DOCTORAL THESIS

Realism, Storytelling and User Experience in HMD-based eXtended Reality for Holocaust Museum

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Declaration of Authorship

I, Yunshui Jin, declare that this thesis titled, “Realism, Storytelling and User Experience in HMD-based eXtended Reality for Holocaust Museum” and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degreeat this University.
- Where any part of this thesis has previously been submitted for a degree or anyother qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. Withthe exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Signed: 金云水

Date: May 8th 2022

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Abstract

Due to the COVID-19 lockdowns and travel restrictions, the demand for remote museum-visiting experiences has increased. Fortunately, technologies like Head Mounted Display (HMD)-based Virtual Reality (VR) and Augmented Reality (AR) have made HMD-based eXtended Reality Museum (HXRM) experiences possible. HXRMs can be one of or a combination of the following: an HMD-based AR museum for on-site experience, or an HMD-based VR museum and an HMD-based Augmented Virtuality (AV) museum for remote online access. HXRM is a new approach for museums to enhance user experience while increasing learning outcomes and accessibility. Though there has been some previous research for HXRM, gaps still exist in the interactive narrative and user experience of HXRM. Thus, this study proposes following three Research Questions (RQ): **(1)** What is the difference between the impact of NUI and GUI on user experience in the HMD-based AR museum? **(2)** What is the user experience difference between HMD VR and HMD AV as the medium for XR remote-site museums? **(3)** How is the user acceptance of HMD-based remote-site XR museums?

Based the Technology Acceptance Model (TAM) and several user experience theories, the author proposed a user experience model for HXRM, an uncanny valley framework for realistic CG character, and an interactive narrative model. Then, in collaboration with National Holocaust Centre and Museum, *The Extended Journey* project was initiated. The project included an AR HoloLens application, *The AR Journey,* and a VR application, *The Virtual Journey*, that can be deployed on AR headsets like HoloLens and VR headsets like HTC Vive, respectively. *The Extended Journey* is an interactive narrative experience that presents the story of a fictional Jewish boy named Leo using virtual CG characters and environments, allowing the audience to participate in his story from the second-person-view. The audience can not only decide the direction of the storyline by helping Leo make choices, but they could also inspect the environments and objects within them to learn the stories behind them.

Three experiments were then conducted using *The Extended Journey*, and a mixed approach of quantitative and qualitative methods were used for analysis. In experiment 1, a between-subjects design was conducted to answer RQ1, and the results showed that the influence of interaction mapping on presences and narrative engagement for an HMD-based AR museum experience is moderated by prior game experience. In experiments 2 and 3, a between-subjects design and a within-subjects design were performed together to answer RQ 2 and RQ 3. The results showed that HMD VR can produce better narrative immersion, presence, and enjoyment, while also increasing CG characters' affinities compared to HMD AV in XR remote-site museums. The data analysis also showed narrative-based HXRM had high user acceptance, within which HMD VR demonstrated significantly higher user acceptance levels than HMD AV for remote-site HXRM. Experiments 2 and 3 verified all the hypotheses for the mechanism behind the extended TAM via regression analysis, confirming the influence of the four external factors of narrative engagement, presence, interactivity, and CG characters' affinity. In addition, the analysis also revealed two other potential external factors with influence over the extended TAM: use environment and device ergonomics. Two independent variables, learning interest and prior game experience, were found to have an impact on these external factors. Finally, the author summarised the design guidelines for HXRM and provide an outlook on the limitations and potential future work of this study.

List of Publication

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List of Abbreviations

2D	**Two-D**imensional
3D	**Three-D**imensional
3DUI	**Three-D**imensional **U**ser **I**nterface
3S	**S**ub-**S**urface **S**cattering
6-DOF	**S**ix **D**egrees **o**f **F**reedom
App	**App**lication
ANCOVA	**An**alysis of **Cova**riance
ANOVA	**An**alysis **o**f **Va**riance
AR	**A**ugmented **R**eality
AV	**A**ugmented **V**irtuality
CAVE	**C**ave **A**utomated **V**irtual **E**nvironment
CG	**C**omputer **G**enerated
COVID-19	**Co**rona **Vi**rus **D**isease 20**19**
CYOA	**C**hoose **Y**our **O**wn **A**dventure
C/INV	**C**ontrol/**Inv**olvement
DoF	**D**egrees **o**f **F**reedom
FCCS	**F**amiliarity with the **C**ultural **C**ontext of the **S**tory
FK	**F**orward **K**inematics
FoV	**F**ield **o**f **V**iew
FPS	**F**rame **p**er **S**econd
GI	**G**lobal **I**llumination
GUI	**G**raphical **U**ser **I**nterface
HCI	**H**uman-**C**omputer **I**nteraction
HDRP	**H**igh **D**efinition **R**endering **P**ipeline
HMD	**H**ead **M**ounted **D**isplay
HRTF	**H**ead **R**elated **T**ransfer **F**unction
HXRM	**H**MD-based E**X**tend **R**eality **M**useum
IK	**I**nverse **K**inematics
ITQ	**I**mmersion **T**endency **Q**uestionnaire
IXRE	**I**mmersive E**X**tended **R**eality **E**nvironment
LCD	**L**ight **C**rystal **D**isplay
LED	**L**ight **E**mitting **D**iode

LMQ	**L**earning **M**otivation **Q**uestionnaire
MARS	**M**obile **A**ugmented **R**eality **S**ystem
Mocap	**Mo**tion **Cap**ture
MR	**M**ixed **R**eality
MRTK	**M**ixed **R**eality **T**ool**K**it
NHCM	**N**ational **H**olocaust **C**entre and **M**useum
NUI	**N**atural **U**ser **I**nterface
OST	**O**ptical **S**ee-**T**hrough
P3DC	**P**hotorealistic **3D C**haracters
PBR	**P**hysically **B**ased **R**endering
PE	**P**erceived **E**njoyment
PEU	**P**erceived **E**ase of **U**se
PLM	**P**recontemplation **L**earning **M**otivation
PoV	**P**oint **o**f **V**iew
PQ	**P**resence **Q**uestionnaire
PU	**P**erceived **U**sefulness
QR code	**Q**uick **R**esponse code
RPG	**R**ole **P**laying **G**ame
SDE	**S**creen **D**oor **E**ffect
SDK	**S**oftware **D**evelopment **K**it
SFoR	**S**tationary **F**rame **o**f **R**eference
SLAM	**S**imultaneous **L**ocalisation **A**nd **M**apping
SoLMI	**S**tage **o**f **L**earning **M**otivation **I**nventory
STEM	**S**cience and **T**echnology **E**nterprise **M**anagement
TAM	**T**echnology **A**cceptance **M**odel
TUI	**T**angible **U**ser **I**nterface
URP	**U**niversal **R**endering **P**ipeline
UI	**U**ser **I**nterface
UX	**U**ser E**X**perience
VE	**V**irtual **E**nvironment
VR	**V**irtual **R**eality
VST	**V**ideo **S**ee-**T**hrough
XR	**E**xtended **R**eality

To my wife, who supports and inspires me everyday to do something that matters…

Chapter 1: Introduction

This thesis examines Head Mounted Display (HMD)-based Virtual Reality (VR) and AR technologies and their applications in interactive narratives for an immersive museum experience. This chapter provides an overview of the thesis by outlining the background and motivation for the research, followed by research questions and objectives. It then summarises the potential contributions to further research and presents an outline of the thesis.

1.1. Background and Motivation

The primary function of modern museums is now considered to be education. With this goal, museums work to make collection items accessible for study, education, or pleasure (Tišliar, 2017). According to Reggio Emilia's concept of the 'third teacher', the physical learning environment and space, such as a museum, plays a critical role in modern learning and act as *primus inter pares* ('first among equals') to create a direct line of communication with the young learners. However, many museums have traditionally perpetuated the concept of the "primacy of the ocular", where they have supported a policy of visitors viewing their artefacts but discouraged them from actually handling or experiencing objects through different sensory modalities (Kiberd, 2002). Though it was found that some museums were using innovative techniques and multi-sensory approaches to augment their audience's learning experience, there are still many opportunities to create compelling educational experiences for visitors that go beyond the traditional visual-only approach.

1.1.1. Narrative approach for museums

Storytelling is a fundamental aspect of human nature (Juul, 2001). Stories not only help us understand our own communities and cultures, as well as others, but they also help us share knowledge, engage and connect with others, and thus communicate in a more relevant way (Juul, 2001). Storytelling is also used to stimulate curiosity and engage audiences, a tactic commonly used by museums to bring their collections to life, connect with different historical periods, cultures, and beliefs, and capture a range of emotions (Johnsson, 2006). Thus, museums preserve not only artefacts but also stories (Beale, 2011).

The National Holocaust Centre and Museum (NHCM) is one of the museums employing the narrative technique to unveil the history and enable young generations to carefully examine, commemorate, and learn from the tragedy of the Holocaust. *The Journey*, one of its permanent exhibitions, uses environmental storytelling techniques to explore history through the eyes of a fictional Jewish boy named Leo who survived the Holocaust and came to the UK via the Kindertransport.[1] The experience is set in a series of six rooms designed to show what Jewish life looked like in 1930s Germany, including Leo's family living room, Leo's classroom, the street after Night of Broken Glass[2], the family's tailor's shop business, a train carriage for Kindertransport, and the refuge Leo found in the UK. In each room, the audience can watch a short video of Leo giving a monologue about what he saw, heard, felt, and experienced at that time during each stage of the narrative (Obama & Biden, 2013). The visitors can experience the complete story by gradually going through each room, interacting with objects and watching videos.

Research in the field of history and museum education emphasises that the emotional engagement and empathy evoked in a museum context may stimulate young people's historical understanding by bringing a past world to life in a more vivid manner (Marcus, Stoddard, & Woodward, 2012; Spalding, 2012). Narratives are a powerful method for empathy, such as perspective-taking and emotional engagement (Busselle & Bilandzic). Many researchers claim a positive association between empathy and prosocial behaviours (Hoffman, 1984; Yunshu Jin, Ma, Hua, & Coward, 2017; Saarni & Crowley, 1990), revealing the importance of encouraging young students to engage in educational exercises that cultivate emotional responses. As mentioned above, empathy is important for young people's education, and an important content of Holocaust education. Therefore, it is believed that its learning

[1] Kindertransport was the title for historical events that the British government made efforts to bring Jewish children out of Nazi Germany and occupied Austria and Czechoslovakia before World War II . 10,000 Jewish children aged between 1 and 17 were transported to the UK in nine months.

[2] It refers to the night of November 9–10, 1938, and the Nazi regime coordinated a wave of antisemitic violence in Nazi Germany on that night.

outcome in NHCM should include empathy in addition to reflection. Besides, since the museum experience is short, learning motivation should also be examined and can be considered as one of the learning outcomes. If young people's interest and initiative in learning are effectively promoted, it will undoubtedly contribute to the acquisition of relevant knowledge and understanding.

1.1.2. The immersive narrative for museums

Museums increasingly use sensorial storytelling devices to enhance participatory experiences between audiences and heritage sites (Kidd, 2018). In the immersive narrative of historical heritage, the public becomes a part of the story being told. Museums and heritage sites use the immersive narrative to construct nuanced historical details and create experiential frameworks that encourage internal dialogue connections with the past and provide complex and satisfying engagements for visitors (Bedford, 2001; Wong, 2015). The emergence of immersive media, including HMD devices, AR, and VR technologies, has fostered both new opportunities and challenges to the design of immersive narrative.

The immersive remote-site museum can be achieved remotely either by using real materials to build a museum scene or by utilising a virtual 3D modelling approach, which is a type of virtual museum. Beginning in the 1980s, the advent of the New Museology movement (Vergo, 1997) broke the old schema of traditional museology by advocating for an evolved concept of the 'museum' by integrating emerging technologies, such as the internet, 3D modelling, and animation, into exhibits. From this movement, the concept of the virtual and interactive museum emerged, the contents of which can be shared through the internet or within the real museum using devices like touchscreen displays.

As technology advances, new technologies such as immersive virtual reality have been adopted by the virtual museum, which can give users a strong sense of immersion and make them feel like they are physically present at the museum (Carrozzino & Bergamasco, 2010). However, the early immersive VR systems, such as Power Wall and Cave Automated Virtual Environment (CAVE) (Cruz-Neira, Sandin, DeFanti, Kenyon, & Hart, 1992; H. Lee, Tateyama, & Ogi, 2010), required expensive equipment and installation. In addition, these display systems are typically stationary and required a lot of space and specifically controlled environmental conditions. Due to the complexity and cost of the equipment, a dedicated space and specialist engineers were required to use the remote-site museums. With the recent development of low-cost HMD devices for VR and AR, such as the Oculus Quest, HTC Vive, and HoloLens, it has become possible to bring immersive remote-site museums into the home at with low cost and maintenance requirements.

Based on these HMD platforms, several successful remote-site museum applications and projects have been released, such as *The VR Museum of Fine Art*, *The Kremer Collection VR Museum,* and *The Grand Museum VR* on the Steam platform. These projects are convenient for users, allowing them to have an immersive sensory experience of a museum without leaving their homes, thereby opening a new chapter for immersive remote-site museums. Unfortunately, the design principle of these remote-site museums is still conservative, grounded in replication and imitation of real museum spaces. Following the concept of the New Museum movement, virtual museums should aim to break real-world limitations and use a different exhibition philosophy from traditional museums by combining museums' educational missions with the ability to involve their visitors emotionally so that audiences may playfully discover new content.

Although there are more than 20 years of research on AR in cultural heritage, few projects have addressed the necessity of utilising the power of stories (Spierling & Kampa, 2014). Even in the rare cases that have, their approach to storytelling has been linear and didactic, where narratives are object-centric or utilise simple game mechanics so that the experience is primarily a game that includes a learning aspect.

With the release of HoloLens in 2017, HMD-based AR technology showed significant improvements, particularly in image display, as HoloLens utilises an optical see-through approach and spatial understanding through 3D scanning; thus, it is capable of seamlessly integrating a vivid hologram into a real-world space. A few applications have been developed for museums using HoloLens over the past four years, but the applications rely on the novelty of the technology and do not employ any narrative. For example, TouristicAR is an AR application that provides context-aware content for tourists at UNESCO World Heritage sites in Malaysia (Obeidy, Arshad, & Huang, 2018); MR Museum in Kyoto is a 10-minute AR experience that combines The Folding Screen of Fujin and Raijin with 3D graphics (Stella

Sylaiou, Kasapakis, Dzardanova, & Gavalas, 2018); ‘HoloMuse’ is an HoloLens application that allows user interaction with archaeological artefacts from the Anonymous Museum’s collection (Pollalis, Fahnbulleh, Tynes, & Shaer, 2017). Despite their developmental implications, the lack of attention to the dramatic potential of the headsets found in these works cause them to miss the opportunity to connect to the site’s stories, touch on the intangible heritage and the physical surroundings, and bring them together in a unifying narrative that creates an affectual experience. These case studies have been useful in gaging audience engagement, however, as aspects of the experience such as multisensorial modalities that provide opportunities for interaction, playful encounters, and emotional and moral engagement have proven to motivate audiences and offer a meaningful dialogue that helps them learn and be entertained (Vagnone, Ryan, & Cothren, 2015).

Immersive technologies and a narrative approach are intended to be used in NHCM to provide a deep and rich experience for the audiences based on the following considerations: Firstly, although there is a significant risk of using complex technology in small, rural museums, NHCM is using new technology to assist museum education for a long time. They have enough experience in the development and maintenance of digital technologies. Secondly, small museums often suffer from a lack of adequate visitors. As NHCM has an established relationship with primary and secondary schools, which allows sufficient young, curious, pro-digital-tech visitors can access to the museum each month. On the other hand, lockdowns during the COVID-19 pandemic stimulate the acceptance of VR/AR headsets and the demand for remote access to the museums, making immersive remote-site museums have many potential users. Thirdly, the narrative approach is used because the exhibition is aimed primarily at young people, and the narrative is usually more engaging and empathetic than conventional exhibits. The narrative in this project was not created from scratch but is based on the museum's existing exhibition titled *The Journey*, which tells the story of a fictional Jewish boy Leo based on historical facts. The project plans to further develop the story in collaboration with museum experts to ensure historical accuracy. Additionally, the interactive narrative can pose questions and make choices, allowing the audience to construct and reflect meaningfully for educational purposes. Finally, as Mosaker (Mosaker, 2001) suggests that the authenticity of the museum is key, AR technology ensures the authenticity that the audience can experience the realistic real-world museum environments on site. The use of HMD devices rather than handheld devices can free the user's hands, which enables the user can still touch and interact with real-world objects and items with the augmented visuals. Meanwhile, HoloLens is the most advanced all-in-one AR device, which is relatively easy to deploy and maintain.

In summary, using the latest HMD AR technology and a branching narrative structure, Leo's immersive and interactive narrative in NHCM can be delivered to the audience in an engaging way that connects them to the past. As with every new interaction technology and scientific research, it is necessary to research the design processes through which the interface and context are harmoniously drawn together to produce a meaningful experience. For example, Mason (Mason, 2016) and Tom Dieck (tom Dieck, Jung, & Han, 2016) used early prototype headsets to study user interaction in a cultural context through AR headsets. Hammady and Ma (Hammady & Ma, 2019) explored consideration for the visual interface design with Microsoft HoloLens 1, while Pollalis et al. (Pollalis et al., 2017) studied gesture-based interactions with holographic artefacts. However, the influence of different user interfaces for HMD-based immersive narratives on user experience and learning outcomes remains unknown, especially between the graphical user interface and the natural user interface with tangible objects.

Through this project, the NHCM has devoted itself to making its exhibitions more compelling and accessible. The timing for this project is also ideal, with the explosion of COVID-19, access to real-world museums has been further restricted. While HMD-based AR is an experience only available on-site at the museum, HMD-based VR allows visitors to access museums remotely, even from their homes. As HMD VR devices began to mature in 2016, the VR application stores such as Quest Store have grown steadily in recent years. Indeed, several HMD-based virtual museums have already been released on the store. However, most HMD-based VR museums attempt to replicate physical artefacts to provide visitors with an experience of authenticity. Instead, the focus should be shifted from the artefact exhibits to the visitors' experience in the virtual museum. Virtual museums should allow visitors to interact via a constructive cultural dialogue like an interactive narrative. In this way, visitors become active participants as they create their virtual tours and paths, thus actively constructing their knowledge concerning the exhibits and themselves (S Sylaiou, Liarokapis, Kotsakis, & Patias, 2009). In our project, we developed an HMD-based VR museum application for NHCM using an interactive narrative, allowing for remote access and a highly engaging experience. Ryan describes the interactive narrative as providing narrative engagement to interactors through the concepts of immersion and interactivity (M. L. Ryan, Press, & ProQuest, 2001). Consequently, for HMD-based immersive narrative, the impact of narrative engagement, immersion, and interaction in the user experience must be examined in depth.

However, it should be noted that there are limitations to this study: the HMD AR headsets are still immature, such as narrow FoV, heavy to wear and expensive price. The hardware is far from marge and consistent use in real-world museums. In other words, this research is a future-oriented study using prototypes and some of the conclusions in the thesis may change as technology advances at a rapid speed. Besides, HoloLens' space recognition functions need to be predefined and are not suitable for dynamic scenes, which may exclude popular and crowded museums.

1.1.3. **The challenges and opportunities brought by COVID-19**

The outbreak of COVID-19 and the subsequent lockdown policy have brought both difficulties and opportunities for my research. The difficulties include two main aspects：

1) It is impossible to deploy the XR application in the museum onsite, but only to set up a simulated museum environment in China remotely using some antique props. However, the simulated environment is significantly different from the real-world museum environment. As the AR experience is a mixture of the real world and virtual objects, the distortion of the real-world environment will also lead to disturbances and loss of overall experience, thus affecting the evaluation of the HMD-based XR museum in terms of immersion, narrative engagement, CG character’s affinity and more.

