the pulsar level. These three pieces are gathered as a bonus for each completed level. When all the pieces of the spacecraft are connected, the spacecraft takes off in a burst of confetti and applause as audiovisual feedback. When the levels are completed, users are informed of the transition to the next level through a countdown that appears after the hand sensor loses track of their hand. This feature can be observed in Figure 4.5. General depictions of the three levels can be seen in Figures 4.1, 4.2 and 4.3.

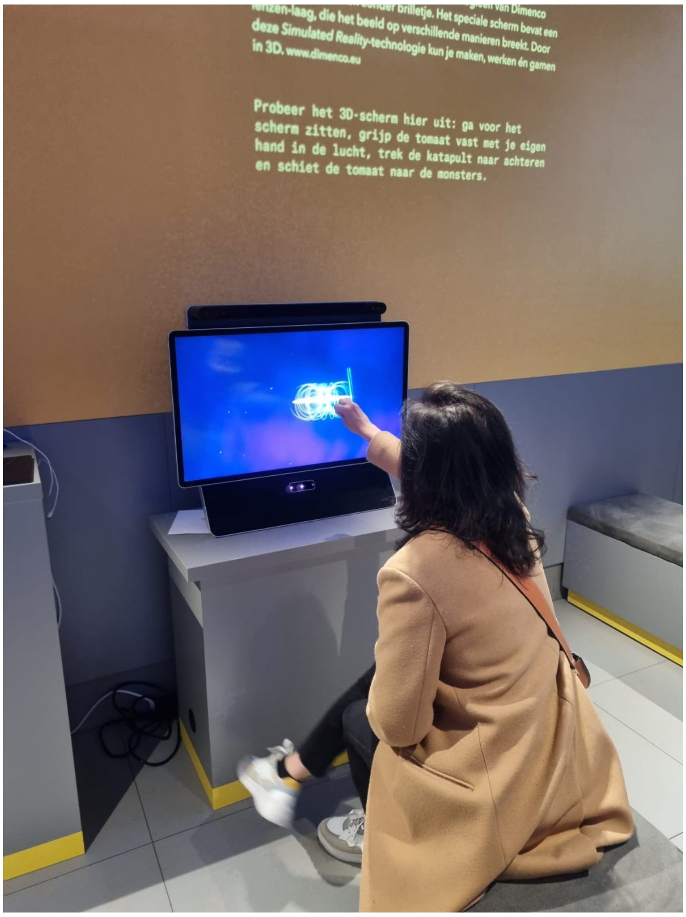


Figure 4.1: Participant connecting the pulsar pieces in the first level. This picture is used with consent.

Figure 4.2: Picture of the Saturn level

4.3 Narrative

Additionally, a short and clear narrative has been included at the beginning of the game to ensure engagement for a more diverse museum audience, according to [121]. The narrative presents a spacecraft that collided with an asteroid. The collision divided the spacecraft into three parts that are now wandering through space.

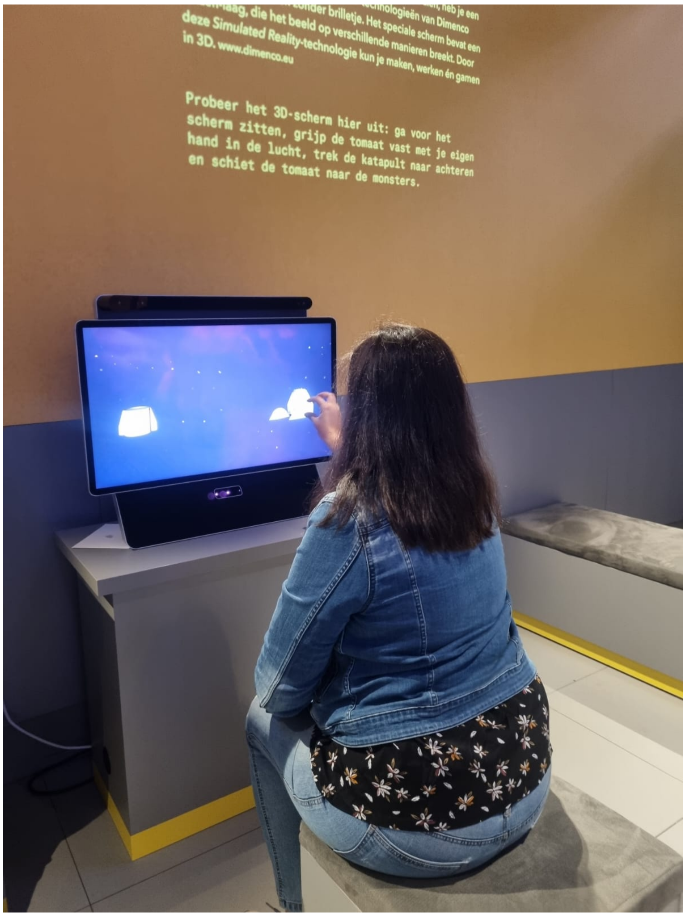


Figure 4.3: Participant assembling the spacecraft in the last level of the game. This picture is used with consent.

Figure 4.4: Picture of the BH level that has been eventually omitted due to pilot study

The parts must be collected while visiting different celestial objects and put together to save the spatial mission. The narrative animation ends with a screen that includes a goal-description text and a "Start" button. For this screen only, a hand pointer has been added to aid users in finding their own hand tracked on the screen. Since there were no other buttons implemented in the game, there was no need to include the

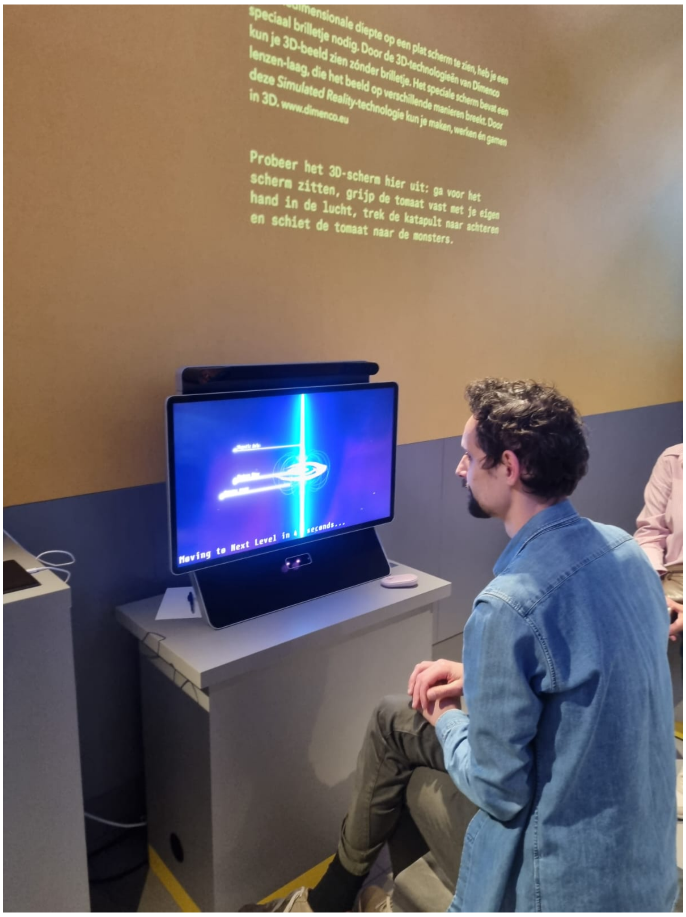


Figure 4.5: Picture of the Next level indication feature (bottom of the screen). This picture is used with consent.

hand pointer into the levels or animations. Moreover, including the hand pointer could confuse users or limit the full experience of manipulating the 3D objects on the SR DevKit since diverse hand gestures were used throughout the game. The hand pointer can be seen in Figure 4.6.

4.4 Information delivery

In order to cover the educational facet of the current research, short, minimal scientific terms were included in the game levels to provide insights on the celestial objects' components. Although a great deal of prior studies have shown the potential of recall tasks and learning outcomes [41][52][56], the reason for this choice is to avoid cognitive overload and the so-called "museum-fatigue" [71][121] since SR

Figure 4.6: Example of the hand pointer used for the Start screen of the game

technology not only implies 3D monitors but also hand gestures as controllers. In order to maintain an identical cross-platform application, same information delivery approach ahs been implemented for both the SR DevKit and the touchscreen tablet. Figure 4.7 presents an example of the scientific term delivery in one of the game levels.

Finally, the decision of creating a game specifically, not a standard application that would deliver information is supported by prior research as well [126][188], since game technologies, especially on novel hardware are more effective in fostering learning and information retention than trivial instructional methods. Thus, the game invites visitors to engage by offering visual aesthetics and easy game mechanics, promoting exploration and curiosity, and giving feedback. Moreover, the SR game benefits from a novel hardware platform. Thus, all game-based learning station criteria have been met.

4.5 Tutorials

Each platform provides users with tutorials, at the beginning of each level, which differ in terms of controllers. That is, the touchscreen application presents instruc-

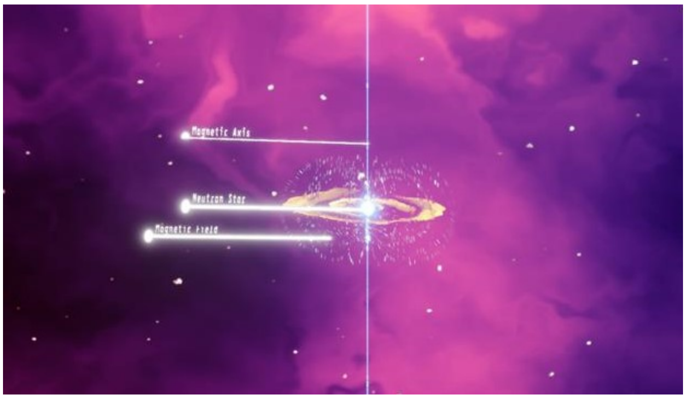


Figure 4.7: Presentation of the scientific terms of the celestial object's components after the level has been completed

Figure 4.8: Picture of a participant (right) watching a level tutorial before playing. Below Saturn planet, a hand gesture (fist) is presented and animated. Picture used with consent.

tions and tutorials with touch gestures while the SR DevKit provides the level instructions with hand gesture tutorials. All cross-platform tutorials included instructions, animations and 3D models identical with the ones in the game. Figure 4.8 presents an example of how the tutorials fit into the user gameplay.

4.6 Pilot study

The pilot study represents a critical stage in the application development process, as mentioned already in the pipeline section. This is because pilot study users had the chance to test the application and share their feedback on the experience. The pilot study had 6 participants with balanced 3D experience and its setup resembles the setup for the following experiment, with small differences. The pilot study had significantly fewer participants, and the location was not in the museum, but in the Dimenco company office.

From their insights, we learned that specific hand gestures of the game had to be changed for the SR DevKit because they were not suggestive or intuitive enough. On the same note, while running the pilot study, it could be easily observed that these gestures generated frustration when the users fail to successfully grab the 3D objects in the environment. Some of the participants suggested specific types of manipulation, such as grabbing with the full fist instead of just pinching. This latter hand gesture might have also been less preferred since the Ultraleap hand-tracker sometimes fail to recognize it, while the grabbing hand gesture involving the fist was recognised almost flawlessly.

Additionally, some participants indicated that the levels are too bright, thus the 3D effect being prone to cross-talk, which means there is displacement in the images on the screen. Careful adjustments have been made to the levels in order to solve this issue.

Another improvement to the application that has been implemented based on the pilot study results and suggestions was increasing the number of seconds to the level-transition countdown. Some participants mentioned that they did not have enough time to study and look at the 3D objects. On a similar note, the animated tutorial was perceived as "too fast", and they had to be slowed down. This happened most probably because of the 3D optical effect present only in the SR DevKit. Together with fast animated tutorials, the 3D optical effect could overload the cognitive functions of the brain, hence the brain being unable to fastly comprehend the tutorials at normal speed. The animated tutorials were slowed down by -0.25.

Finally, the cross-platform application previously contained an additional level. This level depicted a part of the spacecraft that must be saved from a black hole. Users were supposed to perform lasso hand gestures in order to save the spacecraft part, however, none of the participants managed to successfully complete this level. Moreover, some participants mentioned that it was "too difficult" and "confusing" to perform the level and one participant indicated that the game was "too long". Therefore, it has been decided that this level should be omitted.

All these improvements have been implemented for the touchscreen application as well, in order to maintain a fully identical cross-platform application.

5. Evaluation

5.1 Why touchscreen vs. SR?

This chapter presents the experiment design and results from this study. Moreover, additional interviews and reflections of the museum workers and participants are analysed.

The baseline for the current study is a comparison between SR monitors and touchscreen kiosks, since the latter is the most popular technology to be met in museums. However, since the touchscreen kiosks in the museum were not accessible this experiment, a touchscreen tablet was used instead.

The reason behind making a comparison between a 2D and an SR monitor is to take the reviews from previous studies to a further extent, in the museum context. Since interaction, as shown previously, is a significant part of the museum experience, similar interaction types (touch and hand gestures) are also compared. The comparison scenarios will be, therefore, performed, between a touchscreen 2D monitor (touchscreen kiosk) and an SR monitor (3D monitor supporting hand gesture tracking). Surely more comparisons between the two displays and two types of interaction exist, such as switching the interaction types for the 2 displays (2D monitor with hand gestures and 3D monitor with touch interaction), however, one can already visualize that 3D touchscreen monitors will not leverage the user experience in the museum context by any means since the disparity of the parallax can interfere with the touch, leading to the loss of the 3D optical phenomenon. Additionally, as this study focuses mainly on identifying a potential increase in the user experience of museum visitors using SR monitors, they should be compared with the most reasonable and common media interaction device found in museums: touchscreen kiosks. As a result, the idea of adding an extra 2D monitor with hand gestures scenario was disregarded as this type of device is not broadly used in museums.

The devices used for the experiment setup were an SR monitor (SR DevKit) and a Samsung Galaxy Tab A8 tablet. SR DevKit's relevant specifications are as follows:

Display: Dimenco clear view lenticular lens - 32” 8K 3D panel
Graphics: Nvidia Geforce RTX 2080 Ti
Processor: Intel i7 8700 (6-cores @ 3.2-4.2 Ghz)
Sensors: 2x Eye tracking sensor
Hand tracking sensor
Speaker: Spatial sound 12 speaker array + LFE
Others: 4-CH Microphone array
1Gb ethernet + WIFI
4 x 3.0 USB
the DevKit can be visualized in Figure 5.1

Figure 5.1: SR DevKit offered by Dimenco

Samsung Galaxy Tab A8's relevant specifications are as follows:
Screen size: 10.5 inches
Resolution: 1920x1200
Panel type: TFT
Pixel density: 216 ppi
Number of colours: 16M
Multi-touch: Yes

Touchscreen technology: Force touch

Processor chipset: Unisoc Tiger T618 *CPU:* ARM Cortex A75 Octacore 2.0GHz

Graphics Processor: ARM Mali-G52 MP2 *Random access memory:* 3GB

A depiction of the tablet can be found in figure 5.2

Figure 5.2: Samsung Galaxy Tab A8

It is salient to consider the differences in size between the two devices with regard to future research.

5.2 Experiment design

With respect to having more control over the experimental studies, a single cross-platform application was designed and developed in Unreal Engine 5 for the SR monitor and tablet. The experiment was a between-participants study. The experiment consisted of 104 participants (54 male, 49 female, 1 anonymous) over 13 years old playing the proposed game on one of the scenarios below:

- *Application on Touchscreen (44 participants: 22 male, 22 female)*
- *Application on SR autostereoscopic Screen (60 participants: 32 male, 27 fe-*

male)

The order of the scenarios was randomized to mitigate any experience, preference, or fatigue bias. The location of the experiment was at the "Wonder Floor" in the Beeld & Geluid Media Museum. The map of the museum station location can be consulted in Figure 3.5.

In the beginning, the participants were given a GDPR form of consent to sign. Afterwards, they played the game on a randomly-assigned device and then, they were given a questionnaire to complete that contained background questions, CAMIL questionnaire for the sense of presence and agency constructs and the miniPXI questionnaire.

The form of consent, along with the background questions, and questionnaire can be consulted in the *Appendix A* section.

Although measures have been taken to mitigate any occurrence of cybersickness and eyestrain, participants have been informed that they can withdraw from the experiment anytime without negative repercussions. Participants under 18 years old have been required to present a parent's/tutor's consent for their participation.

5.3 Results

5.3.1 Research Question 1

In order to respond to the research questions, a study has been run in this regard. Since the current experiment is a qualitative comparative study based on an AB testing approach with questionnaires that are measured on a Likert scale, Mann-Whitney U tests were performed for both device conditions (Touchscreen application, SR monitor) for the miniPXI constructs. Since CAMIL question constructs (sense of presence, agency) were designed for numerical scales, independent T-tests were performed. These tests are meant to help us respond to RQ1. Then, participants were asked to respond to four open questions in order to be able to respond to RQ2 and RQ3. All the responses to the question constructs and open questions are analysed in this section, starting with the question constructs that will define the response for RQ1.

Figure 5.3 presents an overview of the null hypothesis of the questionnaire, particularly, whether there were different participant responses between the two devices. Thus, it can be observed that five out of 13 question constructs have presented significant p-values after performing Mann-Whitney U-tests, meaning that there were five significant differences between the two device conditions. These questions belong to the following constructs: audiovisual appeal, enjoyment, immersion, mastery, and intuitive controls. The results on the Likert scale for these constructs can be consulted in figure 5.6.

Figure 5.4 shows the significance of the Sense of Presence and Agency constructs that were tested with T-tests. While Presence presents a significant p-value (p=0.042) after the condition comparison, Agency has insignificant effects among conditions, thus leading to an overall of six significant constructs, in other words, six construct differences between the two device conditions.

The following subsections provide an exhaustive overview of the six construct differences between the two conditions in order to understand in which regards may the devices be more effective in reaching a more enhanced visitor experience.