2) It is impossible to compare the HMD-based AR museum with the guided tour on-site. This comparison will be important empirical evidence to verify whether the HMD-based AR museum using interactive narratives can facilitate or even replace the guided tours regarding user experience and learning outcomes. There is a loss that this comparative experiment and

studies cannot be conducted.

On the other hand, COVID-19 also opens up opportunities. Due to the lockdown policy and the limitation of access to the real-world museum, more people began to use and accept remote digital technologies, accelerating the spread of HMD XR devices and applications. Therefore, the remote-site immersive museum becomes a hot and meaningful research topic. Due to the rapid advances in AR devices in the last two years, a new approach to remote museums has become feasible: immersive remote-site museum using AR glasses provides an Augmented Virtuality (AV) experience that a virtual museum environment can be created and overlaid in the real-world space of user's home. But there is still a gap in empirical research on this new AV approach, which is urgent in the context of the lockdown of COVID-19.

In summary, the impact of COVID-19 has shifted my research's focus from AR museums, which place more emphasis on real-world museum environments, to XR museums, which pay more attention to the remote-site virtual museum experience.

1.2. Purpose of This Study

In order to fill in the aforementioned research gaps, the following research questions are addressed in this thesis:

RQ1: What are the differences between the impact of Natural User Interface (NUI) and Graphical User Interface (GUI) on user experience in the HMD-based AR museum?

RQ2: How do the user experiences and learning outcome differ between HMD VR and HMD Augmented Virtuality (AV) as mediums for immersive remote-site museums?

RQ3: How is the user acceptance of HMD-based remote-site XR museum?

This research aims to investigate HMD-based VR and AR technologies for museum education. In order to achieve this aim, this thesis first presents a general critical review of related literature on VR, AR, interactive narrative, and museum education, to provide an overview of the previous work and identify research gaps. The main body of research consists of both technological development and experimental studies. Specifically, this thesis has the following objectives:

Technological development

Objective 1. To design and develop an interactive narrative virtual museum system with alternative storyline branching sub-system and interactive props sub-system;

Objective 2. To construct assets of virtual collections, items, and **C**omputer **G**enerated (CG) characters that are compatible with VR and AR system development;

Objective 3. To implement different versions of the application for a popular HMD platform that allows users to interact and experience the program on-site or remotely.

Experimental studies

Objective 4. To propose the user experience model and to evaluate the external factors for Technology Acceptance Model (TAM) in the context of an HMD-based immersive museum;

Objective 5. To compare the differences in the user experience, learning outcome and user acceptance of HMD VR and HMD AV as the medium for immersive remote-site museums;

Objective 6. To investigate the design guidelines for HMD-based immersive on-site and remote-site museums;

Objective 7. to investigate the user's perceived affinity for a mid-level photo-realistic CG character.

1.3. Thesis Scope

This thesis focuses on the user experience in the context of immersive museums, examining and validating the impact of the factors like interaction, presence and interactive narrative on user experience and learning outcomes. In addition, the study highlights comparing the different user experiences and user acceptance between HMD VR (e.g., HTC Vive) and HMD AR/AV (e.g., HoloLens) as the media for remote-site museums.

The study adopted a design science research approach to explore the research questions presented above. This method requires developing our own HMD VR and HMD AR applications. There are three reasons for using this methodology: (1) although the concept of VR and AR was introduced more than 30 years ago, HMD-based VR/AR hardware and software have only just became stable mass products in recent years, and there are only a few released VR or no HoloLens applications made for museums; (2) the HMD applications for immersive museums in Quest Store are digital replicas of real-world museums that do not fully take advantage of the potential of immersive technology, such as interactive narrative; (3) one of the research objectives is to develop design guidelines for HMD-based immersive museums. Therefore, tracking the design and development of the application are essential, for which the design science approach is applied. The development also aimed at producing a system for HMD-based XR museums, with features like alternative storyline branching functions and interactive props that can be extended for other virtual museums and exhibitions.

A literature review of VR, AR, immersive media, interactive narrative and multimedia-based museums was conducted, and the previous research limitations were identified. In order to propose new models and theories for User Experience (UX) of HMD-based immersive museums, this study summarised the interactive narrative models, explored the uncanny valley framework for realistic CG characters, and investigated TAM, emotional design and UX models in the immersive museum setting.

The study conducted three experiment to validate the proposed models and hypotheses. The quantitative and interviews results allowed us to examine the user experience model in an HMD-based XR museum context and identify the differences in the user acceptance and user experience levels in HMD VR and HMD AV as the mediums for HMD-based XR museum. The interview results were also helpful in summarising the design guidelines for HMD-based XR museums both on-site and remotely.

1.4. Thesis Outline

This thesis is organised into eight chapters.

Chapter 2 reviews literature concerning VR, AR, AV and collaborative use of interactive narrative and these immersive technologies. It concludes with a summary of multimedia learning in moral and Holocaust education, as well as the current status and research gaps in immersive remote-site museums. This chapter concludes with a summary of research gaps that this thesis aims to fill.

Chapter 3 reviews concepts and theories related to the research questions and proposes two models to understand the user experience of HMD-based immersive museums and the uncanny valley for realistic CG characters.

Chapter 4 describes the methodology, including the design science approach and technological development (Objective 1, 2 and 3). This chapter presents the design of the interactive narrative and the user interface and documents the development of the two systems: 1) a room-scale HMD-based AR museum system that can be deployed on-site; 2) an HMD-based remote-site VR museum system. Both systems have alternative storyline branching sub-system and interactive props or items sub-system that can be extended for other virtual museums and exhibitions.

Chapter 5 discusses the design and analysis of Experiment 1. Based on System 1, **Experiment 1** was carried out to explore RQ1. A between-subjects design was used, and two groups of participants experienced *The AR Journey* in 3DUI and NUI, respectively. They were then asked to complete questionnaires and give a short interview. The merits and disadvantages of the NUI and the GUI designs for HMD-based AR museums were discussed according to the quantitative and qualitative analysis in experiment 1.

Chapter 6 discusses the design and analysis of Experiment 2. Based on System 2, **Experiment 2** was implemented to investigate RQ3 and achieve Objective 4. A between-subjects design was employed, and two groups were split and experienced *The Virtual Journey* in HMD VR or HMD AV, respectively. They were then asked to complete questionnaires and participate in a short interview. Subsequent analysis of the results partially validated the proposed user experience model and extended TAM (Objective 4), revealed a high user acceptance of the HMD-based immersive remote-site museum (RQ3), and showed the differences between the user experiences of narrative immersion in HMD VR and HMD AV (RQ2).

Chapter 7 discusses the design and analysis of the Experiment 3, for which the data collection and analysis methods are presented in this chapter. Based on System 2, **Experiment 3** was conducted to examine further RQ2 and RQ3 and complete Objective 5 and Objective 7. A within-subjects design was deployed in this experiment, in which participants were assigned in a random order to experience *The Virtual Journey* in HMD VR and HMD AV. They were then asked to complete questionnaires after each experience and participate in a structured interview. The result revealed the differences between the user experience (RQ2) and user acceptance (RQ3) in HMD VR and HMD AV as the medium for immersive remote-site museums (Objective 5). The results also indicated that media immersion and intelligent interaction behaviours could impact the user's affinity for the realistic CG characters (Objective 7). Based on these experimental results, a revised extended TAM is presented, and the user experience and user acceptance of the HXRM are discussed in detail.

Chapter 8 summarises design guidelines for HMD-based immersive museums based on the application's development process and the results of the interview. The chapter concludes the thesis with a summary of the research findings and contributions, outlines the limitations, and discusses potential future work.

Chapter 2: Literature Review

This chapter begins by introducing the history, concepts, and development of immersive media, presenting an overview of VR, AR, and AV in industry and research, describing the concept and framework of interactive narrative, reviewing examples and developments of interactive narratives based on HMD devices, and summarising the interaction methods and three different interfaces of HMD. Finally, the value, significance, and challenges of Holocaust education are discussed, and an overview of a remote-site online museum using HMD VR is presented.

2.1. Virtual Reality, Augmented Reality and Augmented Virtuality

This section introduces the definitions, concepts, history and latest developments of VR, AR and AV. In particular, it highlights the latest advances in hardware and software for HMD-based VR and MR and their relationship to immersive media. Immersive media's unique characteristics of panoramic visuals, presence and interactivity make them different from non-immersive media. Finally, the latest HMD-based VR and AR applications for education, training, entertainment, and museums' displays are introduced, and their opportunities and challenges are discussed.

Compared to traditional digital media, such as tablets, computers and television, the most distinctive feature of immersive media is the visual wrapping, which directly stimulates the user's audio-visual senses and thus gives the user an immersive feeling. Higher immersion is a positive factor leading to better presences, flow, engagement, enjoyment, and even facilitating learning outcomes for users (Bodzin, Junior, Hammond, & Anastasio, 2020, 2021; Carbonell-Carrera, Saorin, & Díaz, 2021; Lackey, Salcedo, Szalma, & Hancock, 2016). However, some researchers point out that immersive media does not promote user learning because it tends to carry a higher cognitive load, which may negatively affect learning (Jeon, Paik, Yang, Shih, & Han, 2021; Sun, Wu, & Cai, 2019). For example, Jeon found non-immersive VR was more effective in science learning than immersive VR (Jeon et al., 2021). In general, there is a consensus among most researchers that immersive media can help promote a better sense of presence and enjoyment.

In order to achieve panoramic visuals wrapping around one’s head, there are two methods, one is a head-mounted display, where the head is covered by displays directly in front of the eyes, and the display can fill as much of the Field of View (FoV) as possible, e.g., headset Oculus Quest can cover 110° FoV of the human eye, while Pimax Vision 8K can even reach 170° FoV. The other method is a spatial display system using projection or LED to present the visual content in the physical space, and the visuals should cover as much of the space as possible, like the Cave Automated Virtual Environment (CAVE) or Dome systems in Fig. 2.1.

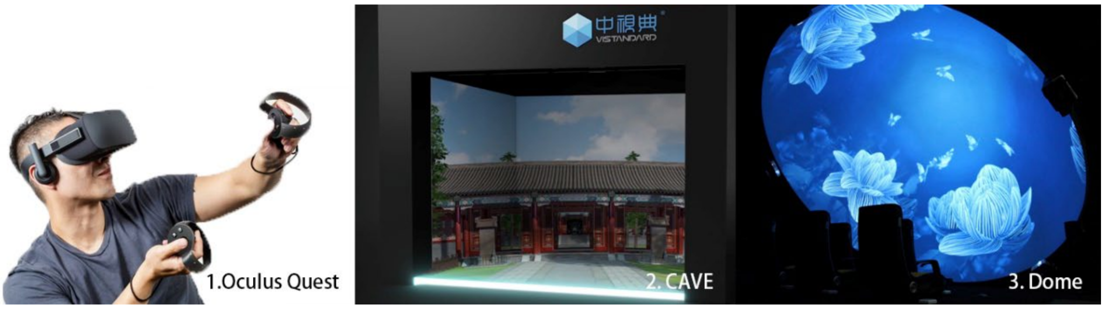

Fig. 2.1 Typical Examples of VR System

The advantages of HMDs are higher accessibility, better interaction controllers, a standard SDK for content development, stereoscopic vision, and lower cost. However, the disadvantages of HMDs are the wearing comfort issue (especially for users wearing glasses), isolation feelings, lack of tactile sense, and insufficient display resolution (Gugenheimer et al., 2019; Qi, Taylor Ii, Healey, & Martens, 2006). The advantage of spatial display systems is the larger capacity of the audience, unlike HMDs, where one person can only wear a headset, and the main problems of spatial display systems are high cost, poor accessibility, limited interactivity, and display flaws. For example, the wall-to-floor folds in the CAVE system can easily cause discontinuities in the visuals.

Immersive media has clear strengths for space perception, training space-related skills, and improving the user’s immersion. Consequently, VR news, VR automobiles, VR fire training, and VR movies have emerged one after another. The concept of immersive environments is not identical to VR and MR, and immersion is not a necessary feature of VR and AR, but immersion is an essential feature of HMD-based VR, AR and AV. So, there is some overlap of concepts and applications between VR, AR and immersive media.

HMD-based VR, AR and AV have advanced rapidly in recent years with breakthroughs in hardware and software. Technology giants like Facebook, Microsoft and others have invested in developing related software and hardware. e.g., Facebook's latest product, the Oculus Quest 2, offers excellent performance at an affordable price. The main advantages of HMD-based immersive media are the sensory experience of stereoscopic and panoramic view, presences and enjoyment from the sensory experience, and the inherently natural interaction experience. At the same time, stereoscopic vision provides users with a better perception of size and space.

There are two types of interaction in HMD-based immersive media: one base type is for the user to interact with the virtual environment by controlling the virtual camera to choose where to look; the other advanced type is to interact with virtual/augmented objects in the world. HMD-based immersive media often offers 6-DoF tracking of the headset, satisfying the basic interaction. Besides, the immersive media usually has controllers with the 6-DoF tracking functions, buttons and triggers. In addition, the latest HTC Vive Pro[3], Oculus Quest[4] and HoloLens2[5] can recognise and track the user's hand and fingers. The tracking function of controllers and hands encourages deeper interaction to manipulate virtual/augmented objects. Unlike traditional media such as film, where the director absolutely determines the content, the content of interactive media depends on the user's interaction. Regarding interaction and content production, immersive media content is closer to a video game than a video. Unlike video games, which usually use peripheral devices based on conventional mappings, HMD-based immersive media uses more natural metaphoric mapping to interact with its controllers. Conventional mapping usually leads to non-intuitive interactions with GUI, while metaphoric mapping can give intuitive interactions with NUI (Macaranas, Antle, & Riecke, 2015). Looking around in a virtual environment is a typical example. In this case, the video game with GUI usually needs users to move the mouse to simulate the rotation of the head while pressing the WASD key on the keyboard to control the back and forth movement. However, the HMD-based VR with NUI allows users to move their bodies

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[3] https://www.vive.com

[4] https://www.oculus.com

[5] https://www.microsoft.com/en-us/HoloLens

backwards and forwards in space and crane their necks to look around. The NUI control with metaphoric mapping is almost identical to the real world.

2.1.1. Virtual reality

This section consists of three parts, firstly reviewing the history, definition and classification of VR, then presenting the progress and development of VR regarding hardware and software, and finally introducing a brief review of the latest VR applications and academic research.

2.1.1.1. A brief history and definitions

In 1965, Ivan Sutherland invented the first head-mounted display (HMD) device capable of tracking the position and orientation of a user's head and updating the virtual image accordingly. At the time, Sutherland envisioned the 'ultimate display' as not just a screen but a window through which users could view a virtual world that looked real, sounded real, felt real, and moved and responded to interaction in real-time (Sutherland, 1965). However, VR devices were cumbersome at the time, and the user experience needed further development. Since then, the concepts and technologies of VR have developed considerably.

Jaron Lanier coined the term Virtual Reality (VR) in the late 1980s. He defined VR as a three-dimensional, computer-generated environment where people can immerse, explore and interact (Lanier & Biocca, 1992). Lanier founded VPL and launched two commercial products: the DataGlove and the Eyephone. Eyephone was an HMD system with an immersive display (Teitel, 1990), while the DataGlove could be used as its controller to measure finger curvature and recognise gestures using sensors (Zimmerman, Lanier, Blanchard, Bryson, & Harvill, 1986). It was the first commercial VR product to attempt general use and got the public into VR devices.

From the 1990s onwards, VR started to enter the entertainment industry for the public through arcades. For example, Nintendo made the Virtual Boy, the first portable game console capable of producing 3D graphics in black and red[6]. However, this product was a commercial failure because of its high cost, the immaturity of the display and hardware, and the lack of

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[6] https://www.youtube.com/watch?v=dWqQBgBYzcA

relevant games and software. In the meantime, more demonstration and experimental systems were developed in laboratories and universities, including the CAVE developed by the University of Illinois Electronic Visualisation Laboratory in 1992 (Cruz-Neira et al., 1992). CAVE encloses the user in a room with projected images on the walls, ceiling and floor. The advantage of the CAVE was that it allowed multiple users to interact in the same environment and prevented the users from wearing cumbersome helmets.

In 1999, Brooks investigated the VR systems of the time and determined that VR could work in production use, with a resolution of 460 x 680 for HMDs and 1280 x 1024 for projection. He also identified end-to-end system latency as VR systems' most technical severe flaw. He defined the VR experience as "any user effectively immersed in a responsive virtual world", implying dynamic control of the user's viewpoint. This definition of VR is then widely accepted in the research community (Brooks, 1999).

2.1.1.2. Current state of the art in VR

The last section introduced that VR once became a hot topic in academia and industry and developed rapidly at the end of the 20th century, but due to the immaturity of computer technology and hardware, it soon reached the bottleneck. VR burst into life again in 2016.

Hardware

Several mass-produced, affordable HMD VR headsets launched in 2016, including the Oculus Rift, HTC Vive, and Sony PlayStation VR (see Fig. 2.2). These headsets also feature a wide FoV, high refresh rate and high-resolution displays with 6-DOF, which were not previously available in headsets. Six-DoF enables rotational movement around the x, y, and z axes (also known as pitch, yaw, and roll) and translational movement along three axes. The above features lift the mass-produced headset to an industrial level (see Table. 2.1). As a compromise, the headsets were used as displays only, required to be tethered to external computers with cables, and these high-end computers computed the real-time content. Besides, additional base stations needed to be configured to track the headset and controllers in real-time over 6-DoF, and it required carefully planned space for the tracking sensors to work properly.

Fig. 2.2 The typical mass-produced VR headset in 2016

Table. 2.1 The detailed information list of typical VR headsets in 2016

	Oculus Rift[7]	**HTC Vive**[8]	**Sony PSVR**[9]
Release Date	2016/3	2016/4	2016/10
Type	Tethered	Tethered	Tethered
Resolution (per eye)	1,200 x 1080	1,200 x 1080	1,080 x 960
Refresh Rate	90 Hz	90 Hz	120 Hz
Field of View	94	110	100
Motion Detection	6-DoF	6-DoF	6-DoF
Hardware Platform	PC	PC	PlayStation 4
Introductory Price	$599	$799	$399

At the same time, mobile-based VR also started to be available on the market, such as Google Cardboard[10], Google Daydream[11], and Gear VR[12] (see Fig. 2.3). Mobile-based VR devices use a mobile phone inserted into the headset to compute the real-time content and display the result on the phone's screen, which is split into two parts, one for the left and one for the right eye, and the headset has an optical lens in front of the screen, providing an FoV of approximately 90°. The idea of mobile-based VR came very early on, in January 2005, when Samsung obtained a patent on an HMD that uses a clamshell feature phone. This design was one of the first times the idea of using a mobile phone as a display in the HMD surfaced. Mobile-based VR has the advantage of being wireless, light-weight and low-cost. It also meets the basic HMD VR requirements for tracking, resolution, FoV and refreshes rate, e.g., The

[7] https://en.wikipedia.org/wiki/Oculus_Rift

[8] https://en.wikipedia.org/wiki/HTC_Vive

[9] https://en.wikipedia.org/wiki/PlayStation_VR

[10] https://arvr.google.com/cardboard

[11] https://arvr.google.com/daydream

[12] https://www.oculus.com/gear-vr

Gear VR with Galaxy Note 4, for example, has an FoV of 96°, a monocular resolution of 1280*1440, a refresh rate of 60 HZ, and 3-DoF headsets that allow users to track rotational motion which relies on inbuilt sensors (accelerometers, gyroscopes and magnetometers). Besides, mobile-based VR is inexpensive, e.g., google cardboard is about $10, and Gear VR is about $100.

Fig. 2.3 Back View (left) and Front View (right) of Gear VR

While mobile-based VR has the above merits, it suffers from two significant downsides. First, the refresh rates and resolutions are restricted by the mobile phone devices on which they are delivered - and while this issue may be overcome as the technology matures, the second issue is more likely to persist: limited options are available to control the devices. Additionally, most mobile VR devices support only the tracking of rotational movements but not translational movements. While equipment like the Gear or the Google Daydream offers handheld controls, the same does not apply to self-contained mobile VR systems, such as the Google Cardboard, as the most affordable form of VR.

Oculus Quest 2, HTC Vive Pro Eye and Pimax Vision 8K represent the latest VR headset's advance, which has achieved the leading tracking technology, large play space, ultra-high-resolution, wide FoV and high refresh rate. As Table. 2.2 shows, Pimax Vision 8K is the first 8K headset with a 170° FoV and a 110 Hz refresh rate, and the high resolution almost eliminates the Screen door effect for most users. On the other hand, HTC Vive offers a tracking space of 100 square metres and can be connected to computers wirelessly, which is sufficient for indoor VR in most situations. Oculus Quest is the first all in one headset, using the four integrated cameras in the headset for tracking instead of the additional base station, enabling 6-DoF tracking of the headset and controllers. The all-in-one headset was possible by advances in VR tracking systems. VR systems use sensor-based methods to track the motions (Zhao, 2009), using built-in sensors in HMDs and controllers and external sensors. For example, Oculus Rift and HTC Vive use two external sensors (base stations) to calibrate a tracked space. The sensors emit timed infrared pulses to establish tracking of the HMD and two handheld controllers. More recent VR devices, such as Oculus Quest use inside-out tracking systems that scan the surrounding environment. This approach supports updates to the simulated graphics in relation to the HMD positions in the real environment without being tethered to a desktop. Such tracking methods are often based on Simultaneous Localisation and Mapping (SLAM) algorithms that recognise the unique static features of the surrounding environment and simultaneously keep track of users' locations within it.

The all-in-one VR headset like Oculus Quest significantly reduced the difficulty of setting up and initialising the device and kept a decent tracking space of nearly 50 square metres, satisfying the needs of most home scenarios. Oculus Quest 2 also has sufficient resolution and refresh rate to minimise the Screen Door Effect (SDE) and has a built-in Android system to run the mobile applications locally. The headset also supports USB-type C tethered mode and the low-latency wireless mode, enabling the external high-end PC to run complicated programs. Moreover, Oculus Quest 2 is about $300, as cheap as a mobile-based VR.

In summary, VR headset hardware has developed rapidly since 2016, with massive progress in resolution, refresh rate, FoV, tracking, playable space, set-up optimisation and price. With the advance of 5G technology and the LED, LCD manufacturing process, the all-in-one headset could be the future direction.

Table. 2.2 The detailed information list of typical VR headsets in 2021

	Oculus Quest 2 [13]	**HTC Vive Pro Eye** [14]	**Pimax Vision 8K** [15]
Release Date	2020/10	2019/6	2019/02
Type	Tethered/wireless	Tethered/wireless	Tethered
Resolution (per eye)	1832 x 1920	1,440 x 1600	3840x 2160

[13] https://www.oculus.com/quest-2/

[14] https://www.vive.com/us/product/vive-pro-eye/overview/

[15] https://pimax.com/product/vision-8k-x/

Refresh Rate	120 Hz	90 Hz	Up to 110 Hz
Field of View (horizontal)	100	110	170
Motion Detection	6-DoF, hand tracking	6-DoF, hand tracking, eye tracking	6-DoF Eye tracking, hand tracking
Hardware Platform	PC/Andriod	PC	PC
Place Space	7m*7m	10 m*10 m	10 m*10 m
Weight	503 g	550 g	850g
Price	$299	$1399	$1599

Software

Apart from the hardware, software for VR has also made significant progress in recent years. There is no standard for VR headsets, and different manufacturers' products are not compatible. Different devices have their own Software Development Kits (SDK). For HTC Vive, there are three good options, OpenVR kit, SteamVR kit and Virtual Reality Tool Kit (VRTK) — all official virtual reality SDKs by Viveport community. OpenVR SDK by Valve is an API and a runtime environment with great samples. It supports multiple VR hardware, and applications are not vendor-specific. SteamVR SDK lets developers create single interfaces that work on different VR headsets, including HTC Vive. Moreover, it gives access to controllers, chaperoning, and models and allows content preview in Unity play mode. VRTK appears to be a collection of handy scripts for VR applications. Though developers can use VRTK for Oculus Rift on Unity, Oculus SDK is the best VR SDK for Oculus. There are Oculus PC SDK, for Windows and Oculus Mobile SDK. It includes various engine-specific kits (for Unity, Unreal, WebVR etc.), samples, assets and audio packages to help build VR apps. This VR dev kit offers lots of features and handles many issues of VR content, like optical distortion and rendering techniques. Besides, the Oculus Mobile SDK can also be used for other mobile-based VR, such as Samsung's Gear VR. The VR headset by Samsung was initially built in collaboration with Oculus. Thus, their kit fits nicely to build apps for GearVR. Oculus Mobile SDK contains tools and libraries for C/C++ development for Oculus and Samsung Gear VR.

Features are essential for creating good 3D assets for VR, including realistic materials, physical-based rendering, and physics simulations. These features are available in most commercial game engines and do not have to be developed from scratch, so game engines dominate VR development. Some of the popular game engines in the industry include the following:

- Unity3d – a cross-platform game engine, which is great for VR, as it supports Oculus Rift and all of the platforms mentioned above. It is popular among developers, offers the asset store with a wide choice, and also allows a free choice of programming language (C#, C Sharp, JavaScript, Python).[16].
- Unreal Engine – a game engine introduced back in 1998, has grown since to become an efficient platform for building games, apps, and animations for VR headsets and mobile devices. UE4 grants full access to the source code and comes with a highly convenient visual scripting mode, has outstanding compilation speed.[17].
- LibGDX is an open-source development framework written in Java. It comes with the unified API for every platform from Windows, Linux, mobile OS to web browsers. Fast iterations and prototyping, rendering graphics via OpenGL ES 2.0, supporting all popular audio formats.[18].
- AppGameKit VR – a game creation system for mobile devices, working on Oculus Rift and HTC Vive. Commercial use is allowed without the obligation to pay royalties. This kit's commands allow quick creation of basic VR experiences.[19].
- CryEngine is an open-source royalty-free gaming engine that provides many features, some being unique, e.g., fog rendering/cloud shadows, weather effects, colour grading, etc. It also is a marketplace for developers to find individual assets, 3D models and sounds.[20].

Unity3D and Unreal are the commonly used engines for VR development. The main strengths of Unity3D include:

- a rich asset library, including models, animations, materials and standard functional modules, plug-ins, etc.;

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[16] https://unity.com/products/unity-platform

[17] https://www.unrealengine.com/en-US/

[18] https://libgdx.com/

[19] https://www.appgamekit.com/dlc/vr

[20] https://www.cryengine.com/

- programming in C#, which is somewhat less complicated and less error-prone than C++;
- good tech support can respond to the users' questions efficiently with highly skilled tech support members;
- a full range of standard modules, including graphics and visuals, particle system, GUI, physics simulation, sound system, postprocessing, visual programming tool, etc.;
- two rendering pipelines meet different development needs, i.e., High Definition Rendering Pipeline (HDRP) and Universal Rendering Pipeline (URP).
- HDRP can provide hyper-realistic graphic modules for high-end real-time rendering, like real-time raytracing, volume light and volume fog, decals projection, sub-surface scattering material and tessellation material;
- URP can keep a good balance between computing power and graphics, suitable for mobile devices such as mobile phones or mobile-based VR;
- The built-in input module can switch between different headsets and input devices, such as porting Oculus programs to the HTC Vive.

The main advantage of Unreal is the rendering technology, which provides ultra-realistic visuals solution with more features while using less memory and resources compared to other engines. In addition, it provides an excellent visual programming tool named blueprint, which works like building blocks, so even artists without any programming knowledge can use the engine to assemble and adjust basic things. However, C++ is still required for completing serious tasks.

The rationale of the hardware and software chosen

As for hardware, HTC Vive Pro Eye was chosen mainly for interactivity reasons, including how the user moves around in space, how they interact and the key parameters of the display. Teleport is a classic method for users to move and transfer in a virtual space, however, this method can easily lead to VR sickness (Riecke & Zielasko, 2021). The other way is to let the user walk directly in the playable space, which avoids the above problem, but limits the user's range of movement to the device's playable space. The interactive narrative in this project takes place in a room approximately 60 square metres in size. The only VR device that meets this requirement is the HTC Vive Pro Eye, allowing free movement in a 10×10 metres space.

The HTC Vive Pro Eye also supports wireless mode and has decent resolution, FoV and refresh rate. As to SDK, OpenVR and Vive Hand Tracking SDK were chosen. Because there is no need for teleport or controllers for the narrative, OpenVR meets the development needs and has better compatibility with different versions of Unity. The Vive Hand Tracking SDK enables recognising and tracking users' hands directly.

2.1.1.3. Advance of applications and academics in VR

Many scholars tend to categorise educational VR applications into two different types (see Fig. 2.4): immersive and non-immersive systems. The former usually refers to a real-time 3D system where users wear head-mounted stereo displays to provide complete visual immersion as well as special gloves that allow 6-DoF input to directly manipulate the environment. The latter also places users in a 3D environment but with a conventional workstation using monitors, a keyboard and a mouse (Robertson, Card, & Mackinlay, 1993).

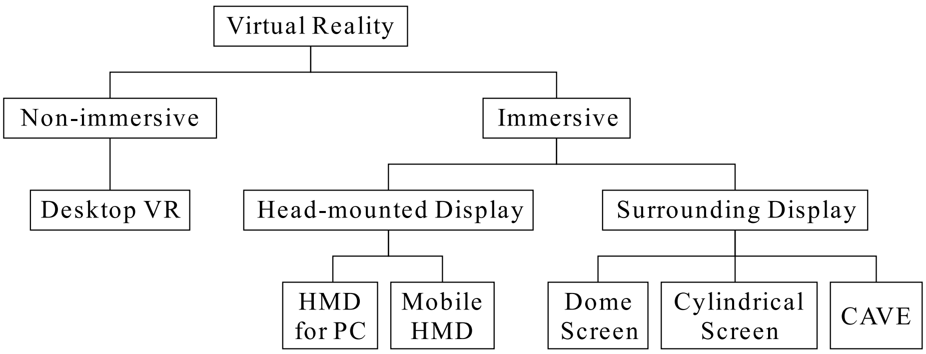

Fig. 2.4 The VR application types

Due to its ability to offer both interaction and immersion at very high levels (L.-F. L. Lu, 2008), virtual reality has been used for educational purposes for quite some time. It has proven to have the ability to enhance perception and memorisation (Chu, Payne, Seo, Chakravorty, & McMullen, 2019) as well as the potential to facilitate the acquisition of higher-order thinking and problem-solving skills (Chen, 2006).

At first, the goal of VR was to replace an actual system or environment with a virtual one for training because of cost, dangers, inaccessibility, or time constraints, so education requiring experience working in a dangerous environment or with expensive practices was already well supported by VR technology. One typical example is education in the medical field, where practising upon real patients is immoral and illegal in many parts of the world. Therefore, plenty of studies have been done on how well VR technology can train medical students in surgery (Seymour et al., 2002), emergency treatment (Reznek, Harter, & Krummel, 2002), etc. Besides medicine, there have also been studies on the application of VR in other fields like the military (Moshell, 1993), industry (Blümel & Haase, 2009), science (Rico, Ramírez, Riofrío-Luzcando, & Berrocal-Lobo, 2017), aviation (Bauer & Klingauf, 2008) and education (Han, 2015; L. Lu, 2013).

There are already several articles that compare immersive VR and non-immersive VR. For example, Harman (Harman, Brown, & Johnson, 2017) found immersive VR has an advantage over non-immersive VR in spatial recognition and information recall. Silva et al. (de Souza Silva, Marinho, Cabral, & da Gama, 2017) concluded, using descriptive statistics as evidence, that immersive VR scored better in "attention" and "relevance", while non-immersive VR did better in "confidence". Greenwald et al. (Greenwald, Corning, Funk, & Maes, 2018) found that immersive VR users completed complex spatial tasks more efficiently, but quantitative analysis showed few significant results.

The iLab-X platform established by the Ministry of Education of the People's Republic of China (abbr. MOE) in 2017 is possibly one of the largest online providers of multidisciplinary VR education. The MOE encouraged the creation and online sharing of all different kinds of virtual experiments for university students to make dangerous or expensive experiments more accessible through a new medium. The organisations that create them must agree to offer this service to the public for free for at least five years. As a reward, 1000 outstanding projects chosen from among the participants were granted national merit awards before the end of 2021. With these policies in place, the iLab-X platform has become one of the foremost government-run efforts to make up the regional economic difference and enhance educational equity. These virtual experiments cover a wide range of subjects, including science, engineering, medicine, humanity, fine arts, and more. By the end of 2021, the number of enrolled projects freely available at iLabX's website http://www.ilab-x.com/ had already reached 3,250. Applications involving the fields of the museum studies, art, and history such as *Virtual Simulation of Flat Prints Production, A Virtual Simulation on the Traditional Production Process of Cloisonné, A Virtual Experiment of Chinese Digital Shadow Animation*, and more were included in this number. These VR apps allow students to learn by doing and experience production processes which would usually be difficult to experience in the real world. As the use of these applications has grown, many have been used in the Chinese university curriculum as alternatives or supplements to the experimental sessions, revealing that non-immersive VR is already a part of teaching and learning to some extent.

On the other hand, since the birth of Oculus Rift, many HMD manufacturers like Oculus, HTC, and Samsung started online application sales similar to Apple's App Store. By attracting 3rd-party content creators, the applications available in these stores were greatly enriched in both theme and form. Rift Store by Oculus[21] was chosen as a typical example for close inspection in this paper because it was among the earliest and most influential online stores dedicated to HMD VR and has a vibrant collection of various applications. By the end of August 2021, there were 1,417 applications online, which were divided into several categories like "Role-Playing Game (RPG)", "action & adventure", and "sports and puzzle games".

Presently, many governmental and commercial resources have been invested in developing virtual reality learning environments as described above, and desktop VR and HMD VR are the two most common types. The recent advances in VR have been strongly driven by the leading technology giants' research and development in making affordable hardware devices for consumers and providing software development platforms and toolkits. This section shows that VR headsets and applications are becoming increasingly accessible to individual users for both entertainment and education.

2.1.2. **Augmented reality**

This section consists of three parts, firstly reviewing the history, definition and classification of AR, then presenting the progress and development hardware and SDK of MR, and finally introducing a brief review of the latest VR applications and academic research.

2.1.2.1. A brief history and definitions

Augmented Reality (AR) was coined in the early 1990s when Boeing created the prototype of

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[21] https://www.oculus.com/experiences/rift/

an AR system to guide construction workers in installing aircraft assembly by overlaying computer-generated images in the real world (Barfield & Caudell, 2001). Later, Feiner et al. developed the first prototype of a Mobile Augmented Reality System (MARS) that guided visitors through the urban environment of Columbia University with graphical guidance messages (Feiner, MacIntyre, Höllerer, & Webster, 1997).

In the early 2000s, Ryan (M. L. Ryan et al., 2001) considered the possibilities of VR for representing ideas and concepts, arguing that interactive and immersive technologies, such as VR, have their precursors in both traditional narrative and arts, and tackles the idea that VR is, as a medium, a metaphor of total art. With this approach, Milgram and Kishino (Milgram & Kishino, 1994) made a taxonomical proposal named "Virtuality Continuum", which presents various intermediate steps in a continuum line, from virtual reality to the physical world (see Fig. 2.5). This continuum is the starting point for further developing theoretical approaches regarding interaction based on the nature of human senses and cognition. In their description, AR sits in-between reality and virtuality, referring to the case in which the 'real environment is "augmented" using virtual (computer graphic) objects'. Augmented Virtuality (AV) indicated the graphic display environments that were either completely immersive, partially immersive or otherwise, to which elements from the reality is added. The focus of AV and AR is different: the focus of AR is on the real-world objects, with the virtual parts serving as a complementary information; the focus of AV is on the virtual world, with the real-world objects displayed as secondary information or supporting interaction. Mixed Reality (MR) refers to cases in which real and virtual objects are displayed together, and Extended Reality (XR) is the expansion of the real world using any display technologies including MR and VR.

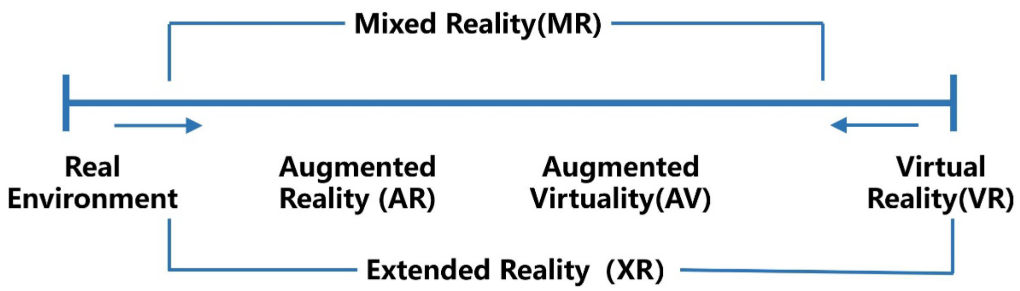

Fig. 2.5 Modified Reality-Virtuality continuum from Milgram and Kishino

Azuma proposed that AR can be defined as a system exhibiting three basic features, i.e., a combination of real and virtual worlds, real-time interaction, and accurate 3D registration of virtual and real objects (Azuma, 1997). This definition accurately describes the three technical characteristics of AR and is widely accepted by academia and industry. Mixed Reality (MR) is defined in different ways by researchers and professionals in academia and industry. As indicated in Speicher et al.'s (2019) survey of MR research and interviews with VR/AR experts, MR has been considered as a synonym for AR or as a superset of AR in terms of a 'mix of real and virtual objects within a single display', or distinct from AR in terms of interaction possibilities. The term 'Extended Reality' (XR) has recently been adopted to refer to the entire spectrum, ranging from reality to virtuality, encapsulating all technologies mentioned above (Chuah, 2019).

2.1.2.2. Current state of the art in AR

The devices primarily exploited for augmented reality refer to displays, input and tracking systems, and computers (Carmigniani & Furht, 2011). Three major types of displays are applied in AR, i.e., HMD, handheld displays and spatial displays. Handheld displays use video-see-through techniques to overlay the virtual graphics onto real-world videos via smartphones or tablets, and spatial augmented reality uses video projectors, optical elements, holograms and tracking sensors to display graphical information directly onto physical objects without requiring the user to wear or carry the display. Compared with handheld displays that show the advantage of accessibility, HMD with a larger FoV and freeing users' hands are more technologically promising. AR HMD can either be video-see-through or optical see-through, and it can be equipped with a monocular or binocular display optic. Over the past few years, HMD exploiting optical see-through technology is leaping forward, with HoloLens and Magic Leap One as the representatives. Tracking systems act as a core part of AR. The systems fall into image-based, model-based, area-based and location-based (GPS-based) systems. The area-based tracking system is known as the latest technology for environment tracking and reconstruction as well as the augmentation of areas and spaces based on both pre-produced and real-time 3D scanning (Vuforia, 2021). By employing such an area-based tracking system, augmentations (e.g., stationary and animated characters and objects) can be delivered in an interior real-world environment, like museums, offices or a floor of a factory. HoloLens is regarded as the most advanced HMD-based AR device supporting the mentioned area-based tracking (Microsoft, last accessed 20120/1/31a).