5.3.1.1 Audiovisual Appeal

Judging by the Mean Rank (MR) in Figure 5.6, the SR application received overall higher ranks (MR=57,55, U=1623.000, Z=2.219) than the Touchscreen application in the audiovisual appeal construct. Although the application was identical for both devices audio and visual-wise, it was somehow expected that a novel technology will impact the audiovisual feeling of the museum visitors.

However, several individual Mann-Whitney U-tests were performed to investigate the cause of the results. Thus, individuals who visit museums a few times a year found the application more appealing than visitors who enter a museum only once in a couple of years. On the same note, visitors who had educational experiences with technology also found the application more audio and visually pleasant(p=0.026, U=544.000, Z=2.226). While gender had no significant implications overall, the touchscreen application presents significant results (p=0.029, U=328.500, Z=2.189) regarding the audiovisual constructs in this regard. Thus, fe-

Hypothesis Test Summary

	Null Hypothesis	Test	Sig.[a,b]	Decision
1	The distribution of Select the option that represents the best how you feel about the sentences. - 1. I liked the look and feel of the game. is the same across categories of I tried:.	Independent-Samples Mann-Whitney U Test	.026	Reject the null hypothesis.
2	The distribution of Select the option that represents the best how you feel about the sentences. - 2. The game was not too easy and not too hard to play. is the same across categories of I tried:.	Independent-Samples Mann-Whitney U Test	.579	Retain the null hypothesis.
3	The distribution of Select the option that represents the best how you feel about the sentences. - 3. It was easy to know how to perform actions in the game. is the same across categories of I tried:.	Independent-Samples Mann-Whitney U Test	.903	Retain the null hypothesis.
4	The distribution of Select the option that represents the best how you feel about the sentences. - 4. The goals of the game were clear to me. is the same across categories of I tried:.	Independent-Samples Mann-Whitney U Test	.158	Retain the null hypothesis.
5	The distribution of Select the option that represents the best how you feel about the sentences. - 5. The game gave clear feedback on my progress towards the goals. is the same across categories of I tried:.	Independent-Samples Mann-Whitney U Test	.333	Retain the null hypothesis.
6	The distribution of Select the option that represents the best how you feel about the sentences. - 6. I had a good time playing this game. is the same across categories of I tried:.	Independent-Samples Mann-Whitney U Test	.003	Reject the null hypothesis.
7	The distribution of Select the option that represents the best how you feel about the sentences. - 7. I felt free to play this game in my own way. is the same across categories of I tried:.	Independent-Samples Mann-Whitney U Test	.836	Retain the null hypothesis.
8	The distribution of Select the option that represents the best how you feel about the sentences. - 8. I wanted to explore how the game evolved. is the same across categories of I tried:.	Independent-Samples Mann-Whitney U Test	.655	Retain the null hypothesis.
9	The distribution of Select the option that represents the best how you feel about the sentences. - 9. I felt I was good at this game. is the same across categories of I tried:.	Independent-Samples Mann-Whitney U Test	<,001	Reject the null hypothesis.
10	The distribution of Select the option that represents the best how you feel about the sentences. - 10. I was fully focused on the game. is the same across categories of I tried:.	Independent-Samples Mann-Whitney U Test	.020	Reject the null hypothesis.
11	The distribution of Select the option that represents the best how you feel about the sentences. - 11. Playing the game was meaningful to me. is the same across categories of I tried:.	Independent-Samples Mann-Whitney U Test	.347	Retain the null hypothesis.
12	The distribution of Select the option that represents the best how you feel about the sentences. - 20. The controls/gestures in the game felt natural to me. is the same across categories of I tried:.	Independent-Samples Mann-Whitney U Test	.009	Reject the null hypothesis.
13	The distribution of Select the option that represents the best how you feel about the sentences. - 21. I could intuit the gestures that controlled the game. is the same across categories of I tried:.	Independent-Samples Mann-Whitney U Test	.131	Retain the null hypothesis.

a. The significance level is .050.

b. Asymptotic significance is displayed.

Figure 5.3: General overview over the miniPXI and the Intuitive Controls construct questions with their significance

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Agency	Equal variances assumed	1.234	.269	-.457	102	.649	-.05505	.12053	-.29412	.18402
	Equal variances not assumed			-.467	99.149	.641	-.05505	.11787	-.28893	.17883
SenceOfPresence	Equal variances assumed	4.332	.040	-2.152	102	.034	-.35485	.16487	-.68188	-.02782
	Equal variances not assumed			-2.064	77.050	.042	-.35485	.17189	-.69712	-.01257

Figure 5.4: General overview over the Sense of Presence and Agency constructs

males that played the touchscreen application found the game more appealing than men. This finding can be consulted in Figure 5.5.

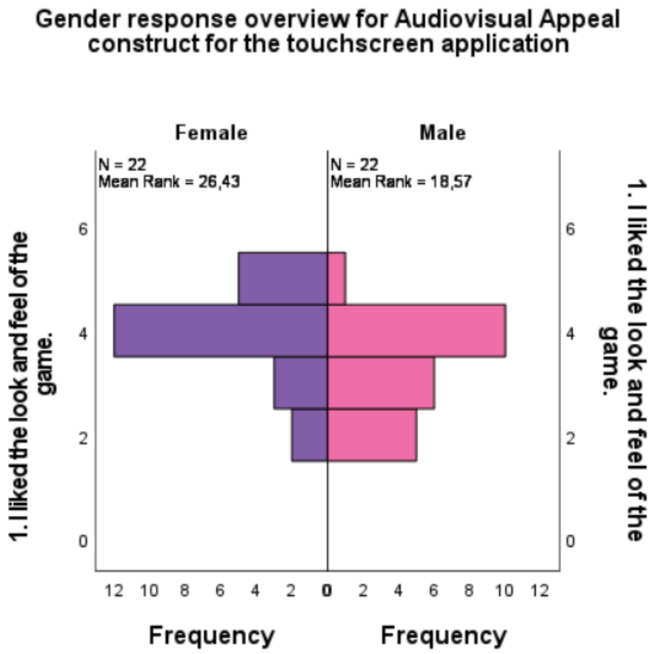


Figure 5.5: Gender response overview for the touchscreen application

5.3.1.2 Enjoyment

Figure 5.6 shows the results on the Likert scale for the Enjoyment construct. Judging by the Mean Rank, the SR application received overall higher ranks (MR=59,45, U=1737.000, Z=2.949) than the Touchscreen application, meaning that participants enjoyed the SR application more than the touchscreen application.

5.3.1.3 Mastery

Figure 5.6 shows the results on the Likert scale for the Mastery construct. Judging by the Mean Rank, the SR application received overall higher ranks (MR=60,18, U=1780.500, Z=3.420) than the Touchscreen application. This shows that SR application participants had a stronger feeling that they were good performing the game, and this might be among the reasons why they also enjoyed the SR application more.

5.3.1.4 Immersion

However, Figure 5.6 shows the results on the Likert scale for the Immersion construct. Judging by the Mean Rank, the SR application received overall lower ranks (M=46,86, U=981.500, Z=-2.332) than the Touchscreen application.

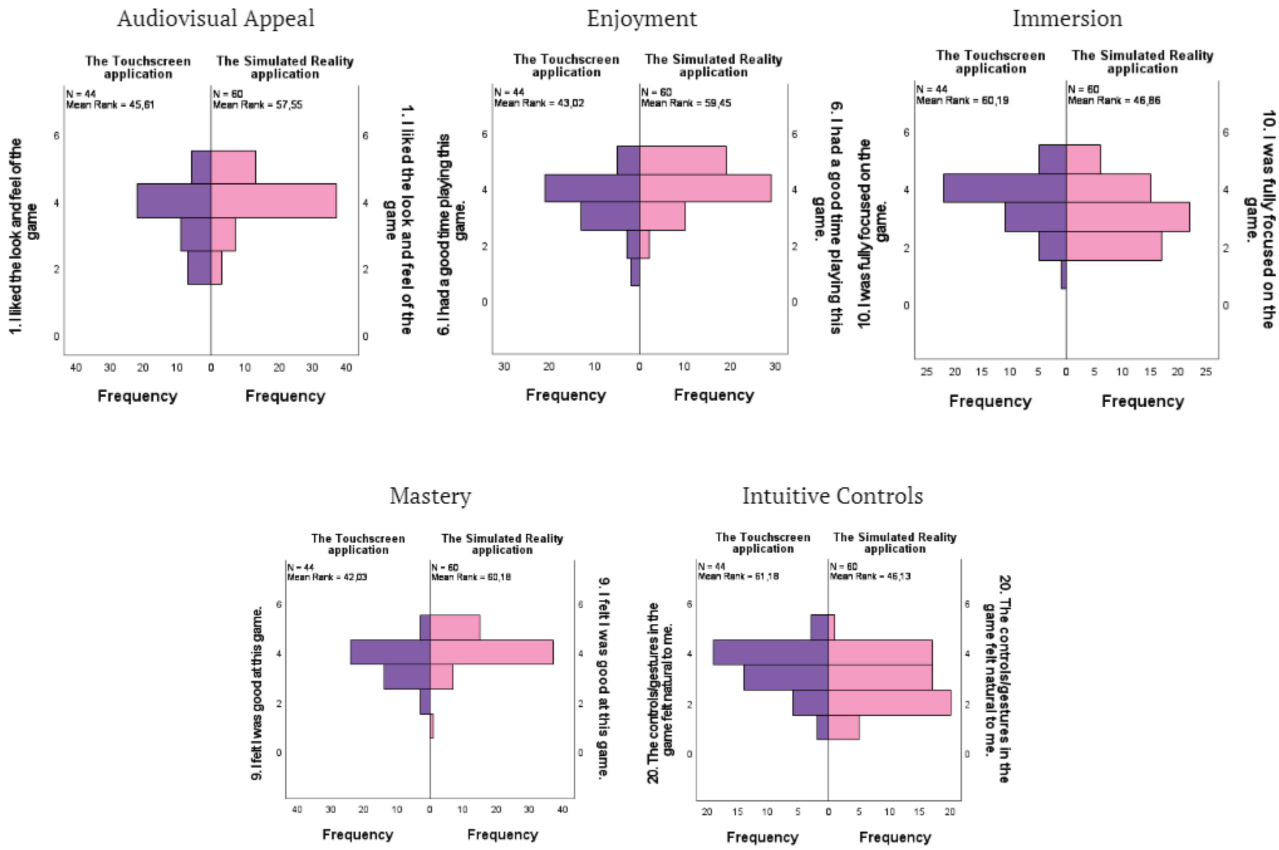


Figure 5.6: Results overview for Touchscreen application (left) and SR application (right) for the Audiovisual appeal, Enjoyment, Mastery, Immersion, and Intuitive Controls constructs

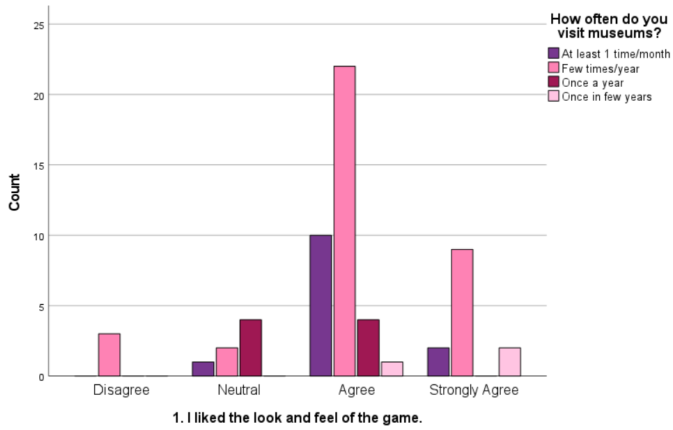


Figure 5.7: Response overview upon the audiovisual construct

Figure 5.9 shows that visitors with educational experience with technology have indicated to feel more immersed in the environment. This might also be because

Pairwise Comparisons of How often do you visit museums?

Sample 1-Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.[a]
Once a year-At least 1 time/month	13.154	6.814	1.931	.054	.321
Once a year-Few times/year	13.778	5.927	2.325	.020	.121
Once a year-Once in few years	-27.667	10.265	-2.695	.007	.042
At least 1 time/month-Few times/year	-.624	4.906	-.127	.899	1.000
At least 1 time/month-Once in few years	-14.513	9.712	-1.494	.135	.811
Few times/year-Once in few years	-13.889	9.112	-1.524	.127	.765

Each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same.
Asymptotic significances (2-sided tests) are displayed. The significance level is .050.

a. Significance values have been adjusted by the Bonferroni correction for multiple tests.

Figure 5.8: Visit frequencies influences over the Audiovisual Appeal construct. these results are from the participants who played the SR application

of curiosity levels. However, there is no relation between Falk's museum personas recorded in the experiment and immersion to validate this assumption.

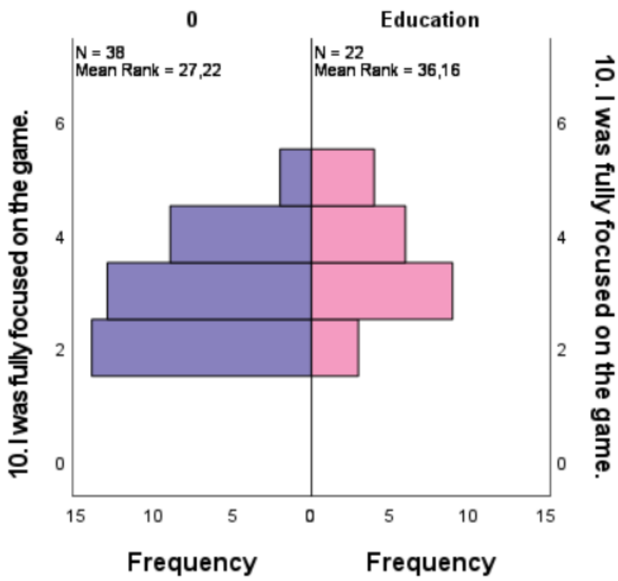


Figure 5.9: Immersion overview for the SR application between people with/without technology experience in

5.3.1.5 Sense of Presence

With regard to the sense of Presence construct, the SR application ranked significantly higher (p=0.042), according to Figure 5.4. The means can be visually consulted in Figure 5.10.

Overall, these measures show that there is a significant increase in the sense of presence for individuals who played the SR game.

Interestingly, although overall museum personas did not affect the sense of presence for both device conditions like other independent variables, a univariate ANOVA test shows that museum personas do influence the sense of presence. The significant relation can be seen in tables 5.11. According to Figure 5.12, Explorers and Rechargers indicated a higher sense of presence for the SR application, while Hobbyists and Professionals felt more present playing the Touchscreen application. Experience seekers indicated a slightly lower sense of presence nevertheless.

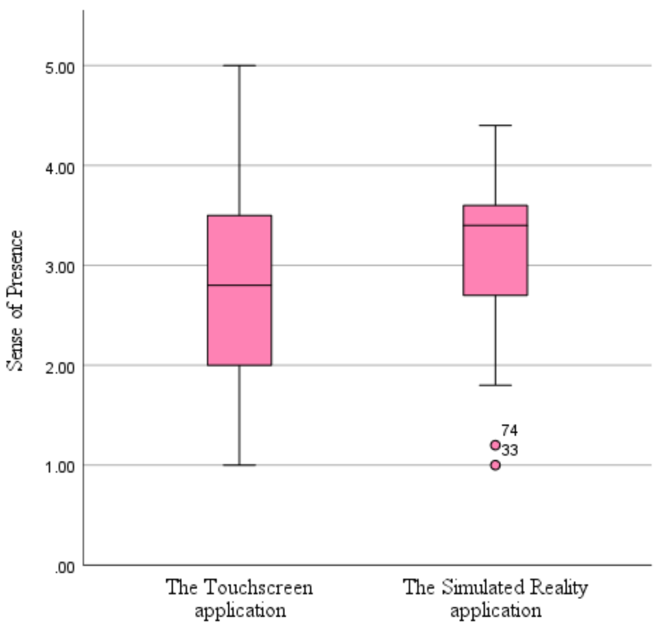


Figure 5.10: Presence overview for Touchscreen application (left) and SR application (right)

Tests of Between-Subjects Effects

Dependent Variable: SenceOfPresence

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	9.875[a]	7	1.411	2.126	.048
Intercept	732.641	1	732.641	1104.029	<,001
Q0F	.802	3	.267	.403	.751
Q0G	1.262	1	1.262	1.902	.171
Q0F * Q0G	6.304	3	2.101	3.167	.028
Error	63.706	96	.664		
Total	1032.520	104			
Corrected Total	73.581	103			

a. R Squared = .134 (Adjusted R Squared = .071)

Figure 5.11: The sense of presence influenced by museum personas in both device conditions, where QF is the museum persona question, and QG the device condition

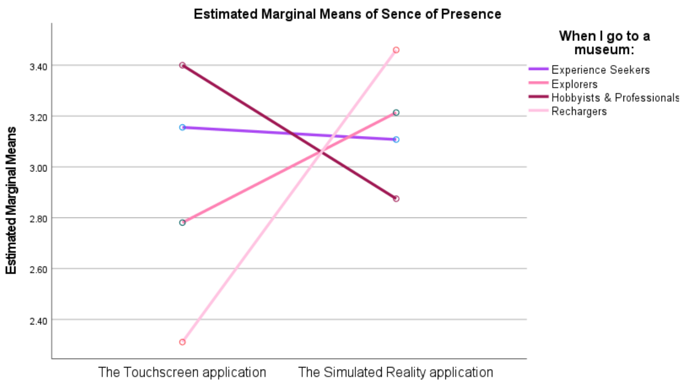


Figure 5.12: The sense of presence influenced by museum persona in both device conditions, where QF is the museum persona question, and QG the device condition

5.3.1.6 Intuitive Controls

Figure 5.6 shows the results on the Likert scale for the Intuitive Controls construct. Judging by the Mean Rank, the SR application received overall lower ranks(MR=46,13, U=938.000, Z=-2.626) than the Touchscreen application. This might be the case due to high familiarisation with touch gestures among participants, while SR technology and hand gestures is less ubiquitous.