Hardware

For handheld AR, a mobile phone is a key device. The better the phone's CPU, GPU, and camera performance, the more powerful AR. Some representative mobile phone models for AR include Phone 13 pro, Huawei P50 Pro, Huawei Mate 50 Pro, and Samsung Galaxy S21. The iPhone 13 Pro is the most powerful handheld AR device, not only because it has the leading A15 CPU and GPU in a mobile phone but also because it has three high-end rear cameras[22]. For HMD AR, see-through HMDs are utilised to make users see the world mixed with virtual objects and physical ones. In this case, the virtual objects are superimposed on the physical objects via either optical or video technologies. They can be divided into optical see-through (OST) and video see-through (VST). Several VR HMDs embed the VST system, such as the Oculus Quest 2 and the HTC Vive Pro. As VR HMDs were not initially designed for AR purposes, there are significant defects in the video display of these headsets, such as low resolution and high noise levels.

In contrast, the mainstream AR HMDs are the OST headset on the market. OST makes the user see virtual objects superimposed and blended with the real world with their eyes, along with a holographic optical layer. In other words, graphics are superimposed on the real environment through additive mixing. Thus, the graphical areas are drawn as black, but they appear transparent to the user to achieve the blending (Klopschitz, Schall, Schmalstieg, & Reitmayr, 2010). One positive feature of the OST HMD is producing a neutral, instantaneous view of the real world with a remarkable result. The real world has an unmodified scene, so the real objects are seen in high resolution and without any delay (Zhou, Duh, & Billinghurst, 2008).

Smart eyewear products have been developed for AR, such as the Google Glass8, Epson Moverio9, Microsoft HoloLens1, and MagicLeap One. HoloLens 1 was released at the end of

[22] https://www.apple.com/iphone-13-pro/specs/

2016, offering a solution for a fully-immersive experience mixing virtuality and reality. HoloLens is an HMD featuring 35◦ viewing angle see-through holographic lenses (waveguides), spatial understanding by real-time 3D scanning, gaze tracking, hand gestures input, voice recognition and built-in speakers for spatial sound (Microsoft, last accessed 20120/1/31a). HoloLens 1 can partly understand and recognise real-world information such as walls, floors, ceilings, chairs and put a stable hologram into the real-world space, e.g., audience can watch a holographic virtual character "seating" on a real-world sofa talking to them.

In July 2018, a similar AR-HMD device named Magic Leap One was launched in the market. It is equipped with an LCOS screen with a higher definition of 1280 x 960, offering a wider viewing angle of 50◦, larger RAM of 8 GB and a better CPU (Leap, last accessed 20120/1/31). It also has several functions similar to HoloLens 1 and the additional eye-tracking function. However, reviewers discovered that Magic Leap One achieved higher Field-of-View (FoV) by sacrificing image resolution and brightness, making text cloudy and the virtual image darker.

In February 2019, HoloLens 2 was released as the most advanced AR/MR device on the market. The HoloLens 2 catches up in FoV with a 52 ◦ viewing angle and a screen resolution of 2K per eye (Microsoft, last accessed 20120/1/31b). Moreover, HoloLens 2 stands out with a much-improved hand-tracking technology, eye tracking, voice recognition and better ergonomic design. Users can directly manipulate virtual holograms by hand (without any symbolic hand gestures) and perform dictation recognition offline. HoloLens 2 outperforms Magic Leap One on almost every aspect except it is heavier.

Software

The tracking methods used for VR and AR are essentially sensor-based, vision-based, or a hybrid use of several tracking techniques(Zhou et al., 2008). Electromagnetic, acoustic, inertial, optical, and mechanical sensors can be used for sensor-based tracking methods. AR systems primarily use vision-based or hybrid tracking methods. Many existing AR applications use printed markers (or image targets) and associate them with 3D objects and information (Billinghurst, Kato, & Poupyrev, 2001). The camera can superimpose virtual information on top of the marker once it recognises the features of the marker.

On the other hand, markerless tracking recognises the features of the surrounding environment to localise the user (the device) relative to the situated environment (Keil et al., 2013). This approach contains information about users' spatial relationship with the augmented virtual information and the recognised real space. Finally, spatial mapping is featured in recent HMDs such as Microsoft HoloLens and the latest SDKs such as EasyAR. It captures the surrounding physical environment by photoelectric sensors and converts it into spatial information (Selleck, Burke, Johnston, & Nambiar, 2018). Spatial mapping can deliver a detailed representation of the physical environment around the user who wears the headset[23]. With the captured spatial information, the headset can generate a 3D-scanned representation of the physical environment (Selleck et al., 2018) to understand better the real-world surfaces like the interpretation of the floor, ceiling, windows, doors, sitting areas, etc. Some outdoor AR applications also use GPS-based tracking and camera-based tracking, such as for tourism in cities and large sites (Vlahakis et al., 2002).

Many SDKs are already in the market, which are essential for building AR/MR applications, either on smartphones or smart glasses/HMDs. Most of them require a game engine, such as Unity3D, to deploy the application on devices.

- Vuforia is widely used in the field of AR mobile applications. It can support Unity3D, Android, iOS and Windows. Vuforia supports two different types of visual tracking: marker-based tracking and markerless tracking. VuMark is a marker-based tracking combination between a Quick Response (QR) code and an image. Regarding markerless tracking, Vuforia supports the recognition of basic 3D objects such as a box, sphere or plan, and a customised 3D object. Besides, Vuforia also supports area tracking, which can track a whole environment like a floor of a building[24].
- ARCore is an SDK for the Android platform for Google, which can understand the real world and make the user interact with the virtual information. ARCore relies on

[23] https://docs.microsoft.com/en-us/windows/mixed- reality/spatial-mapping

[24] https://developer.vuforia.com/

four capabilities: motion tracking, flat surface detection, environmental understanding and light estimation[25].

- ARKit is an SDK for the iOS platform. By using the iOS device's camera, gyroscope, accelerometers, and context awareness. Except standard motion tracking, it has several key features like face Tracking, real-world location anchors, motion capture, people occlusion, and scene geometry[26].
- HoloToolKit is a set of scripts that aids the developers of Microsoft HoloLens to build immersive MR applications. It is employed in the development process by adding them to Unity 3D with the presence of Windows 10 as the managing operating system for the process[27].
- Mixed Reality Toolkit (MRTK)[28] a Microsoft-driven project that provides a set of components and features used to accelerate cross-platform MR app development. It supports Microsoft HoloLens, HoloLens 2, Windows Mixed Reality headsets, Oculus and HTC Vive. It highlights hand tracking, eye tracking, spatial awareness, operation solvers (Microsoft, last accessed 20120/1/31g).
- EasyAR is a world-leading AR SDK for iOS, Android and HoloLens. It is able to perform planar image tracking, 3D objects tracking and surface tracking. Besides, it also can scan and track the interior or outdoor environment and generate 3D meshes in real-time, like a conference room or a block of the street.

In summary, the hardware and software development kit has kept improving during the past five years. Though there are still limitations that affect the audience's immersive experience, such as narrow FoV, limited CPU computing power, great enhancement has been achieved in terms of display quality, input methods, software development modules, which makes narrative in an immersive environment using real-time 3D characters possible.

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[25] https://developers.google.com/ar

[26] https://developer.apple.com/augmented-reality/

[27] https://gitlab.inria.fr/mdiazmel/iRealHoloLens/-/tree/01c49bd3a0e0651effa7d0cb98b35acad0738352/iReal/Assets

[28] https://github.com/microsoft/MixedRealityToolkit

Rationale of the hardware and software chosen

Regarding hardware, considering mobile device users have to use one hand, and have one free hand, while HMD users can have two hands free. In addition, mobile users have limited space for interaction since they have to interact with the augmentations through mobile with small screens. While the HMD users, on the other hand, have a wide space around them to perform interactions. Therefore, I chose to use HMD for this project. HoloLens 2nd is the best available choice for research and study purposes regarding its FoV, spatial understanding ability, hand recognition ability, and eye-tracking. Thus HoloLens 2nd was chosen for study 2 and study 3, however, HoloLens 1st was chosen for study 1. Because study 1 was conducted in 2018, HoloLens was the most advanced HMD AR headset at that time.

As to software, Vuforia, HoloToolKit, MRTK and Easy AR supported HoloLens development. However, HoloToolKit was chosen for the first version of development on HoloLens 1st, as it is the best SDK for HoloLens 1st development with unique features like spatial understanding, input system and several useful examples. MRTK was chosen for the second version of development on HoloLens 2nd, as it is the best choice for HoloLens 2nd development, supporting all HoloLens 2nd's latest features like hand tracking, eye tracking, etc.

2.1.2.3. Applications of AR in industry and research

HMD AR headsets are not as accessible as VR HMDs. Most current AR applications for the mass consumer market are developed for mobile platforms, partly due to the prevalence of smartphones. Pokemon Go12, a mobile AR game that topped the download charts of application stores and reached one billion downloads, is typical of the mobile AR applications currently on the market (J. Smith, Yin, Lee, Ellis, & Ijaz, 2020). The popularity of mobile AR games with location-based 3D interactions demonstrates that smartphones can provide sufficient processing power, convenient tracking of virtual objects with camera sensors, and intuitive interaction controls using touchscreen technology to run these programs smoothly. Users have also been driven by the entertainment experience they provide, and also certain emotional and social benefits, as well as social norms, to use this type of application

(Rauschnabel, Rossmann, & tom Dieck, 2017).

Still, despite its many uses, AR is still mainly used for science education. Due to the lack of theory and the barrier of the technical issues, few attempts have been made to create a character-based narrative with HoloLens. Ramy developed a HoloLens application entitled the Museum Eye which blends virtual ancient Egyptians and artefacts in the physical space of the Egyptian Museum to tell the story of Egyptian history (Hammady, Ma, AL-Kalha, & Strathearn, 2021). In another recent example, *ETERNALS: AR Story Experience*, an AR adventure game and immersive story experience developed by Marvel Studio, also reveals AR's potential in narratives. *ETERNALS* enhances the interactivity and visual richness of storytelling by mixing the virtual characters and creatures into a real-world room.

2.1.3. Augmented virtuality

According to Milgram's reality-virtuality continuum (see Fig. 2.5), Augmented Virtuality (AV), One type of mixed reality, refers to the graphic display environments that are either completely immersive, partially immersive or otherwise, to which elements from the reality are added. In other words, AV adds items from the real world into the virtual world. It differs from AR, where the virtuality is overlaid on top of the real world. In Milgram's concept, the underlying environment of AV and AR is different. The fundamental environment of AR is mainly the real-world environment and objects, with the virtual items blended into the real world. In contrast, the underlying environment of AV is mostly the virtual world, with real-world objects integrated into the virtual environment. AV describes the immersion into a virtual world, which is extended by reality, while the user manipulates mainly virtual objects. For example, virtual meetings can be held in which engineers can jointly manipulate or change 3D models in real-time.

AV can be implemented in head-mounted devices, falling into two categories: Optical See-Through (OST) and Video See-Through (VST). The concept of head-mounted VST approaches (Edwards, Rolland, & Keller, 1993): cameras mounted on the headset close to the user's eyes capture the real world from the user's perspective, while the position and the orientation of the tracked head is used to render the virtual environment. Mass-product VST headsets include the HTC Vive Pro, Oculus rift S and Oculus quest2. The VST camera captures the real world and separates relevant elements from the background, such as people, hands, keyboards, etc. Then the real-world elements are mixed into the virtual environment. For instance, as Fig. 2.6 shows, Mark McGill et al. blended a real-world keyboard and virtual environments to achieve an augmented virtuality experience to access the user's experience (McGill, Boland, Murray-Smith, & Brewster, 2015). David et al. built an AV system using VR head and Kinect to enable people's bodies and real-world objects to be presented in the virtual world as point clouds (Nahon, Subileau, & Capel, 2015). Generally, real-world images can be rendered via several approaches: real-time video keying technology, where an algorithm removes the background and unwanted elements or keying through a depth map generated by multiple cameras. Except for video images, real-world elements could also be reconstructed either through point clouds (Nahon et al., 2015), polygon meshes (Orts-Escolano et al., 2016), or voxels models (Regenbrecht, Meng, Reepen, Beck, & Langlotz, 2017).

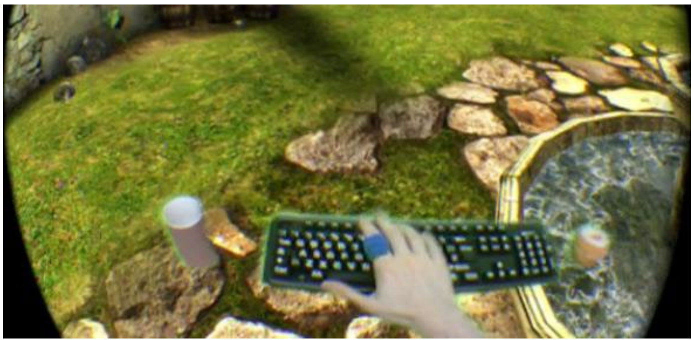

Fig. 2.6 A typical AV scene with the HTC Vive augmenting a real-world keyboard in a virtual world

On the other hand, AV using OST approach is usually overlooked. With the advance in spatial mapping technology and the development of large FoV of OST headsets, the OST headsets like Magic Leap and HoloLens have also become an option for AV applications. The concept of head-mounted OST approaches is to 3D scan and understand a real-world space and then reconstruct the environment via generating and mapping the virtual items like floor, wallpaper, ceiling, doors, windows and tables over the real-world space, thus allowing a virtual world environment to be overlaid on the real-world room. As the headset is optical see-through, real-world objects and elements that are not covered by virtual objects can be observed, such as the user's hands or certain physical items in the room.

HoloLens game Fragments (Studio, 2017) can be considered an AV experience. *Fragments*, a suspense & adventure narrative experience in HoloLens developed by Asobo Studio, is a good exploration and reveals HoloLens' potential in narratives. The AV technology in *Fragments* enriches the profound storytelling and presents more possibilities by integrating virtual characters, furniture, and objects into a real-life room or setting. In *Fragments*, HoloLens projects a complete virtual room over the real-world room, and the user can still see real-world sofa and chairs and interact with the virtual world directly using their hands (see Fig. 2.7). In fact, the boundary between AR and AV remains weak, and there is no exact borderline. A case like Fragments falls within the ambiguous area. From the perspective of Milgram's definition, the experience of Fragments can be considered an AV experience rather than AR to some extent. This classification is because the underlying environment experienced by the user is primarily virtual instead of the real world.

Fig. 2.7 Screen capture of *Fragments*: the room is accurately overlaid a virtual floor, wallpaper, and ceiling, which blends well with the real-world bookcase

Several studies showed that AV could achieve a more realistic simulation experience than VR by augmenting virtual environments with real-world objects. For example, Neges et al.(Neges, Wolf, & Abramovici, 2015) demonstrated the integration of real elements in a virtual environment projected through head-mounted displays to simulate stress conditions during maintenance task training better. Treepong et al. (Treepong, Wibulpolprasert, Mitake, & Hasegawa, 2017) developed an interactive face makeup system in which tangible makeup tools and a 3D face model are used. Enriching the virtual environment with real images and video was demonstrated for virtual design spaces as a means to make the design process more realistic (Wang & Gong, 2007). In addition, several researchers also investigated the user experience in AV. Regenbrecht et al.'s (Regenbrecht et al., 2003) example of an AV videoconferencing system and Pigny and Dominjon's (Pigny & Dominjon, 2019) VST-based AV demonstration showed that the meeting participants could feel physically closer to each other. Bergström et al. (Bergström, Kilteni, & Slater, 2016) and Yuan et al. (Yuan & Steed, 2010) have placed a real element in the form of self-embodiment into the virtual environment and measured the sense of presence. Both studies found an increase in presence by being able to match/link an element from real life into the virtual environment. However, compared to AR, little research has been conducted concerning AV, especially for the OST-based AV.

In fact, the AV experience has become another approach to the remote-site experience other than VR, where a room can be scanned by an OST-based headset to create a virtual environment that matches the real-world room while integrating real-world objects. The difference between an AV experience and a pure VR experience in user experience like presence, engagement and enjoyment deserves to be further investigated. Meanwhile, the possibilities and potentials of AV for remote experiences, such as immersive remote museums and immersive remote meetings, need to be revealed.

2.2. Interactive Narrative in Immersive Media

This section has three parts. The first part introduces theories pertaining to interactive narratives and proposes a model of an interactive narrative based on Chatman's theory consisting of audience agency, kernel, and satellites. The second part reviews several recent interactive narratives works in HMD VR and HMD AR. The third part summarises the interaction methods of narrative in HMD, introducing the mid-air hand interaction and presenting typical cases of GUI, TUI, and NUI.

2.2.1. Key theory and applications of interactive narrative

It is important to clarify the concept of the narrative as this laid the foundations for the following discussion. In his classic 20th-Century narratology, Espen J. Aarseth conclusively described a narrative and its constituent parts (Aarseth, 2012). As shown in Fig. 2.8, a narrative can be deconstructed into two elements: (a) a story that contains events and existents and (b) the discourse that refers to narration (the way story is told) and the sign chain (the media making a story manifest).

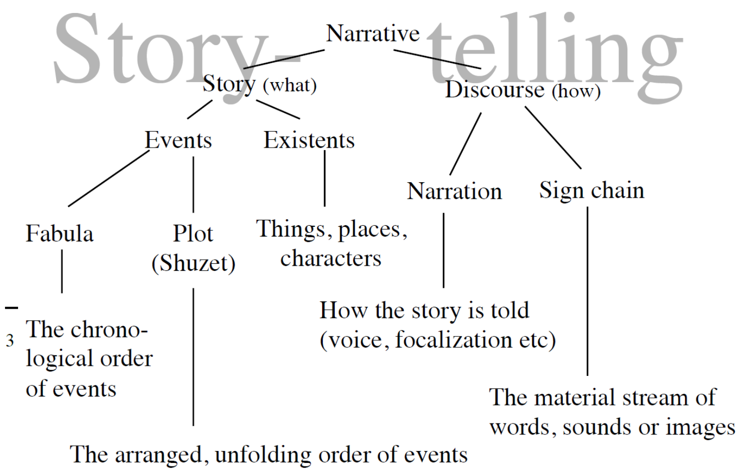

Fig. 2.8 A hierarchical model of narrative, a pragmatic synthesis of many theories

Interactive narratives refer to stories whose unfolding, pace and outcome can be impacted by interventions of a spectator or an entire audience. In existing studies, interactive narrative can be achieved via the autonomous agent, choice-based story graph (branching structure), narrative mediation (M. Riedl, Saretto, & Young, 2003), as well as environmental storytelling (Jenkins, 2004). Branching structure storytelling was made famous by the *Choose Your Own Adventure* (CYOA)[29] and is still prominent as a popular format for narrative videogames (J. T. Murray, 2018), such as the various titles developed by Telltales Games including *Walking dead*, *Wolf among Us* (Taylor, Kampe, & Bell, 2015), and more. In this format, players navigate a plot graph by making decisions at branching points in the narrative.

Apart from entertainment, interactive storytelling has also been incorporated into serious games focusing on topics such as history (Christopoulos, Mavridis, Andreadis, & Karigiannis, 2011; Song, He, & Hu, 2012), STEM (Danilicheva, Klimenko, Baturin, & Serebrov, 2009; Weng, Kuo, & Tseng, 2011), and bullying (Aylett, Louchart, Dias, Paiva, & Vala, 2005). Because branching structure interactive stories can promote audience empathy towards the protagonists (Hand & Varan, 2009a; Salter, 2016), an interactive storytelling approach could

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[29] A series of children's gamebooks with the reader assuming the role of the protagonist and making choices that determine the main character's actions and the plot's outcome

effectively change the perspective of users and provide a measure of moral education. However, the majority of research on educational interactive storytelling games has focused on interactivity (Song et al., 2012; Zhang, Bowman, & Jones, 2019), narrative planning and generation (Hodhod, Cairns, & Kudenko, 2011; M. O. Riedl, Stern, Dini, & Alderman, 2008; Zook et al., 2012), and the game creation process itself (Christopoulos et al., 2011). As a result, there is surprisingly little work assessing the impact of the interface for interactive narrative on learning outcomes.

There is an ongoing debate on the relationship between ludology, the study of games, (*ludus* in Latin principally means 'a game') and narratology. Even now, the boundary between game and narrative is remains vague and controversial. Nevertheless, the broad consensus is that they share a few key elements, namely a world, its agents, objects, and events. The agents can be presented as rich yet static characters (the narrative pole) or shallow and interactable bots (the ludic pole). In addition, agents within an Immersive EXtended Reality Environment (IXRE) have similarities to that in a game as a user is active and can make decisions in the environment.

In that vein, emergent narrative is another important notion popularised by Juul which is defined as, "unpredictable interactions and events emerging from the actions of a player guided by the games' rules or strategies" (Juul, 2002). Coincidently, some researchers have claimed these interesting occurrences are in fact a facet of narrative that—though perhaps not originally and purposely embedded within a specific story—can be retargeted to have a narrative experience for the audience after participation. For example, a ceramic pottery vase crafting workshop held in a museum would meet these criteria (Hall, 2018). This approach appropriates the concept of the emergence as seen in a typical video game: set a goal to create a vase, set the rule to use clay as the material and some handcrafting techniques offered by the museum as the method, then generate an unpredictable 'story' in which everybody can create their own vase with a unique procedure. However, we must critically examine the claim that if any interesting experience is an "emergent narrative," where does it end? With this logic, it becomes increasingly difficult to distinguish narratives from any other type of worldly experience. For example, an ordinary museum visit spent mainly observing collections presented in a showcase may also be analysed as a storytelling experience. Fortunately, Chatman posited a framework composed of the concepts of kernels and satellites (or constitutive and supplementary events), which are sensible for ending the above discussion. He claimed a kernel makes us recognise the story; take away the kernel and the story are no longer the same. Satellites, on the other hand, can be replaced or removed while still keeping the story in its recognisable form (Chatman, 1980). Thus, the missing piece separating a so-called emergent narrative from a life experience is the kernel, though an emergent story could be an ideal form for satellites. This is because the kernel is missing as the audience takes complete control of the agent. From this, the relationship between the kernel and the satellites regarding the audience's agency can be derived (see Fig. 2.9). In order to maintain the kernel of a story, there should exist a bespoke storytelling experience such as a linear, multipath, or branched story. A structured explorable open-world experience involves using a certain strategy such as setting up a goal to maintain the coherence of the audience interaction and thus support the kernel of a story. For example, a special exhibition about ninjas held in the National Museum of Emerging Science and Innovation in 2016 successfully unified the unconstrained visiting experience by setting a goal to collect credit for a ninja master badge, which at the same time also strongly reinforced its kernel story that consisted of several premade animations about ninjas (Innovation, July, 2016). As for this present project, *The AR Journey*, a branched story consisting Leo's parents' discussion and family-run shop shop after Kristallnacht.[30] is used as the kernel of the narrative experience, while keeping some interactive objects like newspapers, a radio, and some posters as the satellites to support the kernel (see Fig. 2.9).

[30] It is referred to as the Night of Broken Glass.

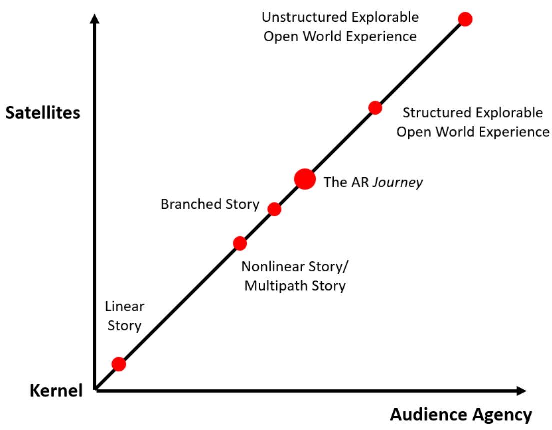

Fig. 2.9 Diagram of different designs of a game in terms of the kernel, satellites and audience agency

In conclusion, this section presents a heuristic perspective on arranging, unfolding and balancing events within a story. Narrative in an immersive environment should:

a) have a kernel or a bespoke story as a core, which could be a linear story, a multipath story or a branched story;

b) include satellites to reinforce the kernel;

c) use the strategy of game mechanics like goals, rules, rewards, and results to unify satellites into an integrated piece;

d) apply existing certified theories, including game flow theory (Schell, 2014) and the Job Demand-Control-Support Model (Karasek Jr, 1979), to better shape the story mechanics.

2.2.2. **Interactive narrative in HMD-based AR and VR**

As digital media technology advances, interactive narrative media has evolved from mediums like text, video, desktops, and tablet video games to immersive media like HMD-based VR and HMD-based AR. HMD AR and HMD VR are set apart from these other forms of media through two distinct properties. The first of these is *presence*, which refers to the subjective user experience of being in the virtual or mixed-reality environment rather than the actual physical locale (Witmer & Singer, 1998). Unlike the flat screen, HMD is a binocular device that allows users perceive the accurate size of an object and adapt to a large part of the user’s vision to generate an overwhelming sensory feeling.

The other feature is *agency*, which refers to the ability to “do something” within the experience — to interact or react rather than simply perceive. Agency is the core of the VR/AR experience because the Virtual Environment (VE) within the headset gives the audience the native agency of looking (Newton & Soukup, 2016). In other words, interaction is built into IXRE as a fundamental aspect because the audience would like to have more ability to interact with the environment rather than just look.

There are a number of VR narrative animations or films on the market. Visual masterpieces like *Lost*, *Henry and Dear Angelica* from Oculus Story Studio, *Rain & Shine, Buggy Night, Help*, and *Pearl*, from Google Spotlight, VR documentaries like *Nomads*, and VR feature films *like Manslaughte*r have achieved great success on the market. *Pearl* even won an Oscar nomination. However, most of them are timid and unimaginative in terms of screen grammar, employing either completely static shots or a continuous long take. Among those listed, the two most creative films are *Pearl,* which explores teleportation across space, and *Dear Angelica*, which employs the collision of intensive colour and abstract shapes to elicit emotions.

The use and study of AR as a narrative medium has been developing for a relatively long time. According to the interaction paradigm, early AR narratives can be classified into three types: Point of View (PoV) based exploration, space-based exploration, and ontological interaction (Shilkrot, Montfort, & Maes, 2014). PoV-based exploration gives user control at the point-of-view level. For instance, in the games *Mad Tea Party* (Moreno, MacIntyre, & Bolter, 2001) and *Three Angry Men* (MacIntyre et al., 2003), users can delve into the stories from different physical points of view. In space-based exploration narratives, users can examine either small props or prominent landmarks generated by the game and integrated within a real-world space (Barba, Macintyre, Rouse, & Bolter, 2010; Nisi, Wood, Davenport, & Oakley, 2004; Wither et al., 2010). Similarly, in the game *Inbox* (Barba et al., 2010), users can explore items with AR markers in a shipping container with a handheld device. Upon interactive with it, they can listen to the story of the container itself and the shipping container industry. Ontological interaction refers to interactions capable of altering the plot or the augmented narrative world, an approach exemplified by the HMD-based AR *Mad Tea Party* (Moreno et al., 2001) and *AR/Façade* (Dow, Mehta, Lausier, MacIntyre, & Mateas, 2006), in which users can alter the stories via speech or hand gestures.

However, few studies of interactive narratives using immersive AR exist. Early HMD-based AR, like *Mad Tea Party* and *AR/Façade*, can only overlay a flat 2D animation or live-action film onto a real-world environment, which does not allow users to move freely throughout the room and does not match the perspective of augmentation and the real world. Fortunately, as area-based tracking technology has advanced, particularly with the invention of HoloLens, 3D holograms can be augmented into a floor-scale real-world space seamlessly without any makers. In other words, HoloLens has presented new possibilities for 3D character augmentation in a room-scale real-world space for AR narrative. The HoloLens applications *Arnold* (Chinara, Feingold, Shanbhag, & Weiniger, 2018) and *Fragments* (Studio, 2017) are initial explorations of interactive narrative in HMD-based AR. *Arnold* is a linear story in which the protagonist dog can run in a physical room, seek out the audience, and play with them. *Fragments*, on the other hand, offers a room-scale mixed reality experience that shows four virtual characters walking and talking in a real-world room. It unfolds the story through user interaction through puzzle solving. However, the practice and research of narrative with HMD-based AR is insufficient, as the existing studies of AR narrative have focused on non-interactive linear stories and fragmented narratives while research on AR narrative with a classic branching structure remains scarce. Moreover, as an HMD AR device with head tracking and speech recognition features, HoloLens can completely free users' hands. However, this new freedom brings with its new challenges to user interface design.

2.2.3. **Interaction strategies for narrative in HMD**

Interaction controls are essential aspects of VR and AR experiences as both aim to provide interactive experiences in real-time. In practice, interaction controls are closely related to users' input devices. There are three main types of interaction approaches for AR HMDs: controller-based, hand-based, and hybrid-based (i.e., a combination of head pointing and hand gestures) (Xu, Liang, Zhao, Yu, & Monteiro, 2019). Hand-based input is the most common interaction method for wearable AR HMDs including HoloLens, Meta 2, Project North Star, and Magic Leap 1 since it is considered intuitive, natural, and cost-effective. In commercial AR HMDs like Magic Leap 1, users are tasked with performing a series of actions to select an object close to them, as they must first hover their hand over the virtual object, then perform a grab gesture to select it (Xu et al., 2019).

According to Bowman et al. (D. A. Bowman, McMahan, & Ragan, 2012), current natural interactions such as the mid-air hand interaction provide little additional productivity, and instead make a task more unnecessarily complicated. The main limitations of mid-air interaction in AR HMDs include limited precision with direct input on intangible surfaces (Szalavári & Gervautz, 1997), arm fatigue (Hincapié-Ramos, Guo, Moghadasian, & Irani, 2014), and an unnatural way of selecting a distant object (D. Bowman, Kruijff, LaViola Jr, & Poupyrev, 2004). Interactive narratives, however, are different from other applications as they do not usually require frequent operations like selecting, moving, and manipulating, the problems described above are not prevalent in interactive narratives. For AR systems, lack of boundary awareness could confuse, frustrate, and discourage users from using the system because misinterpreted gestures or movements that fall outside of the range may lead to unintentional actions and unresponsiveness, causing users to believe that the system recognition is flawed and unusable, thereby leading to an unpleasant experience. Often, visual hands or visual cues are used to alleviate the boundary awareness issue, such as placing a virtual hand mesh mapping on the user's hand or using a visual cue to label and track fingertips.

One of the vital tasks of interactive narrative in AR is creating an appropriate interface for interaction between the user and the mixed reality environments. Interaction in AR applications are mainly achieved using Graphical User Interface (GUI), Tangible User Interfaces (TUI), or Natural User Interfaces (NUI).

GUI in AR, also called 3D User Interfaces (3DUI), refers to direct interaction with virtual objects via controllers or gesture (D. A. Bowman et al., 2006). For instance, in *Fragments*, users can select, grasp, and manipulate virtual items and buttons via air tap gestures, the standard input for HoloLens. TUIs employ physical objects to express virtual entities and information, thereby bridging the physical and digital worlds. These interfaces support direct interaction with the real world by drawing upon real objects (Ishii, 2008). A classic example of tangible user interfaces is the VOMAR application developed by Kato et al.(Kato, Billinghurst, Poupyrev, Imamoto, & Tachibana, 2000), which enabled a user to select and rearrange the furniture in an AR living room design application with a real, physical paddle. NUIs, also known as multimodal user interfaces in AR, enables direct system control via natural human actions like talking or grasping using speech and hand recognition (Falcao, Lemos, & Soares, 2015). Control over a NUI does not require training as manipulating with a controller or an artificial physical object (e.g., a mouse or keyboard) is not necessary (Rafii & Zuccarino, 2014).

Several studies have been conducted on GUI (G. Evans, Miller, Pena, MacAllister, & Winer, 2017; Riedlinger, Oppermann, & Prinz, 2019) and NUI (Cavazza, Martin, Charles, Mead, & Marichal, 2003; Funk, Kritzler, & Michahelles, 2017; Zielke et al., 2017) with HoloLens. The existing GUI studies have primarily interface evaluation, while NUI studies have emphasized on the interface design and prototype. Though GUIs are more accessible and technically easier to develop, NUIs show more potential, especially in a narrative context (Zielke et al., 2017) , particularly given that several studies have considered NUIs of interactive narratives as an ambient interface (Billinghurst, Grasset, & Seichter, 2010). Since NUIs are supposed to ensure that users have seamlessly direct control over the mixed reality environment without intermediate interfaces, users are expected to have less distraction and more immersion in the story. In other words, NUIs should lead to better presence and narrative engagement in terms of an HMD-based AR narrative. However, there were no formal evaluations and comparative studies for NUIs with HoloLens, so whether NUIs positively impact the narrative in AR remains unclear.

2.3. Multimedia and Narrative based Holocaust Education

This section has three parts. The first part introduces significance and importance of Holocaust education and the role and challenges faced by the museums using digital immersive technologies. The second part presents the concept of empathy and how interactive narrative and immersive media could affect audience's empathy. The third part reviews other remote-site online museums, highlighting HMD VR related projects in the Rift store to address the current issues of accessibility to Holocaust education.

2.3.1. Importance and challenge of Holocaust education and museums

Holocaust education builds "civic responsibility through establishing caring, active, and educated citizens" (McBride, Haas, & Berson, 2014). Learning about the Holocaust will "elicit strong emotion" and require those who interact with it to reflect on their own thoughts and perceptions of the event (McBride et al., 2014). Holocaust education can also strengthen students' historical empathy, which is defined as "the process of cognitive and affective engagement with historical figures to better understand how people from the past thought, felt, made decisions, acted, and faced consequences within a specific historical and social context" (Endacott, 2014). Social studies teachers can leverage students' emotional reactions through a process of inquiry, action, and reflection that aids learners' ability to make "self-to-other connection[s]" (Endacott, 2014). By reflecting on the past and looking towards the future, Holocaust education promotes citizenship, historical empathy, social justice, and our ethical and moral obligations as human beings. The teachers surveyed taught the Holocaust through various perspectives, but human rights was the most popular approach selected over the other choices of "historical, literary, religious, or geographic perspectives" (Donnelly, 2006). Books based on personal accounts, such as *Night and Anne Frank's* Diary, were tied with films as the most common methods of teaching the Holocaust, with primary source photos, survivors' testimonies, and documentaries were the other popular choices (Donnelly, 2006).

Narratives have proven to be a powerful method for eliciting empathy by encouraging perspective-taking and emotional engagement (Busselle & Bilandzic). Many researchers support the claim that there is a positive association between empathy and prosocial behaviour (Hoffman, 1984; Saarni & Crowley, 1990). Given these results, NHCM is one of the few museums employing the narrative technique to unveil history and encourage young generations to carefully examine, commemorate, and learn from the tragedy of the Holocaust. *The Journey*, one of its permanent exhibitions, tells a story using environmental storytelling techniques through the eyes of a fictional Jewish boy Leo who survived the Holocaust and came to the UK via the Kindertransport. Six rooms are restored to show what Jewish life looked like in pre-war Germany, including Leo's family living room, Leo's classroom, the street after the Night of Broken Glass, the tailor's shop run by Leo's family, a train carriage of the Kindertransport, and a refuge in the UK. In each room, the audience can watch a short video of Leo giving a monologue of what he saw, heard, experienced and felt at that time. The visitors can experience the complete story by gradually going through each room, interacting with objects, and watching videos. While *The Journey* is a text free and tactile exhibition designed with a young audience in mind, most visitors experience *The Journey* as part of their visit.

The major challenges of *The Journey* exhibition are identified according to the NHCM website (Obama & Biden, 2013), other relevant literature (Nikonanou & Bounia, 2014) and the authors' observation on site:

- Inclusiveness: *The Journey* was designed initially as a group visit experience for a young audience with a tour guide. Thus, the storytelling may feel plain and shallow for individual adult visitors.
- Accessibility: The NHCM is located far from the downtown area of a small city with limited public transportation. Thus, in this setting, it is difficult to make the learning experience accessible in the widest range of places and formats, continually reach new audiences, and provoke attitudinal change across all communities.
- Attractiveness: As younger generations have a preference for modern interactive methods derived from their evolving personal technologies (Best, 2012), storytelling via interactive digital technologies such as video games, VR, and AR could be more effective and appealing.

Many museums are aware of the use of modern digital technologies, particularly immersive technologies, to tackle the above issues. However, several scholars have pointed out that the use of immersive technologies in museums is challenging and poses difficulties in the following four aspects:

First, there are fewer potential users, especially for small, rural museums. Falk (J. H. Falk, 2016) points to experience seekers as a coveted audience for museums, who are often digitally savvy and happy to consume novel experiences. But they tend to gravitate towards urban centres, posing a serious challenge to museums located in the rural areas.

Second, it is easy to overlook collaborative design in the development of projects. Developers are easy to focus on technical and design issues, but in the context of museums, developers must co-design with museums and partners, moving away from a more authorial, artist-led approach to a more community-based approach (Olesen, 2015). Using regular co-design meetings to engage each stakeholder of heritage and creative industries sectors, rather than each working in parallel. Let each stakeholder make contribution to the project from his/her own unique perspective.

Third, it is possible to get misguided immersion of consumer-focused distraction (Prior,

2006) that is far from educational in intention. Champion (Champion, 2005) proposed to create something more than simply a bit of virtual spectacle, instead to develop an "experiential learning mechanism". Mosaker (Mosaker, 2001) suggested the importance of ensuring the authenticity of the immersive museums. Tanya et al. (Krzywinska, Phillips, Parker, & Scott, 2020)concluded in their *Augmented Telegrapher* project by adopting a gaming and narrative approach that engages the audience and helps bridge the gap between entertainment and education and employing a constructivist model of education in an experiential, participatory/game-based design process.

Fourth, it's easy to fall into traps of digital technical complexity which may distracts from the core values of the museum (Krzywinska et al., 2020). Complex technologies usually have high development costs and high maintenance costs, outstripping the affordance and resources of small museums. Besides, some museum staff may feel anxious and excluded about adopting new, unfamiliar technologies. Therefore, the use of complex technology should be avoided wherever possible. Meanwhile, museum staff should be involved in the development and discussion process, which may alleviate their anxiety and familiarise them with the final equipment installation.

In addition, as the Holocaust is a sensitive educational subject, ethical guidelines must be followed when using new technologies for Holocaust application development. In one study, Challenor et al. reviewed previous AR apps in Holocaust museums and memorial, as well as a series of studies on the usage of AR for Holocaust education to ethical guidelines (Challenor & Ma, 2019). These guidelines include creating realistic depictions of history to ensure complete accuracy, avoiding turning interactive elements into gameplay features, eliminating possibilities that allow for empathetic substitution, and keeping content appropriate for the learning experience instead of traumatising the learner (Challenor & Ma, 2019).