5.3.2 Independent Variables

General results over the two conditions indicated five constructs in which the touchscreen and the SR application show differences. While these results are alone significant, it is crucial to further investigate whether independent variables could affect these results. Thus, Mann-Whitney U-tests have been performed to check for significant differences between the independent and dependent variables, which

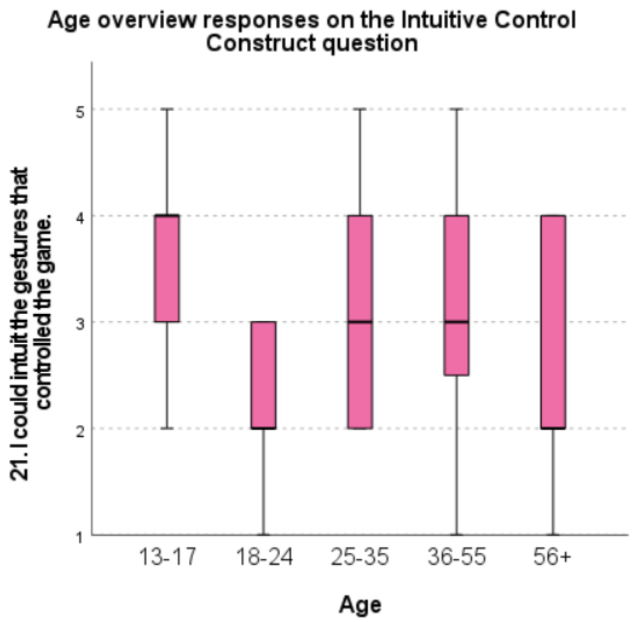


Figure 5.13: Age overview responses on the Intuitive Controls construct

will be presented in the following subsections. While age, museum visit frequency, VR experience, and experience field have shown significant differences, museum personas, experience with Touchscreen, AR, and 3D monitors and gender have presented no significant differences.

5.3.2.1 Age

It is needless to say that younger generations are generally more familiar with technology. Thus, age can be a critical independent variable to affect positively or negatively the results and eventually, the experience of museum visitors. In this experiment, age has shown differences in the Intuitive Controls construct. Figure 5.13 depicts an overview of the results. An exhaustive comparison among age groups can be consulted in table 5.14.

Figure 5.13 shows a significant difference among age groups (p=0.008, H=4, Z=13.824). Visitors under 18 years old have indicated that the controls were intuitive, differentiating themselves the most from the 18-24 and 56+ age groups.

Individual U-tests have shown significant differences for the SR application only, in the Intuitive Controls construct specifically. Figure 5.15 and table 5.16 present significant values between participants under 18 years old and 18-24 group

Sample 1-Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.[a]
18-24-56+	-10.189	12.975	-.785	.432	1.000
18-24-36-55	-25.100	11.962	-2.098	.036	.359
18-24-25-35	-25.105	13.224	-1.898	.058	.576
18-24-13-17	35.838	12.127	2.955	.003	.031
56+-36-55	14.911	8.541	1.746	.081	.808
56+-25-35	14.916	10.234	1.457	.145	1.000
56+-13-17	25.649	8.771	2.924	.003	.035
36-55-25-35	.005	8.916	.001	1.000	1.000
36-55-13-17	10.738	7.188	1.494	.135	1.000
25-35-13-17	10.733	9.136	1.175	.240	1.000

Each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same.
Asymptotic significances (2-sided tests) are displayed. The significance level is .050.

a. Significance values have been adjusted by the Bonferroni correction for multiple tests.

Figure 5.14: Pairwise comparisons of age categories for Intuitive Controls construct

(p=0.001) and 56+ years old group (p=0.005), meaning that youngsters could naturally intuit better the controls of the game. However, after applying Bonferroni corrections to the tests, these findings are less significant.

5.3.2.2 Musem Frequency

Another important aspect of this experiment is the frequency of museum visits. Despite the fact that all visitors should have their experience enhanced by the museum stations, it is understandable that differences in museum frequencies can affect the overall results of this experiment. Therefore, museum frequency has presented important differences in the AudioVisual Appeal and Challenge constructs. The AudioVisual Appeal results (p=0.023, H=3, Z=9.574) are shown as an overview in Figure 5.17 and the comparisons within the age groups can be consulted in Table 5.18. Results show that individuals who visit museums at least once a month liked the audiovisual look of the application more than individuals who visit museums once a year. This can be the case when less frequent visitors have different or higher expectations from the museum stations, or if they are more familiar with specific graphics, aesthetic themes, or similar facets experienced with technologies that were different from the audiovisual styles used in the game.

The results for the Challenge construct (p=0.047, H=3, Z=7.970) are pre-

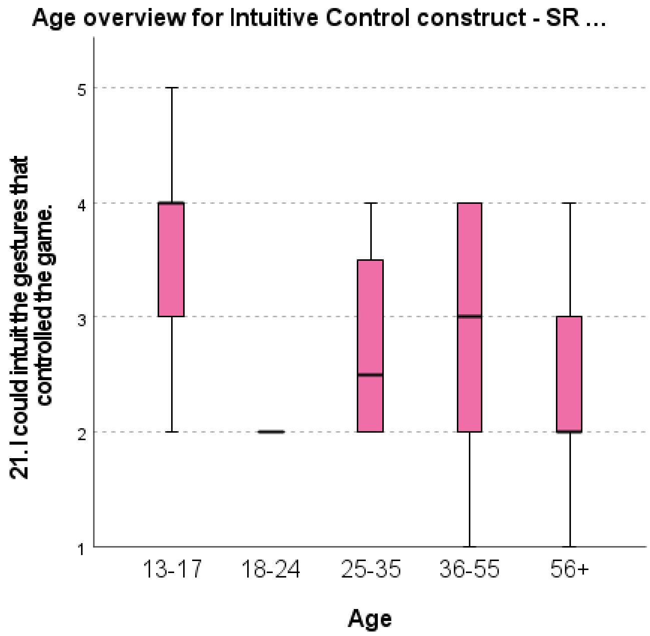


Figure 5.15: Age overview responses on the Intuitive Controls construct for the SR monitor only

Sample 1-Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.[a]
18-24-56+	-8.278	11.158	-.742	.458	1.000
18-24-25-35	-13.000	11.331	-1.147	.251	1.000
18-24-36-55	-15.806	10.437	-1.514	.130	1.000
18-24-13-17	26.682	10.301	2.590	.010	.096
56+-25-35	4.722	8.132	.581	.561	1.000
56+-36-55	7.528	6.833	1.102	.271	1.000
56+-13-17	18.404	6.622	2.779	.005	.055
25-35-36-55	-2.806	7.112	-.395	.693	1.000
25-35-13-17	13.682	6.910	1.980	.048	.477
36-55-13-17	10.876	5.319	2.045	.041	.409

Each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same.
Asymptotic significances (2-sided tests) are displayed. The significance level is .050.

a. Significance values have been adjusted by the Bonferroni correction for multiple tests.

Figure 5.16: Pairwise comparison of age responses on the Intuitive Controls construct for SR monitor only

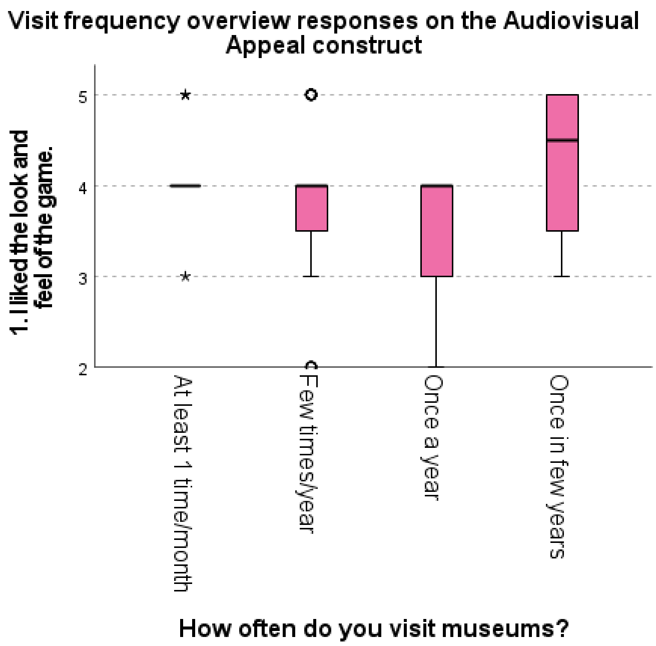


Figure 5.17: Visit frequency overview responses on the Challenge construct

Sample 1-Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.[a]
Once a year-Few times/year	18.643	7.393	2.522	.012	.070
Once a year-At least 1 time/month	24.890	9.046	2.751	.006	.036
Once a year-Once in few years	-30.831	15.058	-2.047	.041	.244
Few times/year-At least 1 time/month	6.247	7.079	.882	.378	1.000
Few times/year-Once in few years	-12.187	13.965	-.873	.383	1.000
At least 1 time/month-Once in few years	-5.941	14.907	-.399	.690	1.000

Each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same.
Asymptotic significances (2-sided tests) are displayed. The significance level is .050.

a. Significance values have been adjusted by the Bonferroni correction for multiple tests.

Figure 5.18: Pairwise comparisons of age categories for Intuitive Controls construct

sented in Figure 5.19 and the comparisons between age groups can be consulted in Table 5.20. Although the adjusted significance value is high, there is still a high difference in the responses of the individuals that visit the museum at least once a month and the ones who enter a museum once in a few years. Since they might feel more acquainted with trying novel technologies in the museum, consistent visitors indicated that the application was challengingly balanced.

Individual U-tests show different results for each of the device conditions.

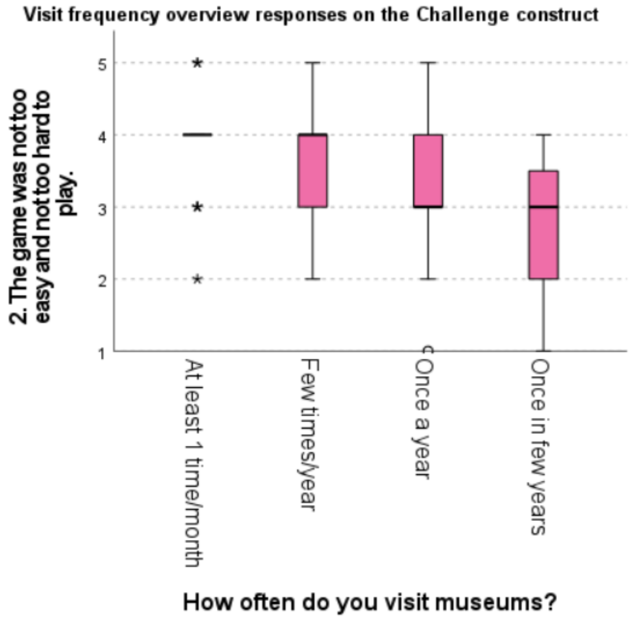


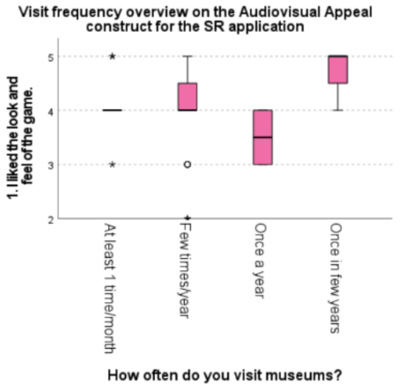
Figure 5.19: Visit frequency overview responses on the Challenge construct - both conditions

Sample 1-Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.[a]
Once in few years-Once a year	11.265	15.127	.745	.456	1.000
Once in few years-Few times/year	23.250	14.029	1.657	.097	.585
Once in few years-At least 1 time/month	32.026	14.974	2.139	.032	.195
Once a year-Few times/year	11.985	7.427	1.614	.107	.640
Once a year-At least 1 time/month	20.762	9.087	2.285	.022	.134
Few times/year-At least 1 time/month	8.776	7.111	1.234	.217	1.000

Each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same.
Asymptotic significances (2-sided tests) are displayed. The significance level is .050.

a. Significance values have been adjusted by the Bonferroni correction for multiple tests.

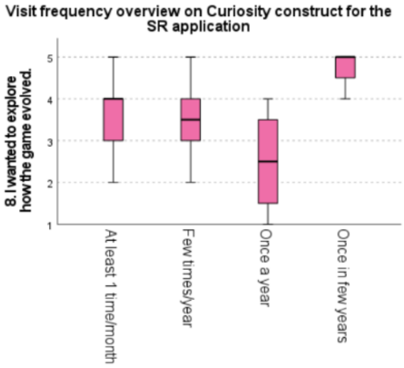
Figure 5.20: Pairwise comparisons of visit frequency responses for Challenge construct - both conditions



Sample 1-Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.[a]
Once a year-At least 1 time/month	13.154	6.814	1.931	.054	.321
Once a year-Few times/year	13.778	5.927	2.325	.020	.121
Once a year-Once in few years	-27.667	10.265	-2.695	.007	.042
At least 1 time/month-Few times/year	-.624	4.906	-.127	.899	1.000
At least 1 time/month-Once in few years	-14.513	9.712	-1.494	.135	.811
Few times/year-Once in few years	-13.889	9.112	-1.524	.127	.765

Each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same.
Asymptotic significances (2-sided tests) are displayed. The significance level is .050.

a. Significance values have been adjusted by the Bonferroni correction for multiple tests.



Sample 1-Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.[a]
Once a year-Few times/year	13.819	6.433	2.148	.032	.190
Once a year-At least 1 time/month	17.683	7.396	2.391	.017	.101
Once a year-Once in few years	-35.042	11.143	-3.145	.002	.010
Few times/year-At least 1 time/month	3.863	5.326	.725	.468	1.000
Few times/year-Once in few years	-21.222	9.891	-2.146	.032	.191
At least 1 time/month-Once in few years	-17.359	10.543	-1.647	.100	.598

Each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same.
Asymptotic significances (2-sided tests) are displayed. The significance level is .050.

a. Significance values have been adjusted by the Bonferroni correction for multiple tests.

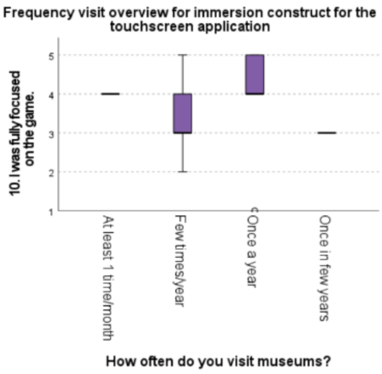
Figure 5.21: Frequency visit overview for Audiovisual Appeal and Curiosity constructs for the SR application

First, participants who played on the SR application indicated higher curiosity and audiovisual appeal. Specifically, participants who visit museums once in a few years found the game more appealing and are more curious than individuals who enter the museum once a year. These findings can be consulted in Figure 5.21. Secondly, participants who played on the touchscreen application felt more immersed and indicated a better understanding of the goals of the game. Specifically, participants who visit museums at least once a month felt that the goals of the game were clear than people who visit museums once a year or in a few years, but also indicated that they did not feel too immersed in the game. On the contrary, individuals who visit museums once a year felt more immersed in the game than people that visit museums a few times a year. However, after applying the Bonferroni correction for multiple comparisons, these results became less significant. These findings can be consulted in Figure 5.22.

Sample 1-Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.[a]
Once in few years-Once a year	11.222	12.577	.892	.372	1.000
Once in few years-Few times/year	18.071	12.143	1.488	.137	.820
Once in few years-At least 1 time/month	27.167	12.888	2.108	.035	.210
Once a year-Few times/year	6.849	4.572	1.498	.134	.805
Once a year-At least 1 time/month	15.944	6.289	2.535	.011	.067
Few times/year-At least 1 time/month	9.095	5.368	1.694	.090	.541

Each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same.
Asymptotic significances (2-sided tests) are displayed. The significance level is .050.

a. Significance values have been adjusted by the Bonferroni correction for multiple tests.



Sample 1-Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.[a]
Once in few years-Few times/year	7.196	12.101	.595	.552	1.000
Once in few years-At least 1 time/month	16.500	12.843	1.285	.199	1.000
Once in few years-Once a year	17.944	12.534	1.432	.152	.913
Few times/year-At least 1 time/month	9.304	5.349	1.739	.082	.492
Few times/year-Once a year	-10.748	4.556	-2.359	.018	.110
At least 1 time/month-Once a year	-1.444	6.267	-.230	.818	1.000

Each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same.
Asymptotic significances (2-sided tests) are displayed. The significance level is .050.

a. Significance values have been adjusted by the Bonferroni correction for multiple tests.

Figure 5.22: Frequency visit overview for Goals and Immersion constructs for the touchscreen application

5.3.2.3 VR Experience

Prior or inexistent experience with technology can impact visitors' perspective upon this experiment. Thus, as far as experience is concerned, only the VR experience field presented significant results, for the Challenge construct (p=0.001, U=890.5000, Z=-3.133) for both device conditions. According to Figure 5.23, visitors with no VR experience found the application more balanced, challenge-wise. Interestingly, although the p-value for the Meaning construct is slightly insignificant (p=0.056, U=1077.00, Z=-1.909), it is still worth mentioning that VR-experienced visitors found the application more meaningful, according to Figure 5.24. This could be due to the fact they perceived their experience as similar as VR, triggering a feeling of functional or psychological desires that might eventually align with their values, according to [181].