2.3.2. Empathy from interactive narrative using immersive media

Feshbach's model (Feshbach, 1975) suggested that empathy has three interrelated processes: a) the ability to discriminate and identify the emotional states of others. b) the ability to take the other person's perspective or role, and c) the ability to evoke a shared emotional response. Shen (Shen, 2010), on the other hand, revealed three distinct components of state empathy:

emotional empathy which refers to one's personal emotional response to the experiences and expressions of others; *cognitive empathy* which involves the perspective-taking through which a person understands and adopts another person's thoughts; *associative empathy* which is the sense of social bonding with another person and the functional base of empathetic response (Decety & Jackson, 2004). In the media context, Shen (Shen, 2010) considered empathy close to identification (Cohen, 2001), the process by which the audience experience the events that take place on the characters in the narrative. Neil also identified that “In empathizing with another whether she be real or fictional, one imagines the situation she is in from her point of view” (Onega & Landa, 2014).

The positive connection between empathy and inclusive and moderate personality and pro-social behaviour is discovered by several scholars(Findlay, Girardi, & Coplan, 2006; Warden & Mackinnon, 2003). Besides, some educators argued that there is a reciprocal relationship between the reading process and empathy. Especially, reading helps to enhance and strengthen empathy (Budin, 2001; Cress & Holm, 1998) while children who have better empathy are able to have the better reading ability by placing themselves in the protagonist in the book. In addition, Hand et al. (Hand & Varan, 2009b) suggested a range of strategies to enhance empathy, including encouraging students to understand different individuals or groups’ perspectives and feelings, highlighting similarities between individuals and groups with different cultures, appreciating characteristics of individual’s own background and ethnicity, and inspiring them to link the learning material to their own personal experiences. In section 2.3.1, Holocaust education is also regarded as an effective approach to strengthening students’ empathy (Endacott, 2014).

Empathy is considered to be intrinsic to audience enjoyment in linear narratives (Zillmann, 2006). Vorderer et al. (Vorderer, Knobloch, & Schramm, 2001) proposed that empathy may actually be negatively affected if the audience is allowed to interact with the narrative, arguing that making interactive decisions may distract the audience from enjoying empathy pressure." Vorderer et al. (Vorderer et al., 2001) explained the empathy pressure as follows: "Whenever audience cares about fictional characters in dramas, they not only want a positive outcome for the protagonist and fear a negative ending, they also share all the emotions with the character as a result". However, Hand et al. validated that interactivity can help to increase audience empathy (Hand & Varan, 2009b), as long as the narrative structure is maintained, which in turn ensures the empathy pressure.

Immersive media, represented by HMD VR and HMD AR, can more easily produce self-locate presence, contributing positively to the affective and associative dimensions of empathy. According to embodied cognition (Varela, Thompson, & Rosch, 2017), individuals are expected to be more likely to experience others' situations when they perceive themselves as occupying the same environment and scenario as the others, i.e. more probable to identify with the figures in the immersive media. Beyond offering an embodied experience, the empathy-inducing potential of immersive media may directly relate to their capacity to aid in perspective-taking (Herrera, Bailenson, Weisz, Ogle, & Zaki, 2018). Compared with video stories on flat screens, immersive media can reduce the effort required to imagine someone else's immediate circumstances and their resulting thoughts, feelings, or actions. In turn, immersive media may be especially apt means by which to enhance cognitive empathy in particular. Recent research further supported the above assumption that HMD-based 360°video rather than a tablet was associated with higher levels of presence and empathy (Fonseca & Kraus, 2016; Schutte & Stilinović, 2017). Immersive virtual environments make it easier to build empathy with the characters in the narrative. It is important to note that AR and VR environments should be used as opportunities for situated learning, negotiating meaning with learners rather than dictating meaning or asking students to find meaning entirely on their own (Mei & Sheng, 2011).

In summary, empathy is a complex hybrid concept and the author adopted Shen's definition of empathy as the ability to take the perspective of another person and emotionally connect with them. Empathy is proven to play a key role in young people's learning abilities, and moral and personality development. Scholars also identified a number of approaches to teaching empathy, of which Holocaust education using interactive narratives has great potential. The review showed that narrative structure should be maintained so that the interaction won't become a distraction to the audience's empathy in the interactive storytelling of the Holocaust. Meanwhile, immersive media such as HMD VR and HMD AR can probably help the audience to gain more empathy and thus lead to more learning outcomes.

The aim of the interactive narrative for NHCM using immersive media is to allow students to construct deeper meaning in the content while developing observational skills. By building an understanding of social, ethnic, and culturally inclusive contexts in the virtual history environment settings of the Holocaust, this can be transferred to other periods in history and other parts of the world. For example, through the NHCM's XR journey project, learners can consider why some ethnic minorities and their friends have suffered social injustice.

2.3.3. **Remote-site online museum**

Presently, other major museums have also begun to offer VR experiences, such as the Forbidden City Museum, the Louvre, and the British Museum. These institutions often use 360°video or 3D modelling to exhibit their collections, architecture, and display spaces through the internet, allowing users to virtually navigate specific places within the museum using a keyboard and mouse and thus gain richer information through interaction within their own home. For example, in *The V Forbidden City* project, virtual interpreters explain the importance and history of the emperor’s bedroom, after which users are prompted to answer multiple-choice questions, solve puzzles, and collect props. Due to advances in computer graphics and the growing popularity of smart mobile devices, the trend in non-immersive VR is to use WebGL technology to allow programs to run in browsers and mobile devices. For example, the author of this paper previously developed a porcelain app titled *Charm of Celadon* [31]that allows users to learn celadon patterns, create their own designs, and preview the final result on a typical Chinese ceramic vessel on their mobile phones.

The applications on the rift store such as this that are relevant to our research can be sorted into three categories: “history”, “narrative”, “museum”. According to the statistics of our analysis (see Fig. 2.10), of the applications that we sorted, there were 73 narrative applications, 58 history-related applications and 39 museum-related applications. Within these categories, VR applications for museums can be further sorted into five groups based on their design concepts: 3D replicated real-world museum (n=10), 360° film or animation (n=10), creative virtual museum (n=15), VR exclusive art museum (n=2), and interactive narrative(n=2).

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[31] The introduction of this project can be found in the following website: https://mp.weixin.qq.com/s/pSps_HJIpTcDSXBUDHDhxw

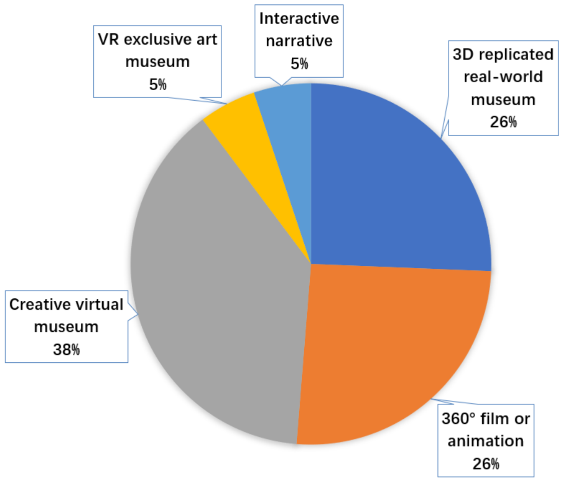


Fig. 2.10 The five groups of VR applications for the museum in the rift store

The first of these, 3D replicated real-world museum, is simply a digital reproduction of a 3D model of an actual museum or a virtual museum based on an actual museum, such as *The Virtual Museum De Fornaris* and *The Grand Museum VR*. The former project shows 70 masterpieces from the De Fornaris collection exhibited in a digital hall (see Fig. 2.11), while the latter project presents users with 3D-scanned virtual relics from all over the world. The second group, film or animation, uses 360° film or animation to present museums or heritages, typified by *Pompeii*, using 360° video to show the most famous ruins of Pompeii, Italy (see Fig. 2.11). The third group, creative virtual museums, is often based on the re-creation of museum exhibits or the restoration of relics rather than simply a digital reproduction of real-world exhibits. A typical example is *Dreams of Dali*, which recomposed elements from Dali's paintings into a whole new immersive experience of appreciation (see Fig. 2.11). The fourth group, VR exclusive art museum, creates and displays new artworks based on the unique cyberspace and media of VR. For example, *The Museum of Other Realities* contains a growing collection of interactive art and experimentation using VR as a medium, such as stepping into a painting, floating through abstract worlds, surrounding yourself with fantastic sounds, and experiencing art as it evolves and takes the form (see Fig. 2.11). Finally, the fifth group, interactive narrative, is an approach exemplified by the *Anne Frank House VR*, which employs an environmental narrative to allow the user to return to the room where Anne and eight other Jewish people were hiding from the Nazis and learn their story (see Fig. 2.11). Anne's story was told entirely through the furnishings and clues in the room, without the presence of characters.

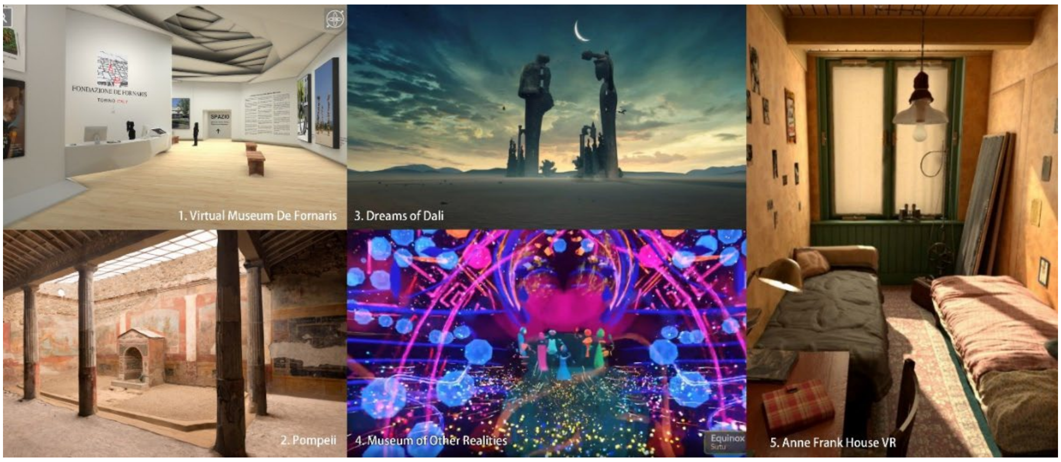


Fig. 2.11 Typical Examples from the Oculus Store

Chapter 3: Realism, User Experience and Storytelling in Extended Reality

This chapter focuses on the models and the theoretical concepts for HMD-based EXtended Reality Museum (HXRM). As photo-realistic CG characters play a critical role in HMD-based XR museums, section 3.1 proposes the uncanny valley framework for creating realistic CG characters in, which could guide the design and development of the application. In addition, as the focus of this study is about user experience in immersive new media, section 3.2 proposes a user experience model for HMD-based immersive museums that combines several theories and prior findings to extend TAM with four external factors from the features of HXRM. Finally, section 3.3 summarises interactive narrative types, strategies, and structures, and sets the interactive narrative design scheme for *The Extended Journey*, the HXRM application.

3.1. A Framework of Uncanny Valley for Realistic CG Characters

This chapter aims to build an uncanny valley framework to create a photorealistic CG character and define the dimension of human likeness for said character. Based on the perceptual mismatch hypothesis and the fourth wall theory in film, media immersion and characters' intelligent behaviour are introduced as new factors into the framework. From this, it is predicted that the new factors would modulate the uncanny valley effect.

3.1.1. The concept of uncanny valley

Uncanny valley was first proposed by Mori Masahiro in his research of robots (Mori, MacDorman, & Kageki, 2012) and has been confirmed by many subsequent researchers. The uncanny valley exists not only in life-like robots and prostheses but also in virtual people and virtual animals. Today, the uncanny valley is an actively discussed topic in research on human-robot interaction (Brenton, Gillies, Ballin, & Chatting, 2005; Burleigh, Schoenherr, & Lacroix, 2013), video games (Schneider, Wang, & Yang, 2007; Tinwell, Grimshaw, Nabi, & Williams, 2011), animated movies (Kawabe, Sasaki, Ihaya, & Yamada, 2017), psychology (Cheetham, Pavlovic, Jordan, Suter, & Jancke, 2013), and philosophy (Misselhorn, 2009). Mori Masahiro assumed that adding human-like attributes to robots increases people's positive emotional response toward them. However, when robots, dolls, or prostheses reaches a threshold point of human likeness, i.e., when they look similar to humans but not the same, their appearance can produce negative feelings or a sudden dip in that correlation between human likeness and acceptance by people. He mentioned zombies and puppets as examples to explain the uncanny valley concept.

3.1.2. An interpretation of the uncanny valley for CG characters

First, it is necessary to distinguish between a stylised character and a photorealistic CG character. Because several different factors can influence the quality of a stylised character, a character's affinity cannot be constructed simply upon the dimension of human likeness. There are design rules for the stylised character, such as a simplified and distinguished silhouette, exaggeration, and the rhythm of the straight lines and curves of their form. Second, with the development of HMD-based VR and AR, real-time photorealistic CG characters are the key to ensuring effective interaction between characters and maximising the benefits of HMD devices. Therefore, this study focuses on photorealistic CG characters and uses human likeness as its primary factor for addressing the uncanny valley issue.

3.1.3. Human-Likeness and affinity

According to Mori's research, human-likeness is not a single quality of artificial characters that could be traced back to specific static, dynamic, or behavioural features. Instead, he labelled the hypothetical human-likeness levels corresponding with the selected examples from L1 to L4 (see Fig. 3.1). In the categories, Mori used industrial robots to exemplify the least human-like characters (L1), stuffed animals and toy robots to exemplify characters that have a human-like appearance but are artificial (L2), prosthetic hands or zombies to exemplify characters that appear human-like but are not wholly the same because of some artificial qualities (L3), and healthy humans to exemplify full-human-likeness (L4). However, this definition is not fully applicable to realistic CG characters animated in real-time, as they are more complex and require three additional factors to constitute human likeness: appearance, motion, and sound. Appearance refers to the static outward facade of a CG character, including their head, facial features, body, clothing, and more. The quality of their appearance is mainly dependent on the visual realism of their structural proportions, the shape of the model, the texture and shading of the material, and the lighting and resolution of the rendering. The motion refers to the animation of a CG character, including their expression animation, body animation, and clothing simulation. The quality of motion is mainly defined by timing and rhythm, using the human body movement principle and rules of physical simulation. Sound refers to the voice and sound effects of a CG character. The sound quality is determined by how well the voice matches the tone and pitch of the CG character's identity and how realistic the sound effects are.

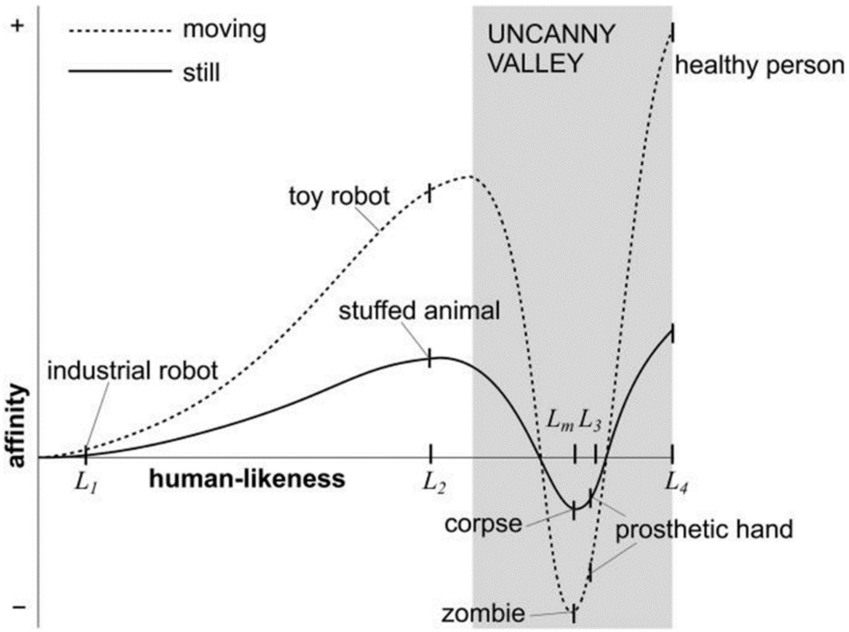


Fig. 3.1 Mori's uncanny valley curve demonstrates the non-linear relationship between the human-likeness (from "artificial" to "fully human-like") and the perceived affinity (from negative to positive) (MacDorman, 2005).

Fig. 3.2 demonstrates a spectrum of the CG character ranged from artificial side to photorealistic side. However, there is the issue of whether the human-likeness dimension of the uncanny valley is perceived continuously or categorically. This is particularly true for a more explicit definition of human likeness containing motion, as it would be difficult to place a photorealistic CG character with a discordant quality of different human likeness factors on a continuum of human likeness, e.g., a character with a high quality of appearance but with rigid animation. Therefore, human-likeness could be perceived as a discrete continuum within the artificial and human categories.

Fig. 3.2 The protagonist of the video game *Tomb Raider* from 1996 to 2018

Categorical perception, an empirically and theoretically established construct in psychology, has been applied to the uncanny valley model in recent empirical studies (Cheetham, Suter, & Jancke, 2014; Cheetham, Suter, & Jäncke, 2011). In these studies, the categories can be divided into artificial and human categories for the photorealistic CG character. Since the new generation of digital natives generally has some video game experience and knowledge of digital technology, the classification can be refined into three categories: decades-old game characters, modern commercial game characters, and humans. The decades-old game character refers to low-quality photorealistic CG characters (see picture 1 of Fig. 3.3), featuring low-poly, plain lighting and materials, low-resolution textures, and simple animation that, though consistent with the animation principle, lacks detail. The modern commercial game character refers to a high-quality photorealistic CG character (see picture 3 of Fig. 3.3), characterised by high-poly, PBR materials and lighting, and natural body motions with some facial expressions. However, the appearance and expressions of the character are still distinctly different from those of real human beings. A character of high-quality modelling and motion but with simple lighting and materials (see picture 2 in Fig. 3.3) could be considered between the categories of decades-old and modern commercial game characters. It is important to note that artificial and human categories are discrete rather than continuous, with some ambiguity between each of the two adjacent categories. A character with an ultra-realistic appearance that is very close to real human beings but has stark expressions animation (see picture 4 in Fig. 3.3) could be perceived as something between a modern commercial game character and a real human being.

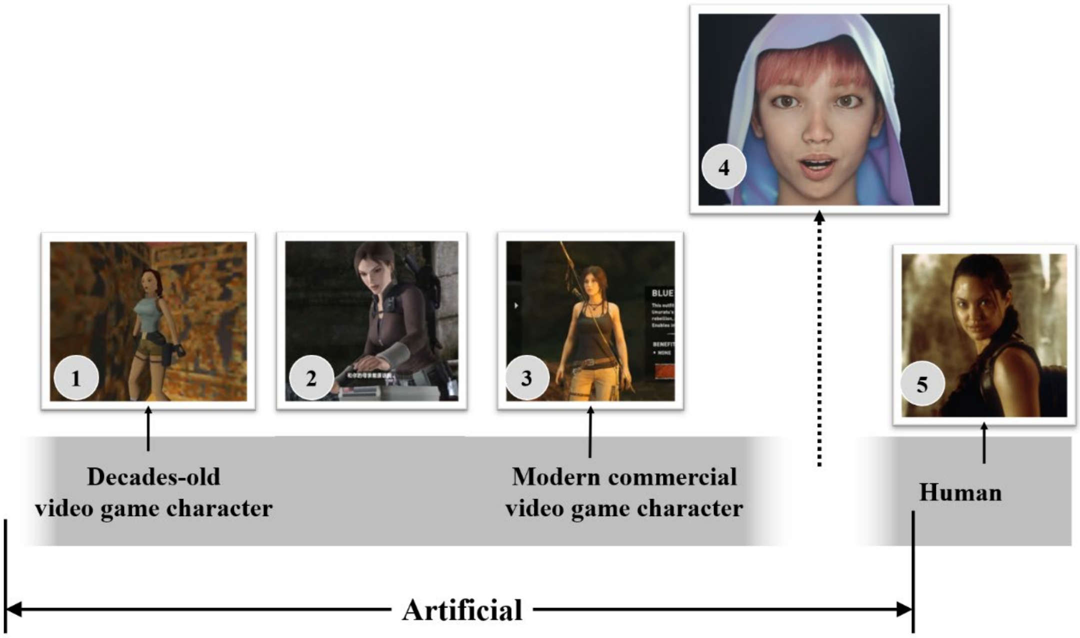


Fig. 3.3 Three categories of human likeness[32].

Mori's original Japanese terms bukimi and shinwakan (or shin-wakan) referred to several different concepts for the affinity dimension. The negative term bukimi translates quite unequivocally into "eeriness" (Ho & MacDorman, 2010), although other similar terms such as repulsion and strangeness have also been used (Moore, 2012). In contrast, the positive term shinwakan is an unconventional Japanese word which does not have a direct equivalent in English (Bartneck, Kanda, Ishiguro, & Hagita, 2007, 2009). The earliest and the most common translation of this term has been "familiarity"; however, it has been argued that "likability" may be a more appropriate translation. In the latest English translation of Mori's original article, shinwakan was translated as "affinity" (Mori et al., 2012). Upon closely inspected the terms of affinity, Kätsyri et al.(Kätsyri, Förger, Mäkäräinen, & Takala, 2015) found that they refer to various aspects of perceptual familiarity and emotional valence. Perceptual familiarity

[32] Picture 1 displays a CG character from the video game *Tomb Raider* (1996), Picture 2 displays CG character from *Tomb Raider: Underworld* (2008), Picture 3 displays a CG character of the video game *Shadow of the Tomb Raider* (2018), Picture 4 displays a real-time character's expression capture demo from Facegood Co. Ltd., and Picture 5 displays an image of the actor playing the character in the shown in the previous pictures in the film *Lara Croft: Tomb Raider*.

is defined as recognising that the perceived character has similar qualities as another object the observer is already well acquainted with, possibly, the observer themself. Emotional valence covers various positive (liking, pleasantness, and attraction) and negative (aversive sensations) emotions the character elicits. Therefore, Kätsyri et al. proposed using emotional valence and perceptual familiarity as the two constituent elements of affinity.

3.1.4. Perceptual mismatch hypothesis and media's immersion

Unlike robots or wax statues, though there are a few scenarios for a completely static photorealistic CG characters, animation and sound are an integral part of a CG character. Therefore, for a CG character in real-time rendering, their level of human likeness is constituted by three sub-dimensions: appearance, motion, and sound (see the lower part of Fig. 3.5). As discussed in section 3.1.3, the degree of human-likeness of a realistic CG character refers to how close the synthetic result of their appearance, motion, and sound is to that of a real person.

One of the most influential hypotheses on the causes of the uncanny valley is the perceptual mismatch hypothesis. This hypothesis suggests that negative affinity could be caused by an inconsistency between the human-likeness levels of specific sensory cues (MacDorman, Green, Ho, & Koch, 2009; Pollick, 2009). Based on this, there are three perspectives to understand the inconsistency. The first is based on the inconsistency within every sub-dimension of human likeness. There may be incoherence and inconsistencies within appearance, motion, and sound. Artificial eyes on an otherwise fully human-like face—or vice versa—are examples of such inconsistency within appearance. The second perspective is an inconsistency between different sub-dimensions. Typical examples are the dissonance between the appearance and motions of realistic CG characters. For example, several researchers found that negative affinity would be caused if the characters' were static (Brenton et al., 2005; Pollick, 2009). The third perspective of perceptual mismatch is higher sensitivity to deviations from typical human norms in more human-like characters (Brenton et al., 2005; MacDorman et al., 2009). For example, deviations from human norms could result from atypical features such as grossly enlarged eyes. In the context of the uncanny valley, a plausible explanation for this phenomenon could be that the human visual system has acquired more expertise with the featural restrictions of other humans than with the featural restrictions of artificial characters (Seyama & Nagayama, 2007). This hypothesis is consistent with previous studies demonstrating that faces with typical or average features are considered more attractive than atypical faces (Jones et al., 2001; Langlois & Roggman, 1990). Kätsyri et al. found support in previous work for the perceptual mismatch hypothesis, which predicts that humans are more sensitive and less tolerant to deviations from typical norms when judging human faces(Kätsyri et al., 2015). In summary, the perceptual mismatch hypothesis proposes that inconsistent levels of realism within or between the sub-dimensions of appearance, motion, and sound in CG characters, as well as atypical features, represent different conditions leading to the uncanny valley.

Due to the rapid development of immersive technologies such as HMD-based AR and VR in recent years, photorealistic CG characters are no longer only presented on flat screens but can now be found in HMD-based immersive media. Immersion within the medium itself has a significant impact on the uncanny valley effect. A more immersive medium leads to a more realistic audio-visual sensory experience, which could amplify those sensory dissonances. The amplified sensory mismatches can thus result in more negative affinity based on the perceptual mismatch hypothesis. Moreover, HMDs usually allow the audience to move and observe freely within a virtual scene, making it easier to spot issues that could otherwise be masked by shot perspective and compositions on a flat screen. For example, in HMD VR, users are more likely to notice abnormal height, unnatural expressions of CG characters, animation flaws where arms are crossed into the body, or culling issues where the model appears empty at a certain angle. Thus, the level of media immersion modulates the uncanny valley of photorealistic CG characters (see Fig. 3.5).

3.1.5. Categorical perception hypotheses and CG characters' intelligent behaviour

The categorical perception hypothesis, which is theoretically independent of the perceptual mismatch hypothesis, has been presented in recent literature as another explanation for the uncanny valley phenomenon. Loosely speaking, categorical perception refers to the phenomenon where the categories possessed by an observer influence their perceptions (Goldstone & Hendrickson, 2010).

Specifically, categorical perception occurs when the perceptual discrimination is enhanced for pairs of perceptually adjacent stimuli straddling a hypothetical category boundary between two categories and decreased for equally spaced pairs belonging to the same category (Harnad, 1987; Repp, 1984). Applied to the uncanny valley, categorical perception would mean that "[. . .] irrespective of physical differences in human-like appearance, objects along the degree of human-likeness are treated as conceptually equivalent members of either the category 'non-human' or the category 'human,' except at those levels of physical realism at the boundary between these two categories." (Cheetham et al., 2011). The declining affinity region lies between humans and non-humans and may otherwise be thought of as the region where the two categories are blurred. Depending on personal and game experience, each person's categories and classification criteria will be different. For example, for a low-poly character with a rough texture and poor lighting effect, some people may classify it as a decades-old video game character. In contrast, others may classify it as a modern commercial video game character similar to the characters of Telltale's interactive narrative *The Walking Dead* (see Fig. 3.4). Therefore, their categorical perception could explain why individuals vary significantly in terms of their perceptions of uncanny valley and how individuals' own experiences influence their perceptions of CG characters.

Fig. 3.4 Screen capture of Telltale' s interactive narrative *The Walking Dead*

The intelligent behaviour of CG characters is another aspect that cannot be overlooked and one that is a new challenge for HMD-based new media. The typical behaviours of intelligent interactive CG characters include gazing and finding. For example, when a CG character interacts with an audience, the character can look for the audience, walk towards them, talk to them face to face, and gaze into their eyes. Due to the inherent interactivity of the HMD medium, the audience can move freely and even get a close face-to-face distance from the CG character. However, if the CG characters do not act naturally like a real person does, and do not look at the audience at all, it is easy for the audience to realise the existence of the fourth wall, in that they are in a different time and space from the CG characters. Conversely, if the characters can behave intelligently by using eye contact and act naturally, it can help the audience maintain the illusion that they are in the same time and space as the CG characters, thereby increasing the audience's presence. In addition to eye contact, intelligent photorealistic CG characters can use natural body language to communicate, dynamically adjusting their position and orientation as the audience moves and even giving feedback to the audience's gestures and reactions.

Therefore, the intelligent behaviour of the photorealistic CG characters also modulates the uncanny valley effect (see Fig. 3.5) by enhancing the affinity of the audience who have not yet entered the descent curve of the uncanny valley while increasing the negative feelings of the audience who is in the descent curve of the uncanny valley.

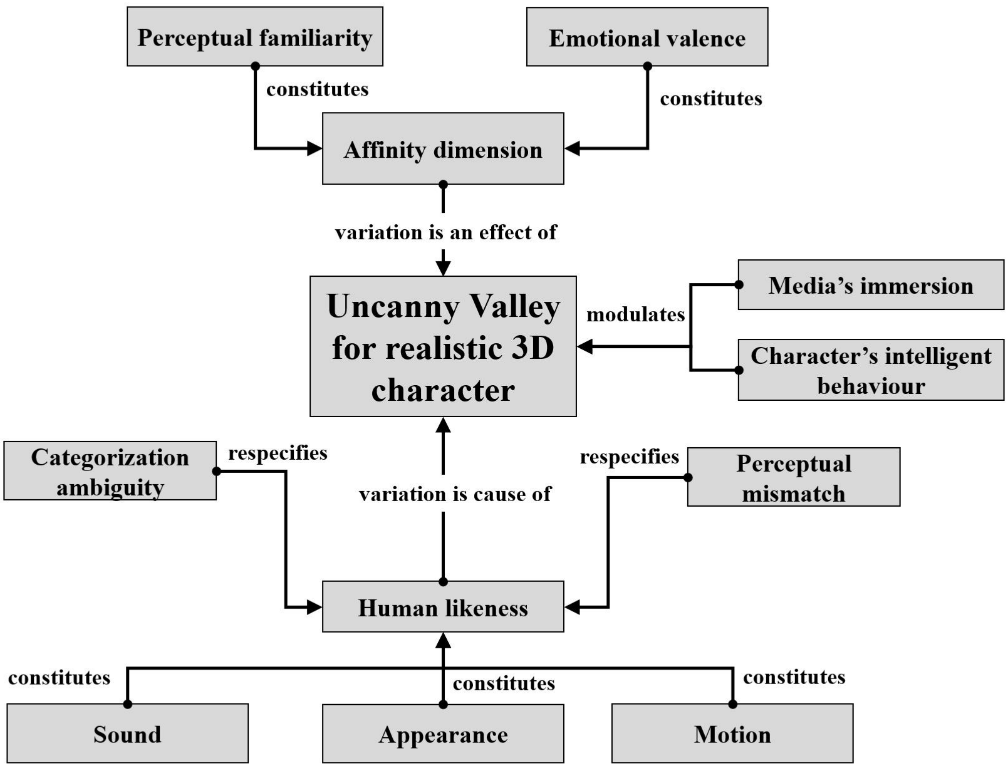


Fig. 3.5 Framework of uncanny valley for realistic CG characters

3.2. Model of User Experience for HXRM

One of the consequences of COVID-19 pandemic is that daily life has changed dramatically. During periodical lockdowns and the need to stay at home, e-services have filled the gap by providing opportunities for visitors and a substitute for standard existence (Gutowski & Kłos-Adamkiewicz, 2020). For example, a digital museum service has become an engaging tool for promoting culture and disseminating knowledge that is particularly effective for visitors (Gutowski & Kłos-Adamkiewicz, 2020). Moreover, HMD-based immersive museums can be potentially more powerful media with the appeal new VR and AR technologies than traditional website-based digital museums. As a result, for such an emerging museum using immersive media, it is crucial to examine what constitutes the user experience and how the user experience works.

3.2.1. User experience theory

The international standard ISO 9241-210 defines user experience as "people's cognitive impression and response to the products, systems or services they use and expect to use". Because of the subjectivity of the user experience, it is difficult for researchers to observe the whole process objectively. Therefore, they build factor models to test user experience from different dimensions. For example, Vyas et al. (Vyas & van der Veer, 2005) used an interaction-centric approach to propose the Aesthetic, Practical, Emotional & Cognitive (APEC) model. Beginning from the 1990s, increasing investments in user research began to emerge with an emphasis on the international stage design in a field called "emotional design", which sought to investigate and understand the role of emotions in the relationship between man and objects. Emotional design is a holistic approach to the needs and desires of the user rather than a mechanism for handling their experience (Tonetto & Xavier da Costa, 2011), and an essential foundation of emotional design is Maslow's hierarchy of needs (McLeod, 2007).

Donald Norman provided an insightful analysis of user experience from the perspective of emotion and information processing. According to the Donald Norman theory (Norman, 2008), there are three levels of processing of the human brain that operate continuously in our relationship with objects. Transporting levels for the universe of design suggest specific strategies to work with each of them in particular ways. The levels are as follows:

- Visceral level: preconscious automatic layer linked to the appearance forms first impressions about the object. This layer is related to physical aspects (physical sensation, texture and weight of materials) and the first impression of a product;
- Behavioural level: the layer that controls the behaviour related to the use and performance of the object or system. It is also associated with function, ease of understanding of the product, usability, how the user physically feels while using it, and its effectiveness and efficiency;
- Reflective level: the conscious and contemplative part of the brain that considers the rationalisation and intellectualisation of something. It is related to a subjective point of view, covering cultural and individual characteristics, affective memory, construction of meaning, self-image, personal satisfaction, and memories. Designing this level requires embedding meanings to products, such as fun and satisfaction.

The interaction with artefacts reflects the three levels of design in different ways: some objects are enjoyed only based on the visceral impact of their appearance (visceral design), some are enjoyed solely based on their function and use (behavioural design), and others to create an image of self-confidence, identity, and fun (reflective design). The levels comprise the human brain structures ranging from the lower layer (sensory) to the more complex and higher layer (reflection). Therefore, the reflective design can extend much longer, thus providing long-term relationships and a more profound and long-lasting impression than visceral and behavioural design (Norman, 2008).

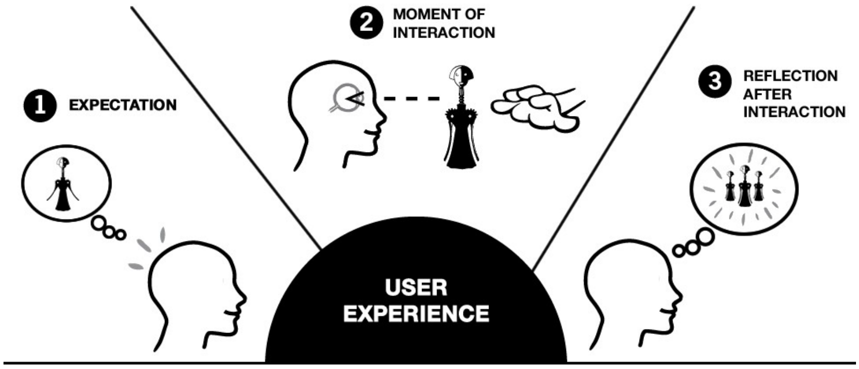


Fig. 3.6 Flow of user experience proposed by Nascimento et al.

By combining the Donald Norman theory with Patrick Jordan's pleasure theory (Jordan, 2002), Nascimento et al. (Nascimento, Limeira, de Pinho, & Santa Rosa, 2014) proposed a new user experience model which included the three stages of expectation, interaction, and reflection while considering the user's cognitive, psychological, emotional, and cultural contexts (see Fig. 3.6). The user experience is the totality of effects felt internally by a user as a result of the interaction which can start even before visual contact due to possible expectation or idealisation, as well as during and after the interaction, where after use reflections on lived experience occur. Therefore, the user experience is related to the cognitive, physical, and emotional processes, while also depending on the context of use and variables such as the temperature range of environment, lighting, noise, social relations, and more.

3.2.2. Expectation stage

According to Nascimento's model, the user experience begins to occur even before a product is used in a process called expectation. In the case of HMD-based immersive museums, the users who have not used the HMD devices before can only have a vague understanding gained from news, media, or advertising, and users who have already had the experience with HDM devices may have their own understanding and impressions based on their previous user experience. For example, inexperienced users may feel fresh and fabulous even with a low-resolution VR headset, while experienced users may feel unhappy about the low-quality images. Due to their prior usage experience, users have different assumptions about VR headsets and VR content. In other words, existing understandings and impressions of the new media can lead to different expectations. Two other factors influence expectation: the user's learning interests and previous game experience. According to the Four Stages of Learning Motivation proposed by Michael et al., learning motivation is a dynamic process within the learning process that occurs even before the learning activities(Cole, Harris, & Feild, 2004). Lynn D. Dierking et al. revealed that the audience's prior interest could influence their learning outcome in a museum (J. Falk & Storksdieck, 2005). Considering that the core purpose of the immersive museum is learning instead of simply entertainment, the learning interests of an audience can influence the expectations of an immersive museum. Previous studies found that prior game experience affects the user's experience in an immersive museum in terms of immersion, interaction, and response (Geslin, Bouchard, & Richir, 2011; S. P. Smith & Du'Mont, 2009), so prior game experience also affects the user's psychological expectation.

In summary, a user's previous impression of the new media, learning interests, and prior game experience can affect their expectations for an immersive museum (see Fig. 3.7).

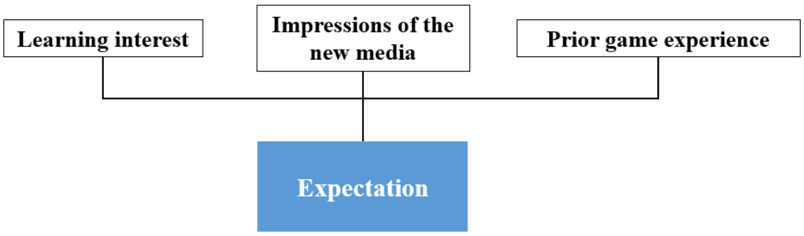


Fig. 3.7 Factors of the expectation stage

3.2.3. **Interaction stage**

Mahlkwe (Mahlke, 2002) pointed out that in the process of information interaction, both technical factors (e.g., system usefulness and ease of use) and non-technical factors (e.g., hedonic quality and visual attractiveness) will affect the user experience of a website. Technical factors correspond with the pragmatic functions of the second level of Norman's theory in section 3.2.1, while non-technical factors correspond with the non-pragmatic features such as emotion and hedonic affect on the third level of Norma's theory. The interaction process, including technical and non-technical factors, can be further analysed based on the Technology Acceptance Model (TAM). TAM has been widely received as a system for measuring and tracking technology acceptance. In a review of information system acceptance and usage work, Venkatesh and Davis (Venkatesh & Davis, 2000) suggested that TAM is now the most influential model in research.

TAM postulates perceived usefulness and ease of use as the two core constructs of user technology acceptance and intention to use. Davis (Davis, 1989) described perceived usefulness as "the degree of belief that the use of a certain system could enhance the user's work performance". On the other hand, the perceived ease of use refers to "the degree of belief that the use of a system is possible without much effort on the user's part". In other words, the effectiveness of any device could be enhanced if it can be easily used. Researchers in the past have examined the relationships among the perceived ease of use, perceived usefulness, and intention to use across various contexts (Joo & Sang, 2013; Mahlke, 2002; Wojciechowski & Cellary, 2013). TAM theorises that the effects of external variables (e.g., system characteristics, development process, training) on intention to use are mediated by perceived usefulness and perceived ease of use (Venkatesh & Davis, 2000). Therefore, perceived usefulness and perceived ease of use are two solid technical factors that require attention.