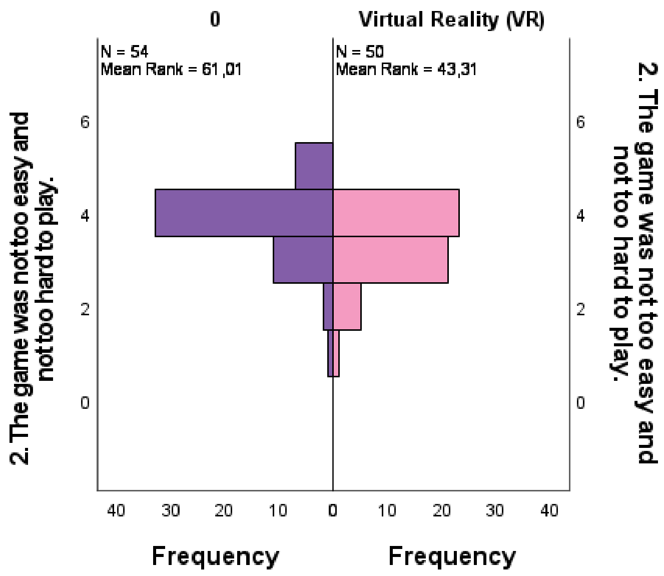


Figure 5.23: Overview of the VR experience for the Challenge construct. 0 value means no experience with VR

5.3.2.4 Experience Field

While the field where participants gained experience with technology may be worth investigating more particularly, this is not the aim of the current research. Thus, exhaustive charts with the participants' responses influences on each construct for both device conditions can be consulted in the Appendix.

According to the results from all constructs together with the independent variables, it was established that H1 has been inferred, even though the differences between the device conditions for some constructs were negligible.

5.3.3 Interviews and open questions

5.3.3.1 Open questions

To understand a bit more visitors' reasoning for the questionnaire, the questionnaire also included four open questions. These questions were:

- *What had the most impact on you in the experience?*
- *In general, what do you think about technology in museums?*
- *Would you recommend SR technology for museums? Why?*

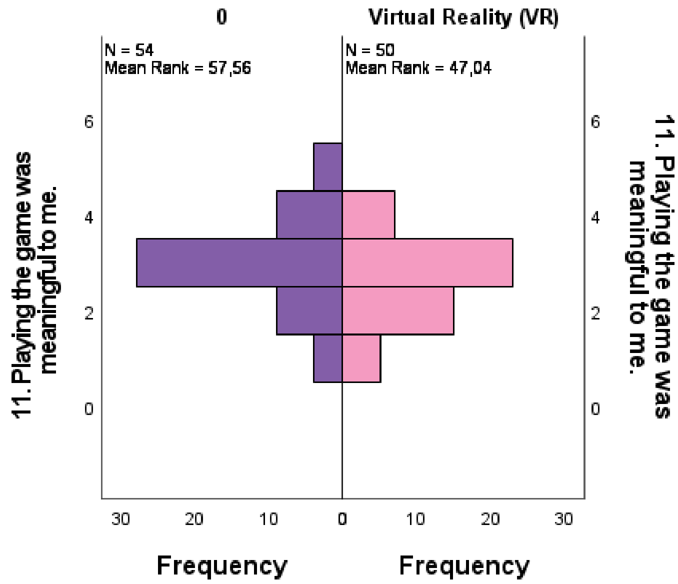


Figure 5.24: Overview of the VR experience for the Meaning construct. 0 value means no experience with VR

- *Write (educational/non-educational) things that you remember from the game:*

The first three questions were addressed in order to comprehend visitors' opinions on the devices they performed, hence responding to RQ2. The last open question is meant to help us respond to RQ3.

5.3.3.2 Research Question 2

Overall, for the first open question, the most common responses among the participants playing the SR application were the 3D visual effect without the need for glasses and hand gesture interactions that controlled the game. On another note, 2 participants indicated tiring eyes after the performance but they did not want to stop the experiment. For the touchscreen applications, the most common responses among the participants were the game effects (visual and audio), and "nothing really" or neutral.

The second question reveals visitors' positive attitudes regarding technology in museums. The most common responses to this question were *"positive", "cool"*, and *"very good"*. Some participants that performed on the touchscreen application responded the following: *"Technology is very important in the current digital age"*, *"I enjoy it when it is easy to use, interactive, and adds value to the exhibit. No need* *to overuse."*, *"It is more than just delivery. Interaction, action, reaction - is nicer to discover things"*. SR application users responded the following: *"It's useful because it helps you understand things better"*, *"Has a lot of potential to make the experience more interesting if applied in the right way"*, *"Interaction makes the museum visit more enjoyable"*.

For the third question, only 55 participants out of 60 SR participants responded to the question, with a majority inclination to *"Yes"* (43 responses), 7 neutral, and 5 responses against SR technology in museums.

5.3.3.3 Research Question 3

The last question is meant to check for information retention. While only one touchscreen application participant remembered the scientific terms used in the game, the rest of the participants from both conditions answered by mostly describing the levels of the game. This can be due to a lack of self-regulation, given that as museum visitors, they can get excited to study, see or interact with artifacts and their primary goal might not necessarily be only learning. However, since some of the participants responded exhaustively to this question, there can be stated that there is a potential for information retention, meaning that H3 is inferred. However, it is worth investigating which device enhances information retention better, and for what period of time.

5.3.4 Museum Workers Interview

While contacting application experts was crucial, getting perspective from museum workers was also considered salient since they observe visitors' behavior and feedback to museum stations the best. Thus, we asked a couple of museum workers what they think about the SR technology and its information delivery medium, and what age groups and personas are more attracted to this technology. A few responses were: *"I think it's really cool! Works much better than the [previous] old game, at least. Nobody really seemed to intuitively get that one but this one is really easy to follow."*

"As a museum worker, from what I've seen so far I can conclude that people who tried both 2D touchscreen kiosks and the SR technology are way more attracted

to the latter one, due to its 3D effect and novelty. It is true that the 3D monitor possessed by this museum is a discontinued model and sometimes the applications do not work due to overheating, but when they do, they attract lots of visitors, and the visitors like it a lot. I also believe that this is the future due to the progress of technology, and most probably soon we'll have even more holograms and other 3D presentation media. Not maybe necessarily games, but animations or presentations - where people can interact naturally with the objects by zooming or rotating them. That works better than 2D devices because I see everyday visitors that struggle with interacting via keyboards, and touch, where they have to press something, especially to older generations. But the SR controls are so natural thanks to the gestures that would allow you to naturally rotate the object when you feel the need for rotation for example."

With respect to the delivery of information, a museum worker responded: *"It was much easier to play the game with the added depth vision. I was surprised how accurate it was! Imagine this with 3d objects like skeletons, I bet they're way easier to explore in SR."*

Lastly, in terms of visitor personas, other museum workers replied: *"Generally young people would gravitate towards this I feel. People wearing glasses might be scared off by the warnings, but I think most would be willing to give this a shot. Overall I think most would be curious to see what SR technology has to offer! Especially in museums."*

Thus, museum workers believe that the progress of technology will impact museums as well in the near future. Technologies like holograms, VR and SR might be more present in museum environments, even though at the moment there is a plethora of aspects to improve. Additionally, technologies in museums (and particularly SR) will probably impact younger generations' experience the most due to their familiarity with technology in general. This latter aspect might be the reason why for some participants the gestures felt extremely intuitive and natural, while others felt that they needed to learn the gestures first.

5.3.5 Additional reflections

Some participants were willing to share more of their experiences after the experiment. Their reflections were categorised into 3 perspectives: reflections on the SR application, reflections on the touchscreen application, and use cases.

Individuals who tried the SR application were generally amazed by the glasses-free 3D effect and the intuitive controls of the game: *"Touching the button [from distance] felt very weirdly real. I liked that I could manipulate objects"*, *"The 3D effect is weird! But good weird!"*, and some individuals felt that the 3D effect is *"real"*. In terms of controls, one participant exhaustively stated that controlling the objects on the screen by hand felt more suggestive and natural than using fingers to manipulate them on a 2D touchscreen, since when seeing 3D, the first reaction is to use hand gestures. However, the same participant acknowledges that *"other generations [older] would prefer the 2D touchscreen if they don't have experiences with novel technologies"*.

Two participants who work in the AR and VR-meta fields respectively indicated that while the SR monitor is not as immersive as VR, it's still a cool technology, and works better than AR glasses: *"I work with Hololens and I have to say - this option of seeing 3D without glasses is amazing. The 3D is more natural and less constraining; it's like a 3D bubble monitor."*

A participant who tried the touchscreen application was expecting to see more textual information and similar details about the components of the objects in the game *"because I believe it's easier to see more text on 2D than maybe in 3D; it was still a fun experience"*. This can mean that touchscreens might be used for more detailed information delivery, while 3D monitors could facilitate a better visual investigation and study of the objects on the screen.

After analysing the reflections from participants and museum workers, we concluded that H2 could not be either inferred or rejected. This is because of the different perceptions due to age, personality, and background with respect to the museum experience. Thus, we can only state that H2 can be inferred only for younger generations since they seemed to respond more positively to most of the constructs and open questions. On a similar note, H3 has been inferred based on the responses from the last open questions from the questionnaire.

From use case perspectives, some individuals consider that the SR application would be a suitable addition to science museums specifically, since *"you can see molecules and how they look like rotated"*. One individual felt that 3D effects for studying objects in space *"is better than in 2D, but maybe not with gamification features, but more as a visualisation or presentation application"*. Studying objects that cannot be normally seen in everyday life through a 3D medium intrigued participants who work in the medical field as well. According to one of these participants, hospitals only have 2D images of brains, however being able to see 3D brain scans and study the blood vessels on the brain *"would change the game and help learning, because [sometimes] you don't understand dimensions in 2D"*. On a more general note, one participant mentioned that *"It's more intuitive to have 3D monitors for visualisation, especially for the places or objects that you can't normally see, also because it's more natural to control how you want to rotate the object; and it's also easier for kids"*, thus meaning that the naturality of the controls could impact the experience for some museum visitors. On the contrary, one participant stated that they had to *"learn"* the movements in order to control the objects on the screen.

6. Discussion

Museum visitors have been impacted by the fast pace of technology development [1][2][189][190]. Being used to interacting more and more with novel technologies, visitors' experiences may be limited by the absence of technology in museums, or technological museum stations which lack a user-centered design approach. Previous research has run experiments with technologies like touchscreen, AR, and VR in order to find suitable methods through which museums can enhance visitors' experience, however, all the above-mentioned technologies somewhat fail to deliver a fully user-centered design approach that would also provide accessibility and engagement, sometimes accompanied by technology limitations as well [2] [19].

In order to solve this issue, I proposed a comparative study of the visitors' experience and engagement between 2D touchscreen kiosks and SR monitors. Touchscreen kiosks were chosen since they are currently the most common stations in museums, while the SR monitor was chosen since it can somewhat provide the same benefits as VR without most of its drawbacks. Unlike touchscreen kiosks, SR monitors provide 3D visual effects, and hand gestures as a form of control. Moreover, since it is a novel technology, it may create interest among visitors which can enhance their experience. These benefits, along with the hypothetical analysis of the museum station interactive design based on [136] led to the following hypotheses: **H1.** There is a difference in the ways SR technology and touchscreen kiosks enhance visitors' experience, **H2.** SR technology is a better museum experience enhancer than touchscreen kiosks, and **H3.** There is potential for a learning curve and information retention when using SR technology.

Therefore, to reach our goals, we used several frameworks and questionnaires to structure and measure the data and the findings of the experiment. First, we run a pilot study to investigate what hand gestures are the most intuitive and natural to implement in the application. Then, the MiniPXI questionnaire [185] is used to measure the visitors' experience and self-determination[129] with respect to the application. Since SR is a technology similar to AR and VR in terms of immersion, presence, and controls, the CAMIL framework[71] and questionnaire were used to measure the sense of presence and agency of the visitors. Then, we checked whether the hand gestures felt more natural and intuitive than touchscreen gestures through two additional questions in this sense.

With respect to game design, we included a short narrative at the beginning of the game to ensure emotional arousal that can trigger attention, enjoyment, involvement, immersion, and sense of presence, according to [111], when perceived realism is also present[116]. Hence, the game revolved around the space topic, with realistic graphics and 3D models included. Moreover, with respect to learning frameworks, we focused on creating a multimodal exhibition with physical interaction, based on a user-centered design approach in order to avoid "museum-fatigue" and cognitive overload[121]. Thus, the information implementation in the game has been reduced to mininum, that is avoiding long texts and rather focus on space terms and concepts. In this regard, and also due to museum constraints, we consulted Falk & Dierking's Contextual Learning Model for the museum environments, however only focus on the Personal Context.

6.1 Findings

After running the experiment, we found that the SR application was significantly more enjoyable and audiovisually appealing than the touchscreen application based on the nonparametric results. Similarly, participants had a more developed sense of mastery while performing on the SR application. These results may be the consequence of exposing visitors to novel technology which could trigger their interest, motivation, and curiosity in interacting with their bare hands while seeing 3D without glasses.

Additionally, SR participants felt a higher sense of presence than the touchscreen application, which was expected due to the 3D effect. According to CAMIL framework[71] presented in Figure 2.12, sense of presence triggers one's cognitive and affective factors, meaning that museum visitors is this case can present more interest and motivation throughout their entire experience. Additionally, this aspect can be influenced by museum personas, since Explorers and Rechargers felt more present in the game, while Hobbyists and Professionals, and slightly Experience seekers felt more present playing the touchscreen kiosk game. This finding might be critical for museum station designers that target specific or unspecific museum personas when trying to make the right choice for a new immersive museum station design. Interestingly enough, SR participants felt less immersed in the game, while still feeling present. As prior research has shown, presence offers the feeling of being aware of one's current existence in a particular place or time period [78], while immersion presents an extent to which the virtual world can be "shut down" the real world[80]. We could argue that since some participants perceived the SR DevKit as a "3D bubble", the display offered enough optical 3D phenomenon to visitors in order to have their sense of presence triggered. However, the SR monitor could still not cover the whole visual field which is the case in VR environments, this becoming a prospective reason why visitors did not indicate a high level of immersion, especially for those who experienced VR before the experiment. Additionally, after further investigations, we found that participants that used technology in educational backgrounds felt more immersed in the application, which can mean that they were more curious and focused on learning something new. Nonetheless, there is no valid backup for this assumption.

Finally, the touchscreen application was considered to have more intuitive controls than the SR application. We believe this is the case due to the ubiquitous familiarity of touchscreen technology nowadays. However, after further investigations in this sense, younger generations found the control for the SR application intuitive and natural, while the older age groups felt the opposite. Additionally, one of the participants stated that "you have to learn the movements", while touchscreen interaction is everywhere. Overall, this aspect highlights that along with a triggered sense of presence, younger visitors may present the highest interest and motivation during the experience.

6.1.1 Museum Workers Interviews

After analyzing several interviews with museum workers, we found out that visitors like and enjoy the SR monitor due to its glasses-free 3D effects and natural hand gestures. However, younger generations may love exploring and learning by interacting with novel technology in museums more, while older generations might still prefer touchscreen kiosks. On the same note, participants' reflections show that while the 3D effect was attractive, different generations might have different opinions regarding the naturality of controls. Additionally, it was considered that the touchscreen application should contain more text than the SR monitor since the latter should be used mainly for studying and visualising 3D objects to learn more about them.

Overall, the SR application can enhance visitors' experience in museums due to a higher sense of presence and slight increases in some of the engagement constructs. Due to narrative inclusion and its visual realism given by the graphics, 3D models and the 3D effect, the SR application may be prone to emotional arousal, sense of presence, immersion, enjoyment and involvement[121]. However, touchscreen kiosks seem to be preferred with regard to agency and ease of control. Participants think positively about including SR monitors in museums, which responds to RQ2, and lastly, after analyzing the open questions for participants, there is potential for information retention with SR monitors. This finding is not surprising since prior research has confirmed that interaction facilitates engagement, understanding, and recall of exhibits[121][125]. However, it is for future work to investigate whether the information retention levels are higher for the SR application than touchscreen kiosks, and for what period of time.

6.2 Advantages & Disadvantages

Since the results are shown, it is important to understand what they mean, and how can museum exhibition designers benefit from the findings of this study. Therefore, an analysis of the benefits and drawbacks of each device has been created and can be consulted in Figure 6.1.

Thus, while touchscreen kiosks are ubiquitous in museums, Simulated Reality is a novel technology that can attract more visitors and trigger their enjoyment, involvement, engagement, and curiosity. Due to the 3D effect, the sense of depth is present in the Simulated Reality technology, particularly in the SR DevKit, that can provide a strong sense of presence and visual realism, unlike touchscreen kiosks, in this case, the tablet, where the 3D effect was absent. This matter had an obvious

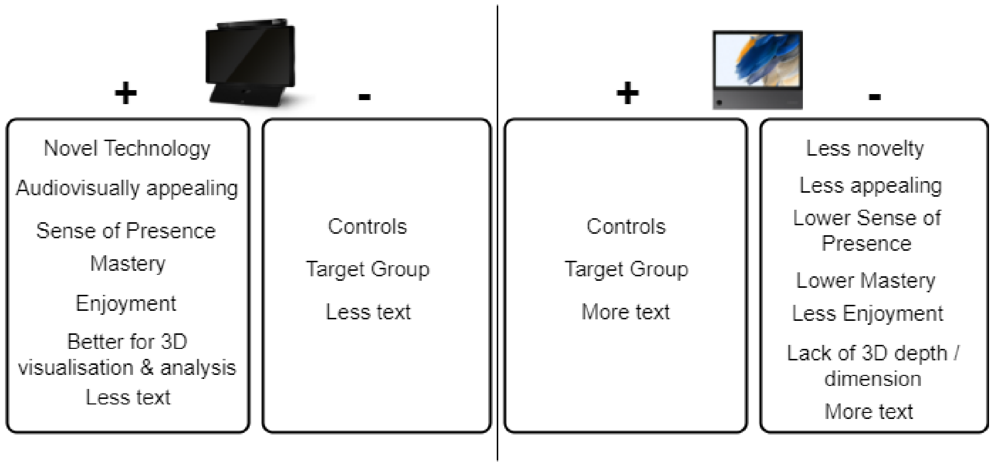


Figure 6.1: Device advantages and disadvantages comparison

effect on the lower sense of presence perception. Additionally, as previous studies confirm[44][45][46][47][48][49][50], autostereoscopic monitors offer a better 3D visualisation, object manipulation, and analysis. Lastly, in order to avoid cognitive overload, SR technology delivered less text than usual touchscreen kiosks, an aspect that can be seen as both a benefit and a drawback. The factor that can trigger this aspect to fall into a single category (benefit or drawback) is the choice of the museum designer who can use this finding as needed in order to deliver a user-centered design for museum stations. The touchscreen tablet delivered the same amount of text as the SR DevKit, however, some participants expected more from the device and thus, this aspect can be similarly seen as both a benefit and a drawback (for more curious visitors).

While the controls from the touchscreen applications were suggestive, natural and provided a sense of agency, the SR DevKit rated lower in this aspect. However, younger generations still felt that the controls were intuitive and natural, meaning that Sr technology might revolve more around a younger audience, unlike touchscreen kiosks that can be used by a broader generation. This means that SR technology should be wisely and strategically used in multimodal stations that focus more on visualisation for broader audiences, and also object manipulation, with less text, for younger audience stations, while touchscreen kiosks can complement with additional textual information. Therefore, in Figure 6.2 we propose a decision tree that would aid museum station designers in making the best choice when considering touchscreen kiosks (or tablets) or SR technology in museum stations. This decision tree considers first the aims of the museum (providing immersive experiences or prioritising information display) and then the target audience, based on the current study's findings. Nonetheless, this decision tree might need adjustments or expansion based on the specific requirements or preferences of museum designers.

Although the results of this paper are promising, the current research has its limitations. First, since the experiment was held in a museum, the experience was constrained to five minutes, time in which participants played the game and responded to the questions. Hence, the questionnaire included the single item per construct PXI questions[185], which might not be too reliable although it was created for time-constrained experiments. On the same note, the questions were measured on a 5-point Likert scale in order to ease participants' action of assigning a grade to a feeling. Another factor that limited the experiment was the SR DevKit itself. Since it is an old, discontinued device, it was prone to overheating and thus, some participants' experience might have been impacted by this malfunction. Moreover, due to the eye tracker constraints, 3D visual effect is provided for only one person at a time, limiting the SR monitor for individual use. Another factor that could affect participants' experience is the difference in the screen sizes of the devices. Since the SR DevKit is a 32" display, its size is considerably larger than the 10.5" touchscreen tablet. Finally, Beeld & Geluid Media Museum is a Dutch museum, with mostly Dutch visitors, hence all the data could be biased by participants who are Dutch natives.

6.3 Future work

With regard to future research, it is expected that younger generations will embrace novel technologies in an easier manner from all perspectives. Thus, it is worth further investigating how to bridge the SR monitor controls with broader audiences (including older generations), specifically with different hand gestures, different controls, or specific older age groups. One suggestion is to investigate whether hand meshes (similar to the hand pointer) that would resemble users' hand positions and gestures used for the start screen could improve the control experience for broader audiences, since adding this feature to the application may offer an experience closer to VR (due to the small visualisation of the hand gestures) with which

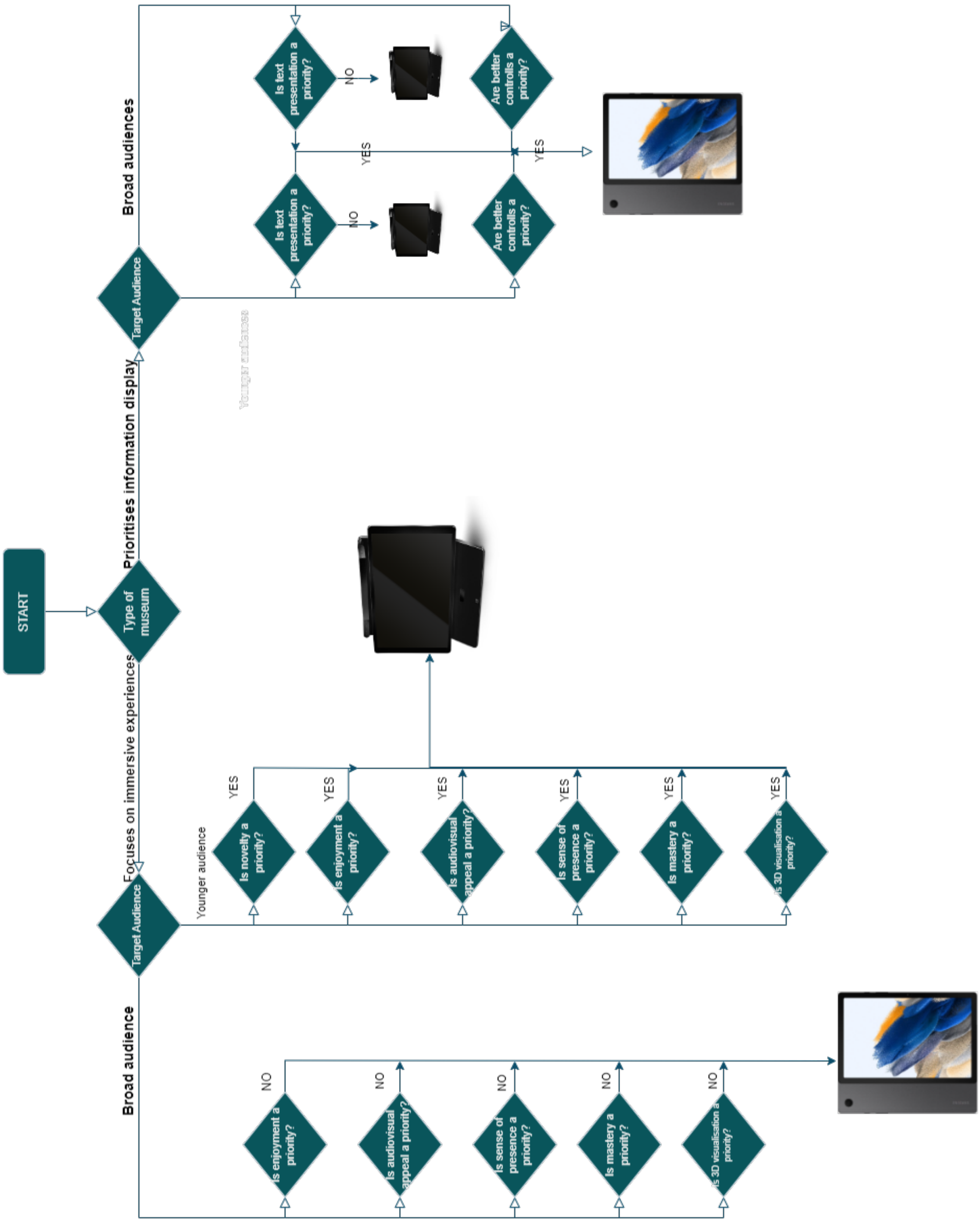


Figure 6.2: Decision tree for choosing the appropriate technology for museum stations

users might be more acquainted, and therefore feel more immersed. Moreover, experimentation with hand mesh colors or text that indicated that the hand gestures are in progress to be performed is worth investigating, especially in older generations interacting with SR technology. This experimentation may show whether older generations need more feedback when interacting with the SR DevKit, and if this is the reason why they did not perceive a sense of control over the virtual world.

Additionally, since 3D interaction is most appreciated for object analysing and visualization, future research can take advantage of the flexibility that SR monitors have to offer. This is because they can focus on creating an application specifically for older generations without gamification features or creating visualising applications without controls, emphasising the glasses-free 3D effect.

Finally, it has been shown that SR technology has potential in information retention due to the provision of 3D effect and the physical interaction with the virtual world through hand gestures. Future work should focus on investigating if the information retention is perceived as higher for the SR application than for touchscreen kiosks, and for what timeframe.

7. Conclusion

In this current paper, some shortcomings of the current museum stations have been highlighted, with a strong focus on user-centered design approach, accessibility, hygiene to enhance visitors experience in museum environments. Hence, with the purpose of an antithetical comparison with touchscreen kiosks, SR monitors have been introduced, since they are wheelchair accessible, hygienic in the sense that its controls are touch-free, and facilitate a stronger sense of presence for visitors which can trigger their interest and motivation for content and museum exploration even more.

The current research has demonstrated the potential of SR monitors as museum experience enhancers. While the glasses-free 3D effect represented an attraction to visitors, a thorough examination of the results showed that younger generations may benefit the most out of the SR monitor inclusion in the museum stations. The reason behind this aspect is their indication of higher rates for the sense of presence and sense of control. Thus, the first research question along with the first hypothesis are inferred: there is indeed a difference between the way SR and touchscreen kiosks enhance museum visitors' experience. We argued that SR monitors could better enhance the museum experience for visitors that belong to younger age groups, even though older generations recommend SR technology in general, while touchscreen kiosks are still an appropriate tool for a broader audience. This means that the second hypothesis could not be fully inferred. Therefore, we proposed a museum station technology decisional tree for museum designers to aim them in choosing the suitable technology depending on the specific requirements or aims of the museums. Furthermore, the second research question highlighted the open and positive opinions of the museum visitors towards SR monitors, while a minor part of the participants indicated that even if the application could have been different, improved or modified, there is still a great potential of SR technology in museums. Finally, the third hypothesis presumed that SR technology has the potential for information retention. The third research question manages to indeed present the potential for recall and information retention, based on the open questions.

As further applications are concerned, the current paper's findings indicate that SR monitors can enhance museum visitors' experience, particularly better than touchscreen kiosks for younger generations. However, in order to maintain a focus balance on all visitors' expectations and experiences, touchscreen kiosks should not be fully replaced by SR monitors. Thus, museum station designers are still in charge of choosing the right setup for each museum station, keeping in mind the purpose of their design and choosing what aspects they want to highlight (audiovisual appeal, presence, controls, etc) and also taking into consideration the limitations for both devices. Overall, an exhaustive overview of museum technologies with their advantages and disadvantages and taking a wise decision regarding the technology implementation in museum stations can enhance visitors' experience, mitigating obstacles such as physical accessibility, hygiene, and visitor flow, but also facilitating a better study, visualisation and manipulation of objects or artifacts with strong potential for learning outcomes and information retention.

A. Appendix A

A.1 Questionnaire

The questionnaire used in this study contained 2 parts: construct questions for measuring visitors' experience, and open questions, for a better understanding of participants' perspectives and reasoning. The English version of the construct questions can be found in Table A.1. The Dutch version of the construct questions are the following:

1. Ik vond het spel er leuk uitzien en voelen.
2. Het spel was niet te makkelijk en niet te moeilijk om te spelen.
3. Het was makkelijk om te weten hoe je dingen kon doen in het spel.
4. Ik snapte wat ik moest doen in het spel.
5. Het spel liet me weten hoe goed ik het deed.
6. Ik had een leuke tijd tijdens het spelen van het spel.
7. Ik voelde me vrij om het spel op mijn eigen manier te spelen.
8. Ik wilde ontdekken hoe het spel zou veranderen.
9. Ik was helemaal gefocust op het spel.
10. Ik had het gevoel dat ik goed was in het spelen van dit spel.
11. Het spelen van het spel was belangrijk voor mij.
12. Tijdens het spel had ik controle over mijn ervaringen en acties.
13. Tijdens het spel leek het alsof ik niet zelf bepaalde wat er gebeurde.
14. Het voelde het alsof ik mijn eigen ervaringen creëerde in het spel.
15. De virtuele omgeving leek echt voor mij.
16. Ik had het gevoel alsof ik echt in de spelwereld was en niet van buitenaf iets bestuurde.
17. Mijn ervaring in de virtuele omgeving leken op mijn ervaringen in de echte wereld.
18. Ik had het gevoel dat ik echt in de spelwereld was.
19. Ik was helemaal betoverd door de virtuele wereld.

Source	*Construct*	*Question*
miniPXI	Audiovisual Appeal	I liked the look and feel of the game
	Challenge	The game was not too easy and not too hard to play
	Ease of Control	It was easy to know how to perform actions in the game
	Clarity of Goals	The goals of the game were clear to me
	Progress Feedback	The game gave clear feedback on my progress towards the goals
	Enjoyment	I had a good time playing this game
	Autonomy	I felt free to play the game in my own way
	Curiosity	I wanted to explore how the game evolved
	Immersion	I was fully focused on the game
	Mastery	I felt I was good at playing this game
	Meaning	Playing the game was meaningful to me
CAMIL	Agency	During the game, my experiences and actions were under my control.
		During the game, I felt that my experiences and actions were not caused by me.
		During the game, my experiences and actions felt self-generated.
	Presence	The virtual environment seemed real to me.
		I had a sense of acting in the virtual environment, rather than operating something from outside
		My experience in the virtual environment seemed consistent with my experiences in the real world.
		I had a sense of "being there" in the virtual environment.
		I was completely captivated by the virtual world.
	Intuitive Controls	The controls/gestures in the game felt natural to me.
		I could intuit the gestures that controlled the game.

Table A.1: The questionnaire used in the study

20. De besturing in het spel voelden natuurlijk aan voor mij.
21. Ik snapte meteen welke gebaren ik moest maken om het spel te spelen.

The open questions used in the experiments were as follows:

1. What had the most impact to you in the experience? (Wat had de meeste impact op je in de ervaring?)

2. In general, what do you think about technology in museums?(Wat vindt u in het algemeen van technologie in musea?)

3. Would you recommend SR technology for museums? Why? (Zou u SR-technologie aanbevelen voor musea? Waarom?)

4. Write (educational/non-educational) things that you remember from the game: (Schrijf (educatieve/niet-educatieve) dingen op die je je herinnert uit het spel:)

A.2 Overview on question constructs from Technology and Field Experience

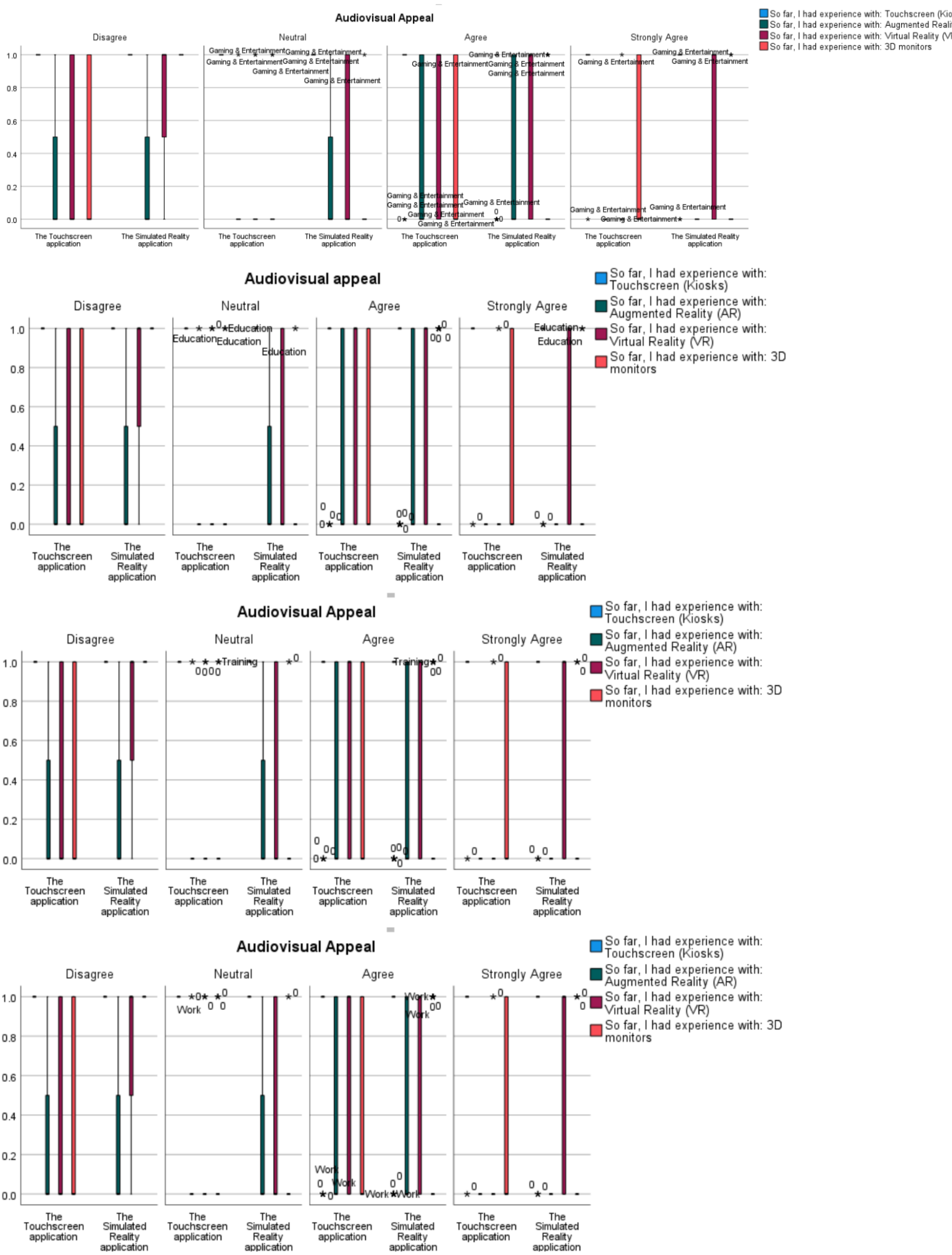


Figure A.1: Audiovisual Appeal Construct

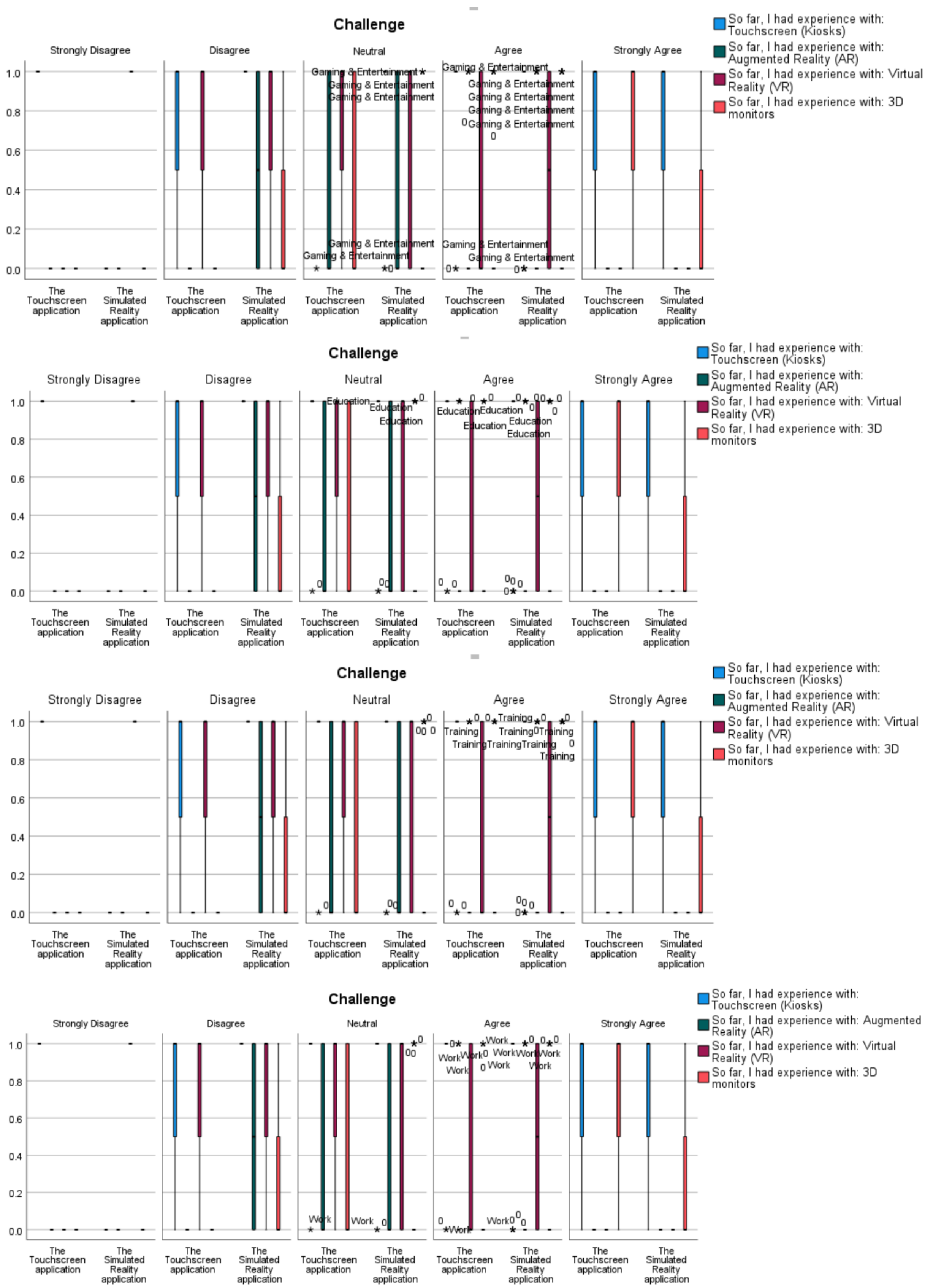


Figure A.2: Challenge Construct

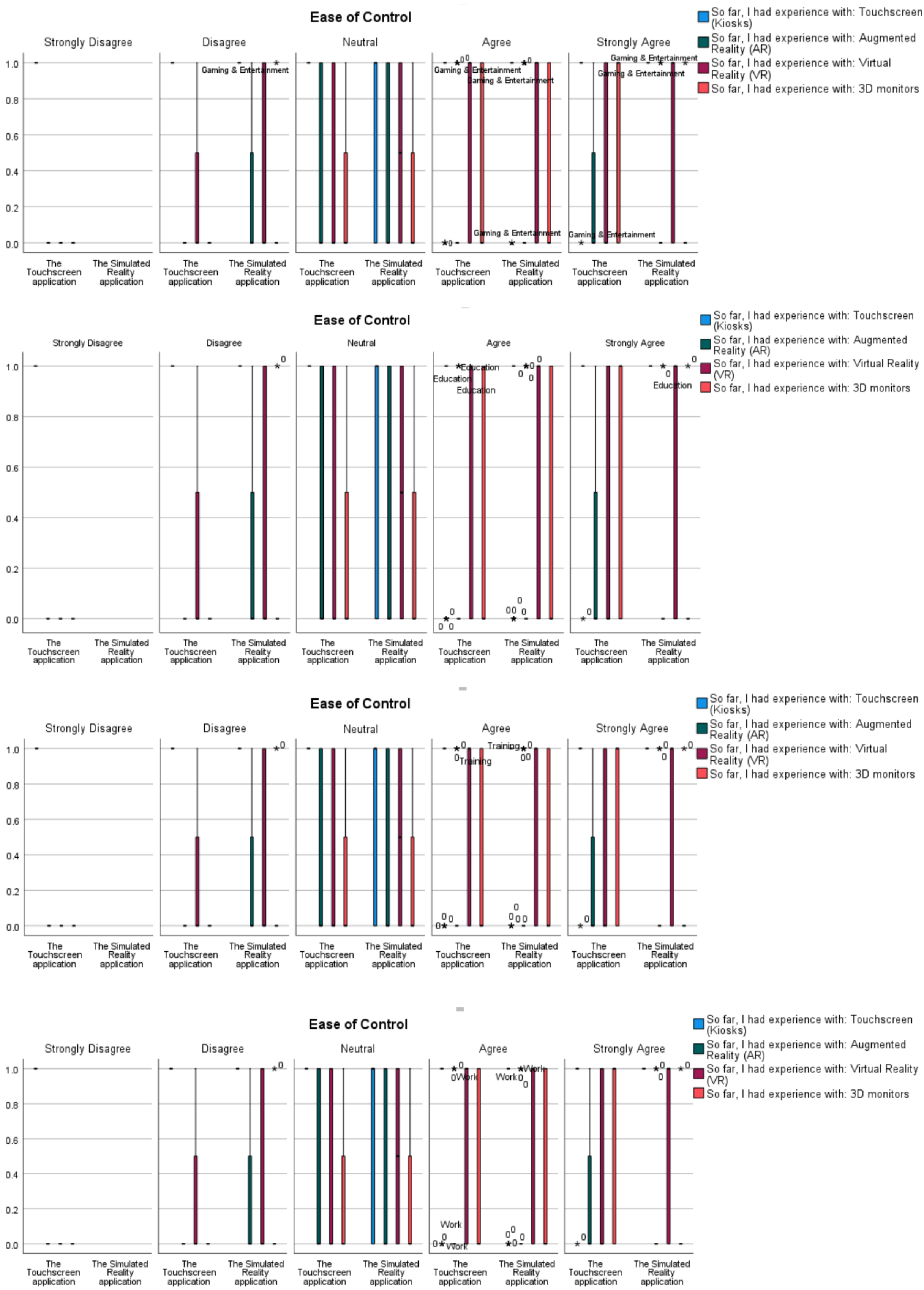


Figure A.3: Ease of Control Construct

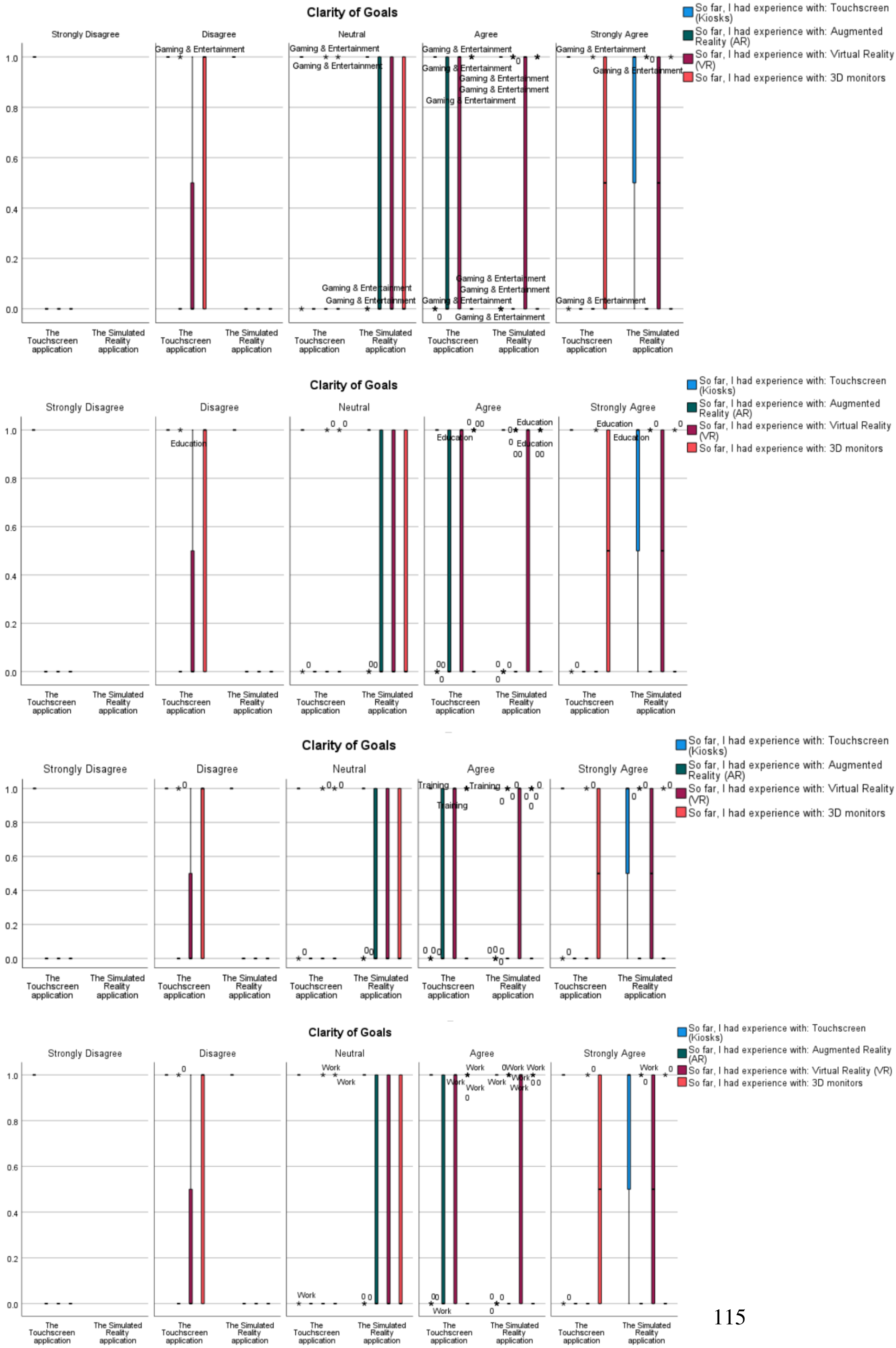


Figure A.4: Clarity of Goals Construct

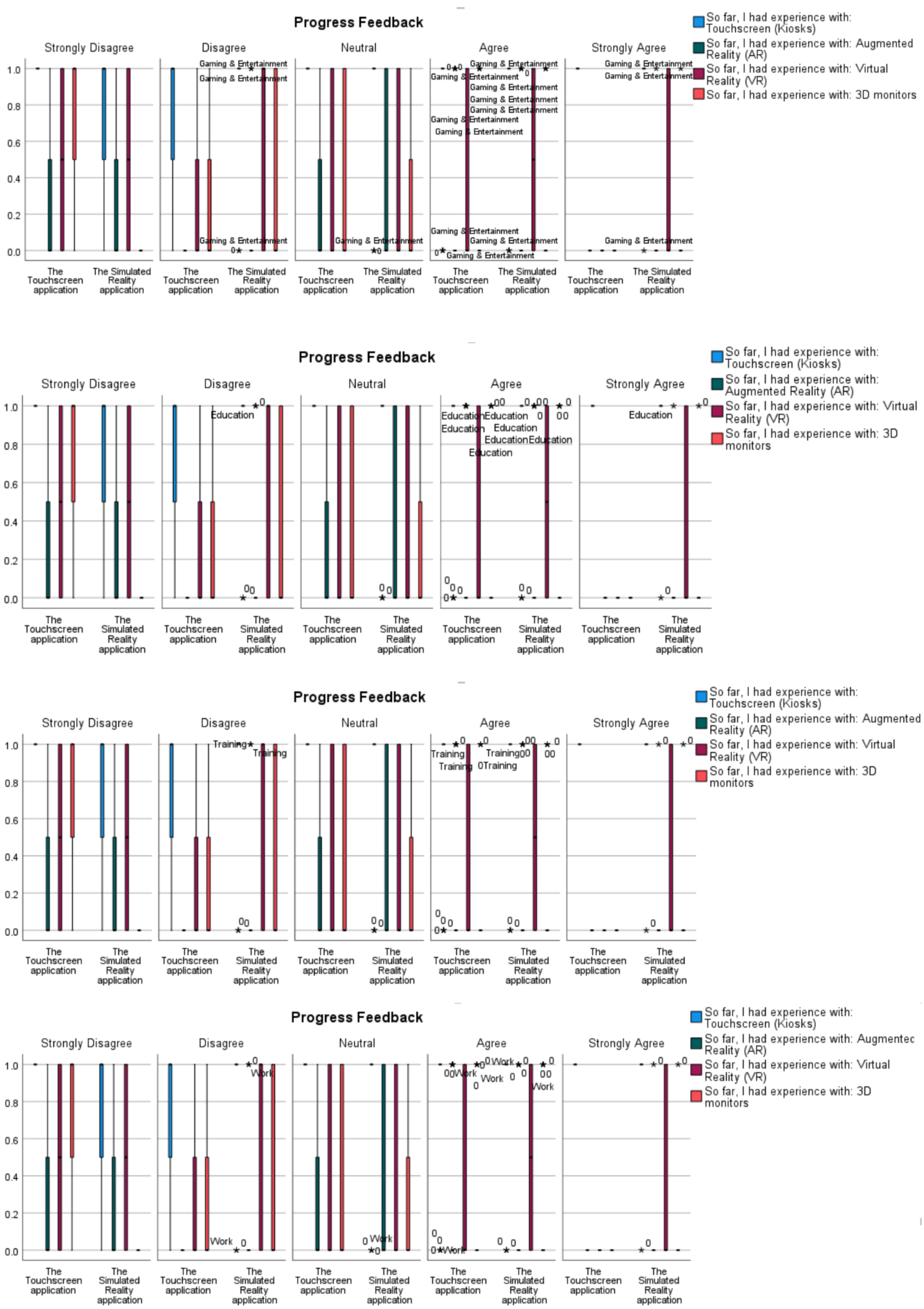


Figure A.5: Progress Feedback Construct

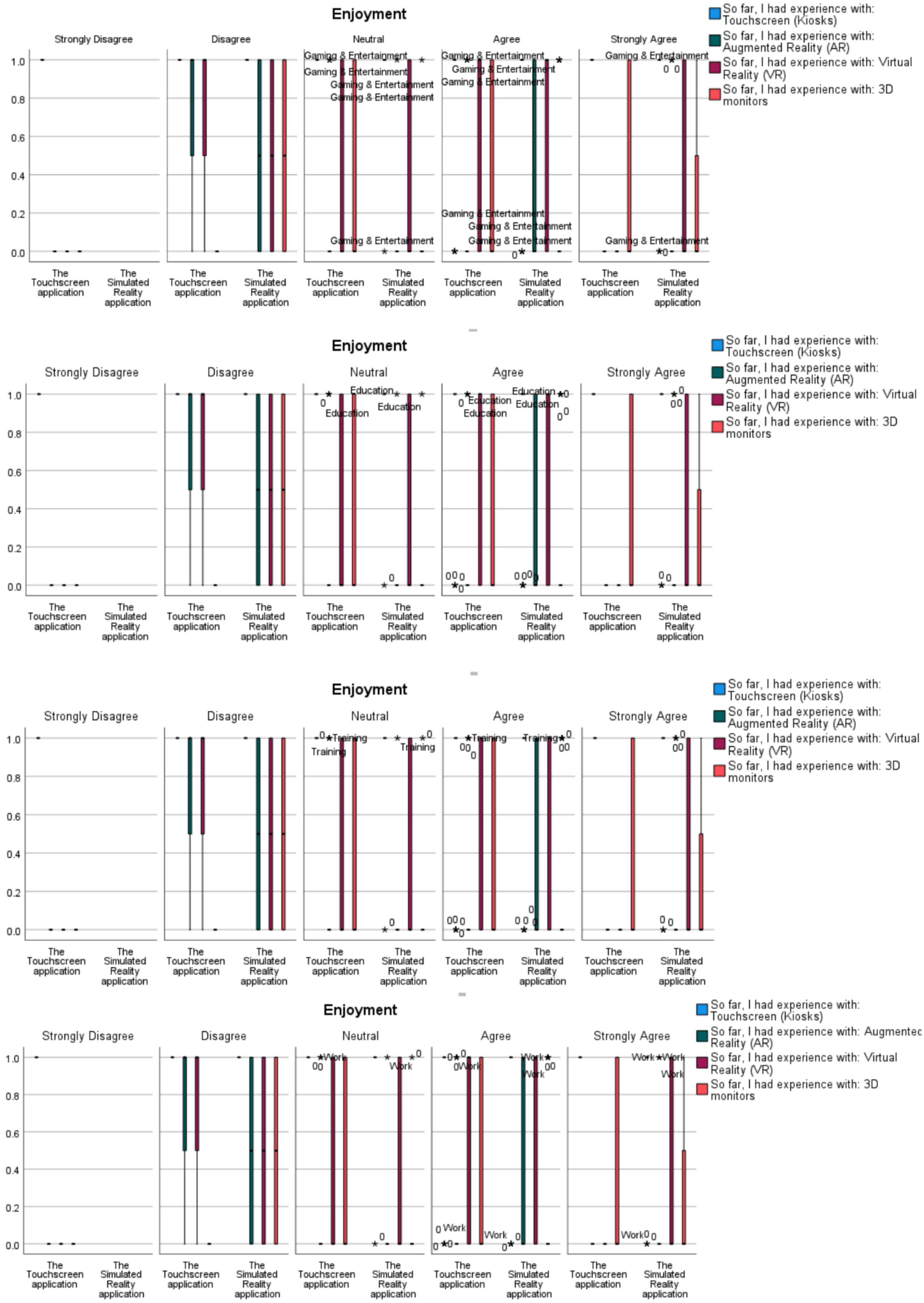


Figure A.6: Enjoyment Construct

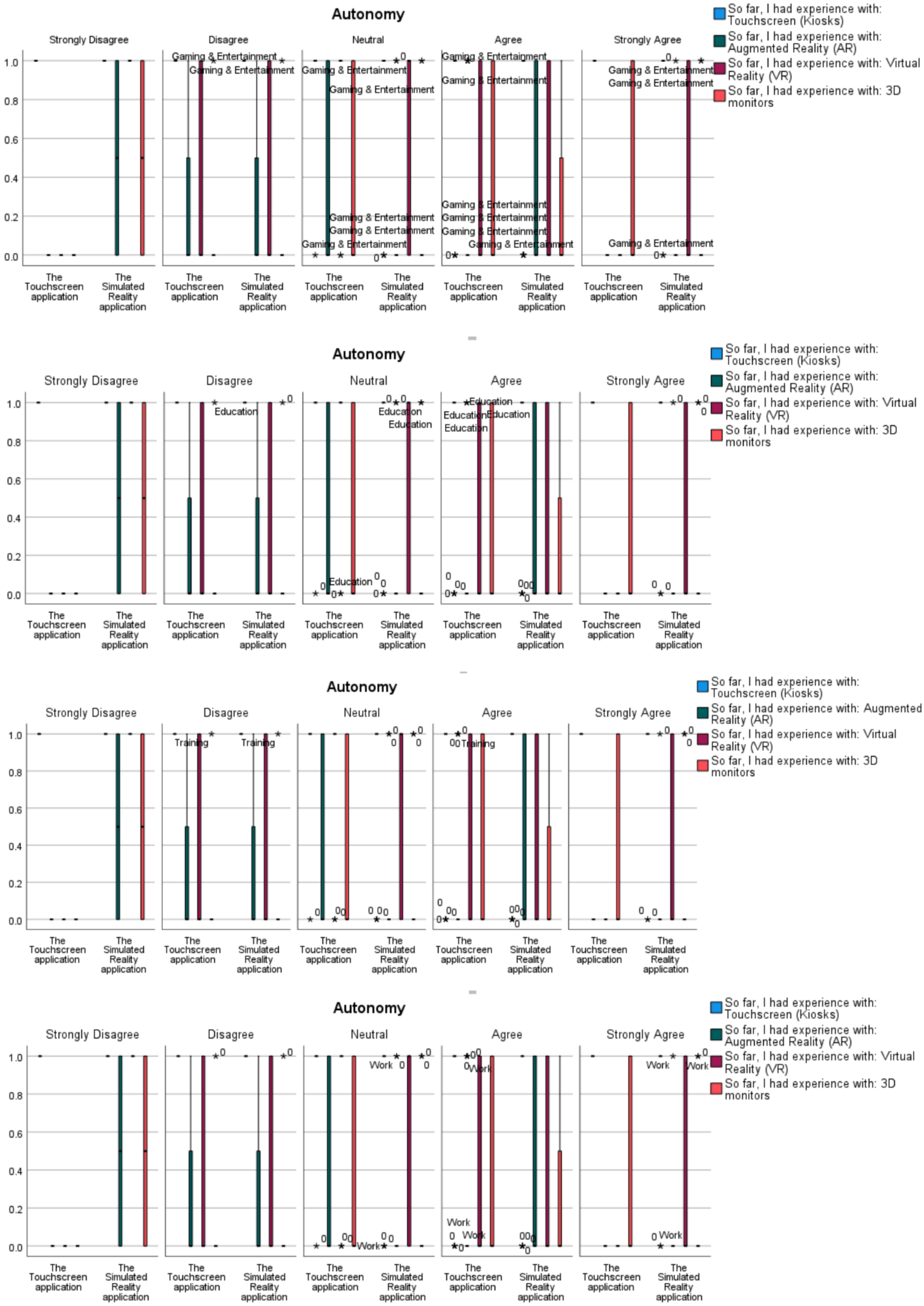


Figure A.7: Autonomy Construct

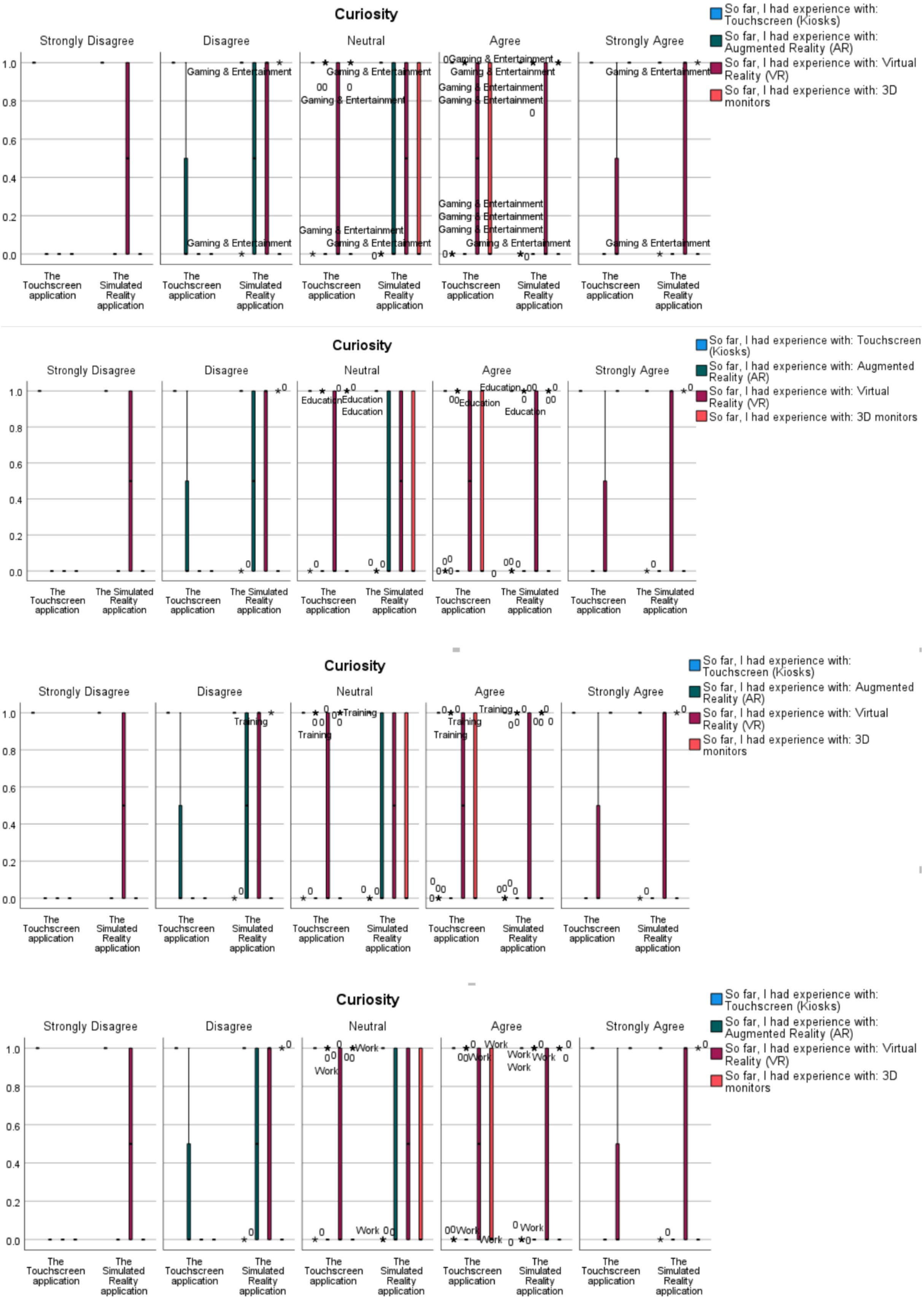


Figure A.8: Curiosity Construct

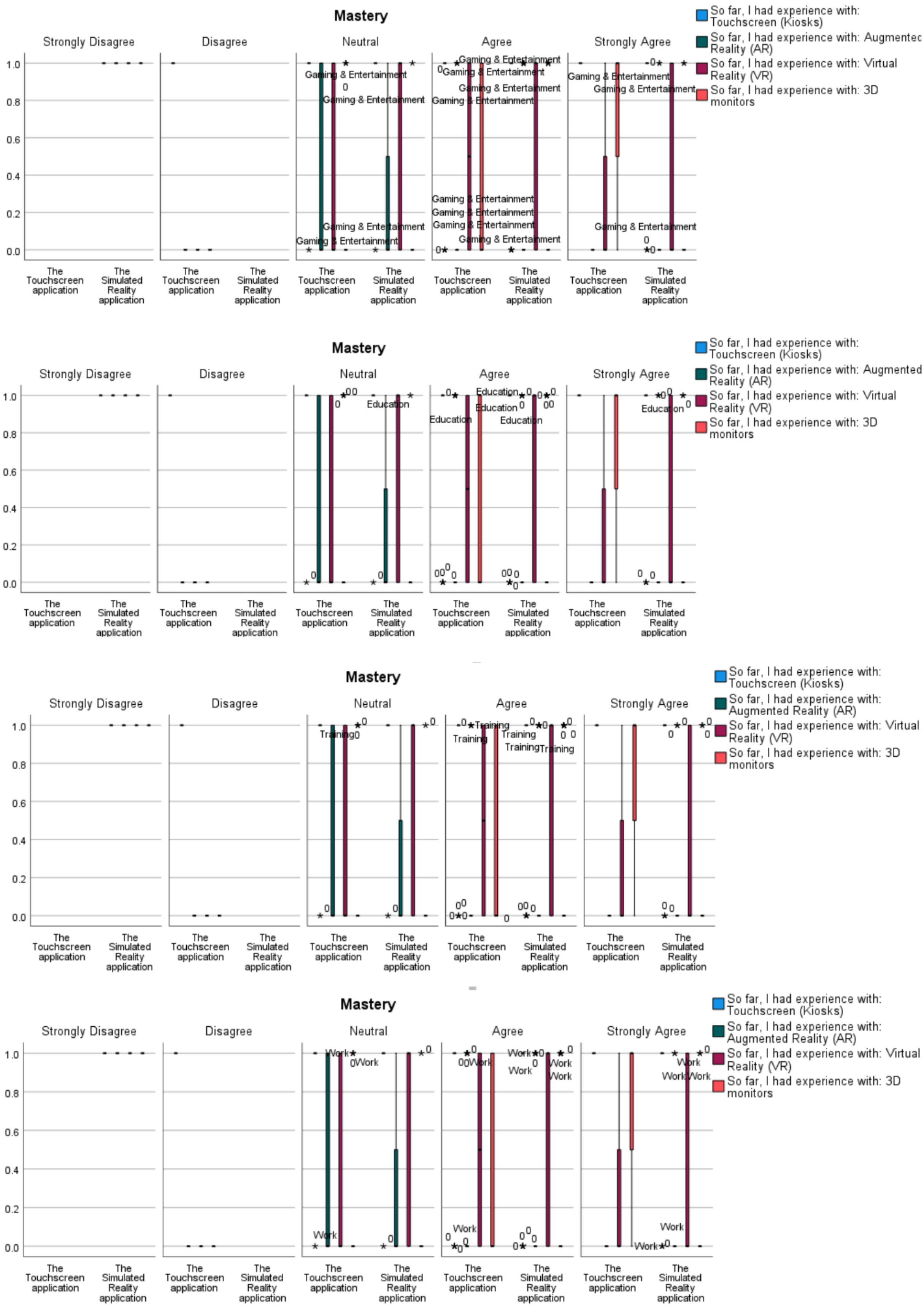


Figure A.9: Mastery Construct

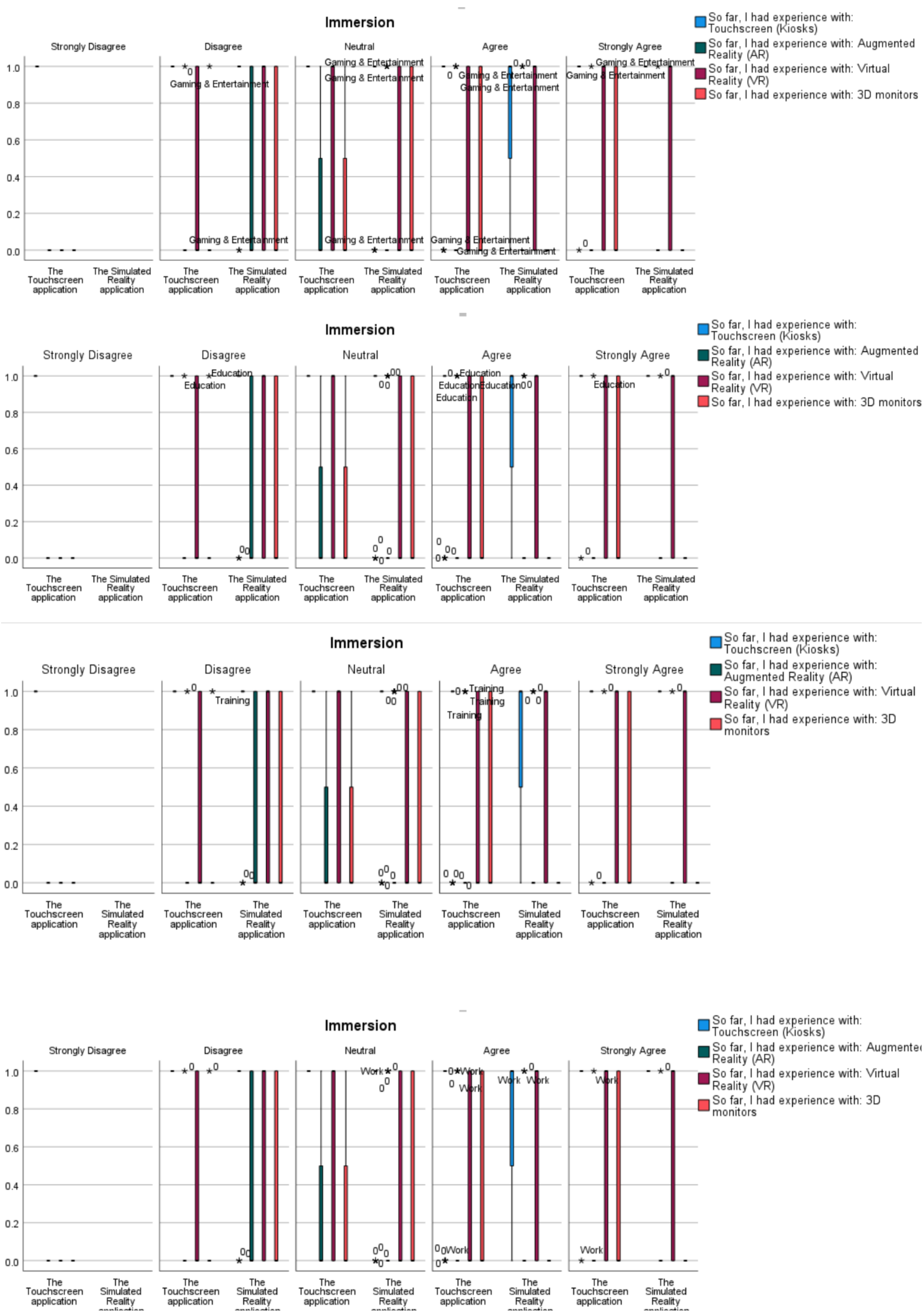


Figure A.10: Immersion Construct

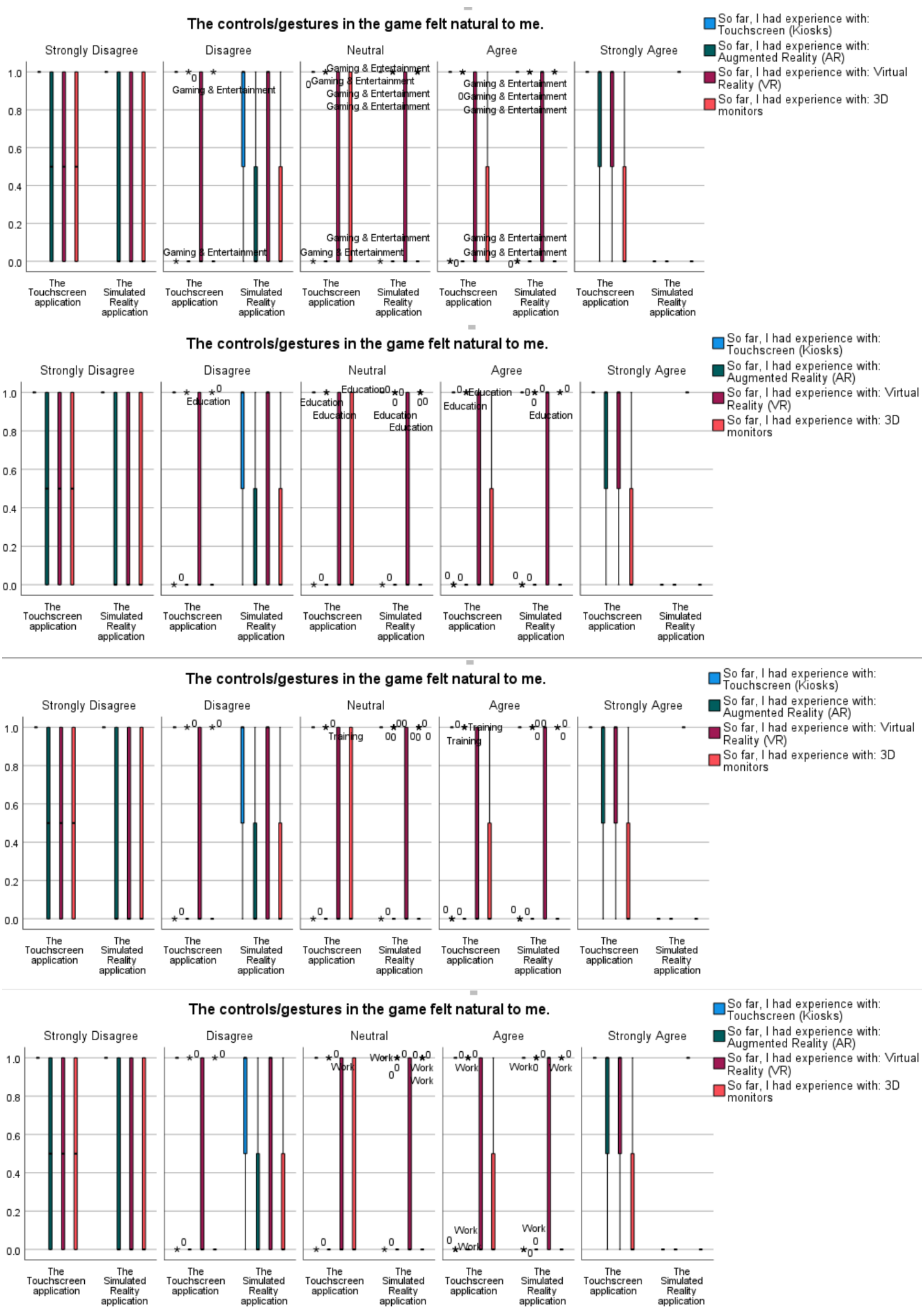


Figure A.11: Intuitive Controls Construct

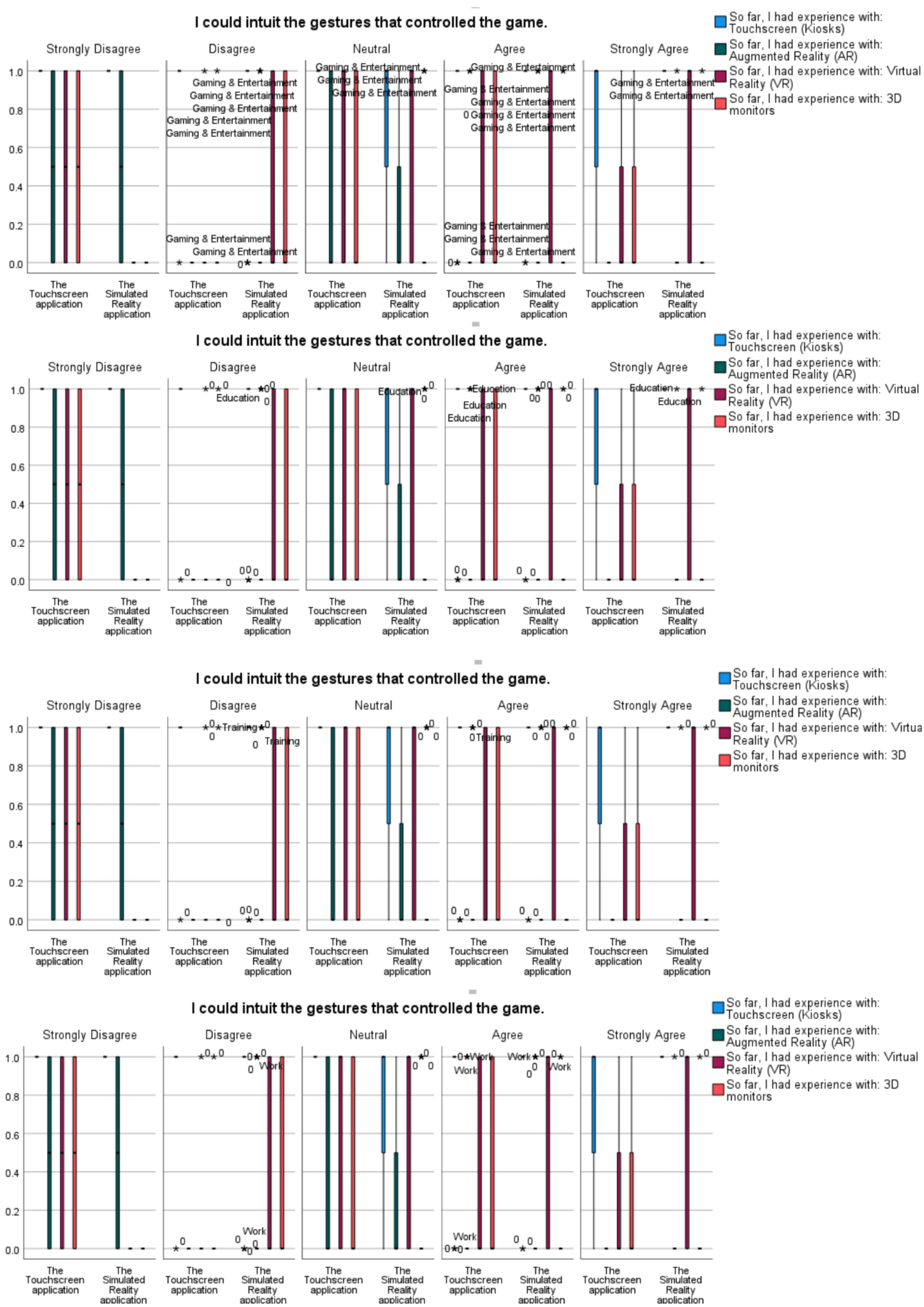


Figure A.12: Intuitive Controls Construct

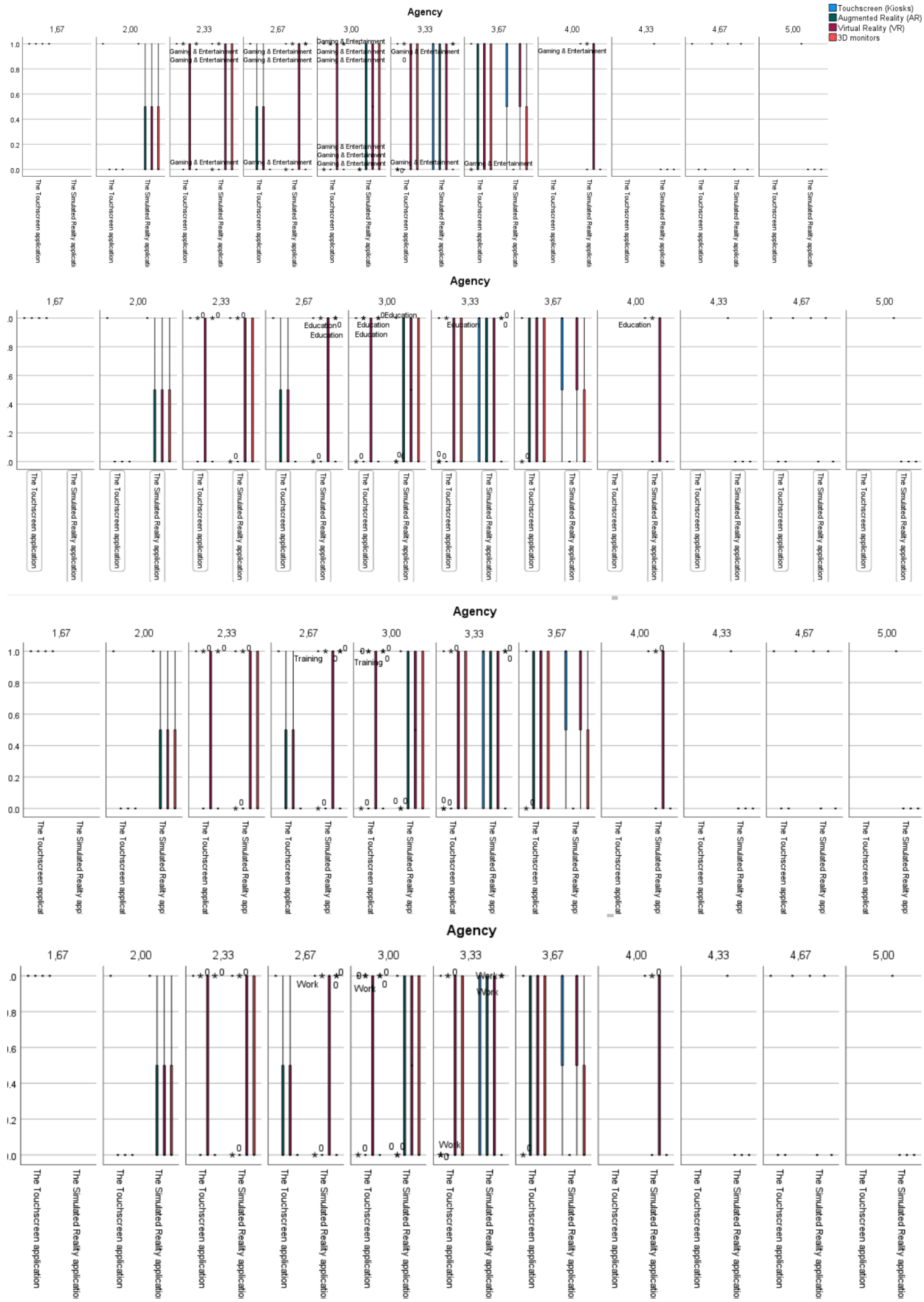


Figure A.13: Agency Construct

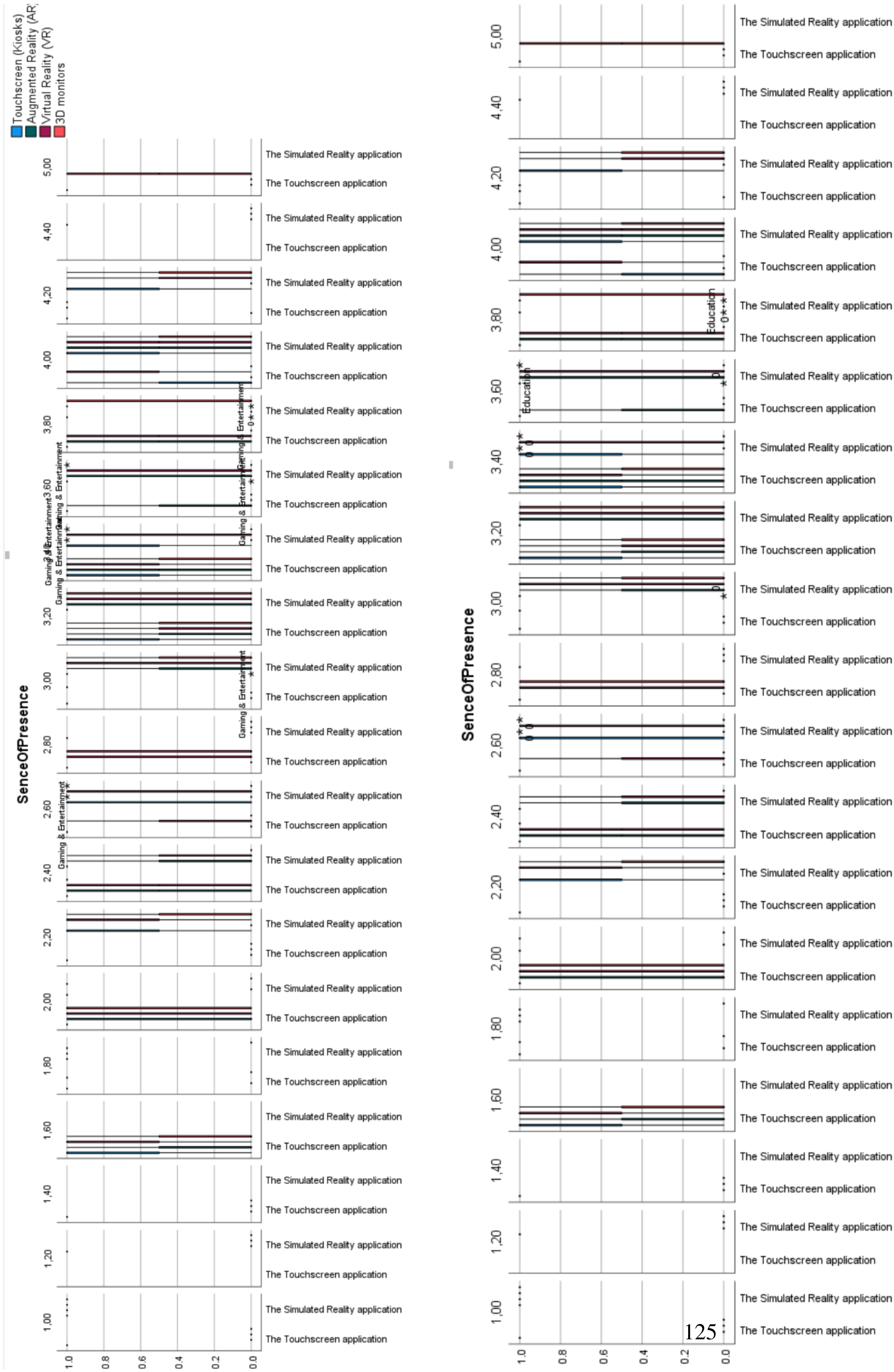


Figure A.14: Sense of Presence Construct

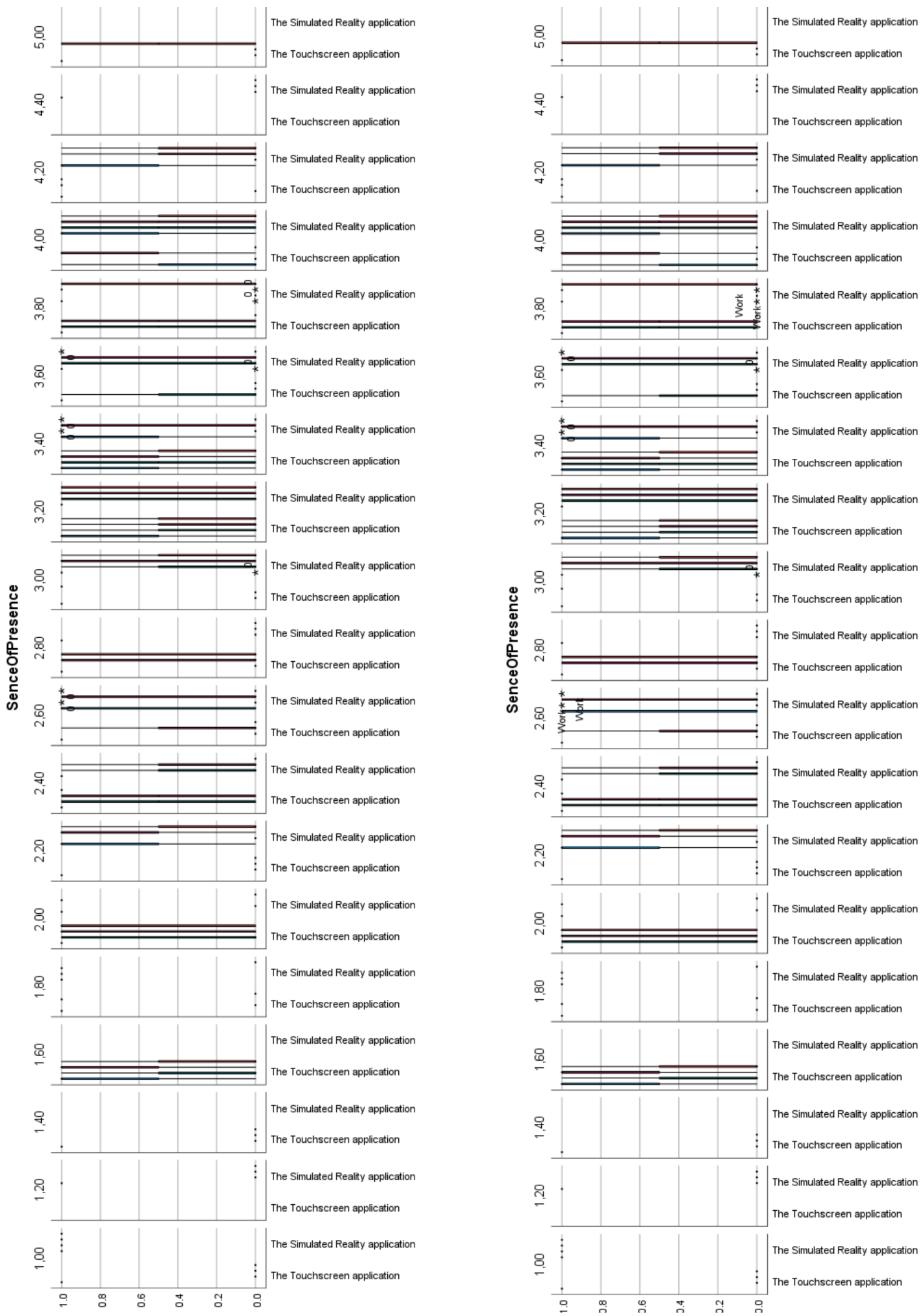


Figure A.15: Sense of Presence Construct

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