As discussed in section 3.2.1, affective experience is an essential part of the user experience. In immersive media, several studies used the TAM model to analyse user experience. They found that perceived enjoyment can be a factor that directly affects users' intention to use in AR environments(Wojciechowski & Cellary, 2013), desktop VR learning, digital museums(E. A.-L. Lee, Wong, & Fung, 2010), VR tourism(Vishwakarma, Mukherjee, & Datta, 2020), the acceptance of VR hardware(Manis & Choi, 2019), and e-learning systems(Cheng, 2014).

The perceived level of enjoyment traces its root in the flow theory proposed by Csikszentmihalyi (Nakamura & Csikszentmihalyi, 2014), which concentrates on differentiating human behaviour's cognitive and emotional components. As per Davis et al., perceived enjoyment is like intrinsic motivation and can be defined as "the degree to which the activity of using technology is perceived to be enjoyable in its right apart from any performance consequences that may be anticipated." (Davis, Bagozzi, & Warshaw, 1992) In the context of the current study, perceived enjoyment has been conceptualised as the extent to which customers believe that taking part in the activity of experiencing destinations through VR would be enjoyable. In the context of human-computer interaction, previous studies have stated perceived enjoyment as one of the essential hedonic determinants for understanding the users' virtual experience (Y.-C. Huang, Backman, Backman, & Moore, 2013). Therefore, perceived enjoyment should be a core non-technical factor in the interaction process.

Despite its popularity and usefulness, TAM has previously been criticised for not considering external variables. To fill this gap, TAM2 was developed to extend the original TAM model by introducing factors including subjective norm, image, job relevance, output quality, and result demonstrability as external variables, as well as experience and voluntariness as moderating variables (Venkatesh & Davis, 2000). However, the main external factors of TAM2 are about social influence, and the HMD-based immersive museum has unique features like high-degree immersion/presence and interactivity, which distinguishes it from a conventional online museum on the website. A key aspect of VR systems that separates them from other digital systems is their facilitation of high levels of immersion (Slater &

Wilbur, 1997). High interactivity and vividness, some of the main properties of VR simulations or games, results in higher immersion and emotional responses (Sheng & Joginapelly, 2012). Thus, the immersive power of a program is a critical element of VR (Peng & Ke, 2015). Heldal (Heldal, 2007) identified that users working in an immersive environment are more efficient and feel more present compared to a non-immersive environment. Kothgassner et al. (Kothgassner et al., 2012) stated that the acceptance of VR increases with an increased level of immersion. Thus, it is crucial to focus on the role of immersion in the endorsement of VR applications. Immersion was found to be a construct related to loss of self-consciousness, the merging of action and awareness, and an altered perception of time (Fang, Zhang, & Chan, 2013). Immersion is sometimes referred to as the hardware properties, while presence is the measure of one's subjective experience (Slater, 2018). Therefore, to avoid ambiguity, presence as defined above is used in the present study. Though Sagnier et al. failed to validate that presence could significantly influence intention to use in HMD VR (Sagnier, Loup-Escande, Lourdeaux, Thouvenin, & Valléry, 2020), several studies have expanded the TAM model to include presence and interactivity as external factors. For example, Makransky found that presence had a significant effect on motivation and enjoyment in his study on the effect of VR features on learning effectiveness (Makransky & Lilleholt, 2018). Similarly, Vishwakarma et al. found that perceived immersion had a significant effect on intention to use VR and enjoyment in their study on VR tourism (Vishwakarma et al., 2020). Finally, Huang et al. found that immersion had a significant effect on perceived usefulness (H.-M. Huang, Liaw, & Lai, 2016).

As for interactivity, Cheng found in his study of e-learning systems that interactivity significantly influenced both perceived ease of use, usefulness, and enjoyment (Cheng, 2014); Papakosta also found that perceived interactivity significantly influenced perceived ease of use and usefulness in his study on the use of mobile-based AR fire training (Papakostas, Troussas, Krouska, & Sgouropoulou, 2021). In another study, Steuer determined that interactivity is the key to a virtual environment's ability to generate presences. Interactivity is constituted by three factors: speed, range, and mapping. Speed refers to the response time of an interactive response. Range, or the amount of choice of interaction, refers to the number of attributes of a mediated environment. Mapping, or the method of interaction, refers to the ability of a system to map its controls to changes in the mediated environment naturally and predictably. Notably, interactivity is the most critical element in technology-enhanced learning environments (Spector, Christensen, Sioutine, & McCormack, 2001) , and as such the role of interactivity in increasing learning has important implications for the design of e-learning systems (C. Evans & Gibbons, 2007). In summary, this section introduced presence and interactivity as features specific to the immersive museum and as critical external factors to expand TAM into the model. Based on the above discussions of previous studies, interactivity can influence the perceived ease of use, usefulness, and presence, while presence can impact perceived usefulness and enjoyment (see Fig. 3.8).

The narrative is another central feature of the immersive museum. Most museums use narrative to a certain extent to achieve better communication with their audience and elevate user experience, and the remote-site museum is no exception. With the help of computer technology and HMD devices, the use of the narrative in the immersive museum is closer to the game narrative than the traditional narrative. Unlike traditional stories, the audience can interact with the stories in games. Meanwhile, traditional narratives as found in novels, movies, or television are linear and fixed. Narrative can influence player immersion into the game story world and encourage them to be curious, concentrated, and empathetic (H. Qin, P.-L. Patrick Rau, & G. Salvendy, 2009). Following Busselle and Bilandzic (Busselle & Bilandzic, 2009), the narrative experience as a whole will be referred to as narrative engagement within this study. Elements from the conceptualisations of the phenomenological experience of narratives may form dimensions of narrative engagement. The multi-dimensional nature of narrative engagement is confirmed by recent empirical research that found dimensions of narrative engagement relating to narrative understanding, attentional focus on the story, emotion for and with characters, and the sensation of being there in a narrative world (Busselle & Bilandzic, 2009). Therefore, narrative engagement is included as the third external factor in TAM that embodies the immersion of immersive museums. Narrative engagement may affect the enjoyment and perceived usefulness, while interactivity can influence narrative engagement (see Fig. 3.8).

Given the importance of effective immersion, a CG character's appearance and character animation are central to the storytelling experience in an immersive audio-visual narrative.

According to the uncanny valley theory reviewed in the last section, the perceived affinity of the audience to the character is a vital indicator of the overall evaluation of a CG character. Therefore, CG character's affinity may positively impact the narrative engagement. In addition, affinity is a positive emotion, so a CG character's affinity may also be positively influenced by the audience's perceived enjoyment of the program (see Fig. 3.8).

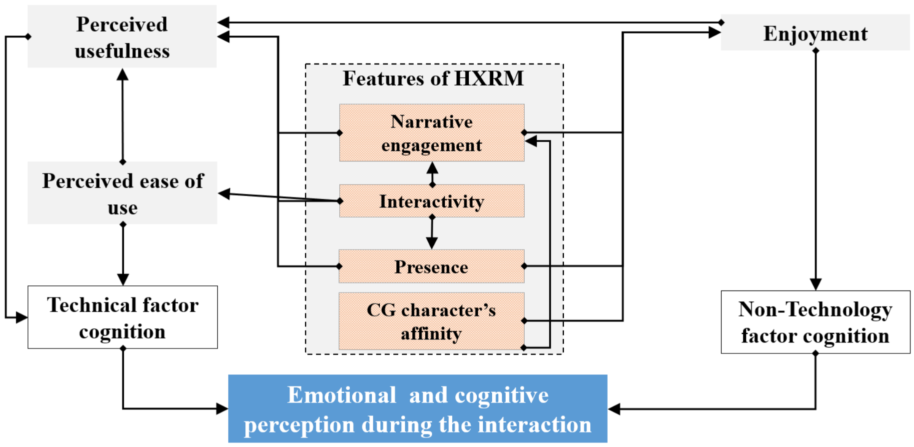


Fig. 3.8 Factors of the interaction stage

3.2.4. Post-interaction stage

The post-interaction stage is the third stage of Nascimento et al.'s model and the third level of Norman's model known as: the reflective level. The user's satisfaction with their previous experience is evaluated in this stage. In conjunction with or after this overall evaluation process, a further reflection of the previous experience may follow, which may consist of (a) a summary of knowledge or critical thinking from the perspective of emotional empathy; (b) intention behaviours, such as actively and spontaneously learning after usage, consulting for more information, or showing enthusiasm for the relevant topics; or (c) an intention to use in the future (see Fig. 3.9).

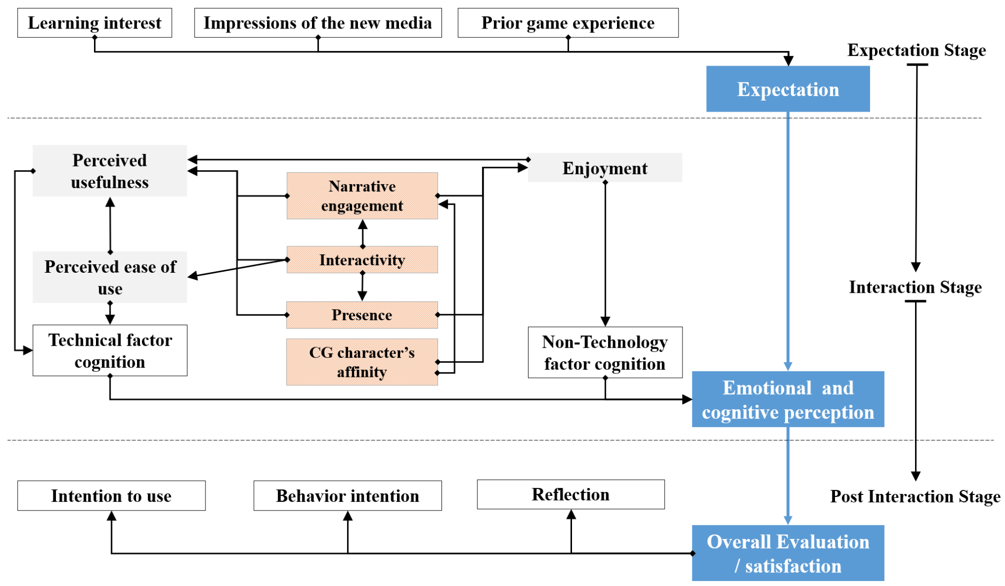


Fig. 3.9 Proposed model of user experience for HMD-based immersive museum

This section focuses on the user experience with HXRM by investigating its features and the dynamic process involved. This study draws on the relevant theories proposed by Nascimento et al. to form the dynamic phase model of user experience to guide the following research (see Fig. 3.9). The model consists of expectation, emotional and cognitive perception, and overall evaluation. The core of this model is an extended TAM based on emotional design and Patrick Jordan's pleasure theory.

3.2.5. Hypothesis of extended TAM for HXRM

A detailed analysis of four characteristics of HIM from previous research were used as external variables for TAM: narrative engagement, interactivity, presence, and the CG character's affinity. Meanwhile, the learning interest and prior game experience of the expectation phase were integrated into the proposed extended TAM, after which the two variables' impacts on the four factors of HXRM features were hypothesised as follows (see Fig. 3.10):

H1: Prior game experience affects the user's presence and narrative engagement, meaning that an experienced user has lower presence and narrative engagement than an inexperienced user.

H2: Interactivity affects narrative engagement and presence. The more natural the mapping, the higher the narrative engagement and presence. Specifically, the NUI version for HMD-based immersive museum could yield more presence and narrative engagement than the GUI version.

H3: Learning interest affects overall narrative engagement with a positive relationship.

H4: Prior game experience affects the CG character's affinity. The more experienced the user, the lower CG character's affinity.

H5: The CG character's affinity can affect user enjoyment with a positive relationship.

H6: Narrative engagement can affect the perceived usefulness and perceived enjoyment, and the factors have a positive relationship.

H7: Presence affects perceived usefulness and perceived enjoyment with a positive relationship, meaning that higher presence results in higher perceived usefulness and perceived enjoyment.

H8: The CG character's affinity can affect the narrative immersion, and the factors have a positive relationship.

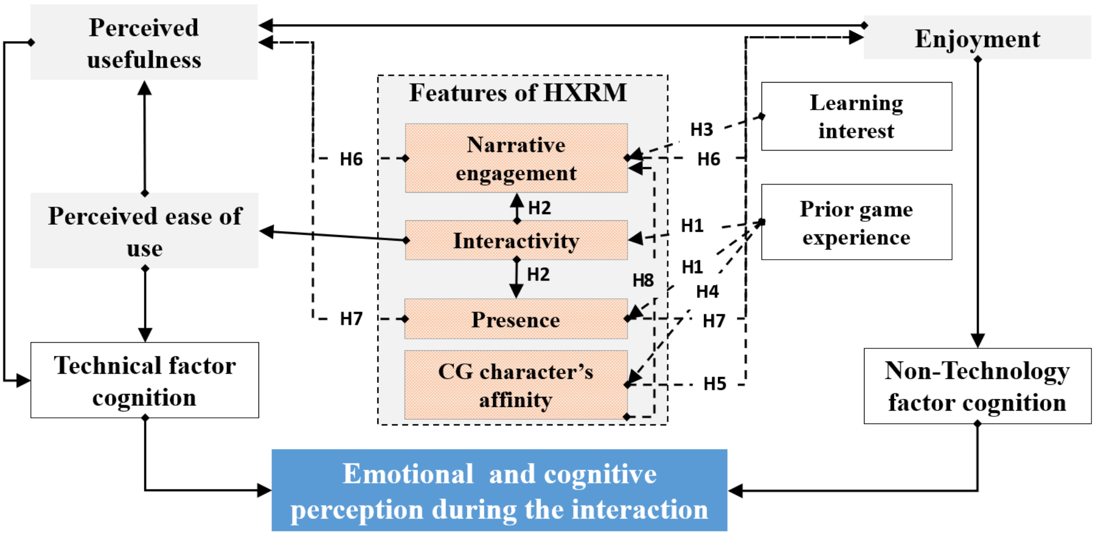


Fig. 3.10 The final hypothesised extended TAM model (The dotted line is the hypothesised relationship)

3.3. Interactive Narrative Model

This section begins by exploring the various interactive narrative types and their characteristics based on Aarseth's narrative model (Austin & Chatman, 1980) for games. With this as the theoretical background, we further distinguished the difference between games and storytelling to locate *The Extended Journey* project narrative as positioned between non-linear story and interactive drama. Following this, the detailed narrative strategy, which consisted of the introduction, narrative world, narrative path, narrative presentation, and point of view, was analysed following Koenitz and Chen's model (Koenitz & Chen, 2012). Lastly, the narrative structure of this project was discussed in-depth, and a branch-and-bottleneck structure was adopted as the main structure. The details of the storyline and different branches are further described in this section.

3.3.1. **Narrative type**

From an academic standpoint, the fields of ludology and narratology have had a long-standing controversy about the role of the narrative. For narratologies, games are just one of the mediums for narrative as they are a subset of stories and thus subject to a primarily narrative analysis. In 1999, however, Gonzalo Frasca first used the word "ludology" in his paper on the debate of the unfolding story and what philosophies and approaches could be applied to in-game studies(Frasca, 1999). As ludologists, Gonzalo Frasca and Jasper Jull claimed that stories were only a subset of games and that games should not be analysed primarily in terms of narrative (Juul, 2005). However, in another study, Murray distinguished between the underlying mechanics and purposes in games versus narratives by pointing out that narratives satisfied the need to interpret causes and effects and engage people emotionally and morally. Games, meanwhile, delivered delight through shared attention with others created in shared pattern recognition and the invention of shared rituals (J. H. Murray & Murray, 2017). In other words, though there is some intersection in the roles of the game and the narrative, an intersection known as interactive storytelling, the game and the narrative are fundamentally separated (see Fig. 3.11). Interactive storytelling in a game, such as in linear or quest games, is different from interactive storytelling in narratives such as interactive dramas or CYOA stories. While the former, represented by *Halo 2* and *Half-life 2*, aims to give players mental satisfaction through game mechanics, the latter, represented by such games as *Florence* and *The Walking Dead*, focuses on telling providing a good plot that engages with and delights the audience. In the case of this project, the storytelling of *The Extended Journey* sits somewhere between interactive drama and non-linear story (see Fig. 3.11).

Fig. 3.11 Narrative-game continuum

The next step was to find an appropriate interactive narrative model for *The Extended Journey*. Aarseth's narrative model (Aarseth, 2012), grounded in Chatman's concept of kernels and satellites (Austin & Chatman, 1980), provided a means to organise events in interactive storytelling. In terms of the combination of different kernels and satellites, Aarseth (Aarseth, 2012) defined the different narrative types as the following: linear story, non-linear story, linear game, quest game and "pure" game. By further categorising the aspects of the narrative, Aarseth's model was further developed and refined.

Table. 3.1 below clarifies the differences between pre-determined alternatives and generative dynamics. Generative dynamics usually refer to using AI or algorithms to generate content dynamically, meaning that no player will experience the same event. For example, *Façade* allows the audience to type sentences to "speak" with the characters, and the AI-driven characters will respond naturally. However, pre-determined alternatives refer to statically pre-made events, which can only be triggered and played. For instance, *The Walking Dead* made all possible branches and feedback in advance while the audience jumped forward to different pre-determined events.

Moreover, the difference between fixed kernel and alternative kernels with possible satellites was identified. For fixed kernel points like in *Florence*, though the audience can interact with the story through playable satellites, the audience could feel they have no control over where the story went or how it ends; rather, they only had control over the narrative pace. However, for alternative kernels like *The Walking Dead*, the audience felt that their decisions truly influenced the plot's development.

Table. 3.1 Classification of narratives based on kernels and satellites

***Satellite* Influence** / ***Kernel* Influence**	**No Satellites**	**Alternative Satellites (Pre-determined)**	**Dynamic Satellites (Generative)**
No kernels	N/A	N/A	*Minecraft* an open-world game
Fixed kernel	*War & Peace* a linear story	*Florence* an interactive comic	*Half-Life 2* a linear game
Alternative kernels (Pre-determined)	N/A	*The Walking Dead* A non-linear story *Sleep no more,* ***The Extended Journey*** an interactive drama	*Halo 2* a quest game
Dynamic kernels	N/A	N/A	*Façade* an interactive drama

Though *The Extended Journey* is a story that follows a fictional character name Leo and is based on historical events including *Kindertransport* and *Kristallnacht.* Upon clearly stating the name of one of these events, the final ending of the story is determined. Though a pre-determined alternative strategy is better and more controllable than a generative dynamics strategy, the audience must feel they can have some influence on part of the story instead engaging with a fixed kernel. In this way, engagement and depth of the narrative experience can be increased. To meet these needs, *The Extended Journey* adopted a branched structure of the main storyline (choose-alternatives kernel) and alternative supplementary events (pre-determined satellites). As Fig. 3.12 shows, audience can explore the environment and interact with the props to gain different story events and plots. Most props only contain story fragments while the key prop can trigger the main storyline that includes the family's arguments and discussions that occur in the living room on a stormy night. In *Florence,* users can perform interactions such as clicking on objects and playing puzzles, but these interactions do not affect the plot or the story itself. Unlike in *Florence*, users of *The Extended Journey* can make decisions for Leo to experience different storylines (see Fig. 3.12) as seen in *The Waling Dead*'s and *Sleep No More*'s selectable and multiple storylines.

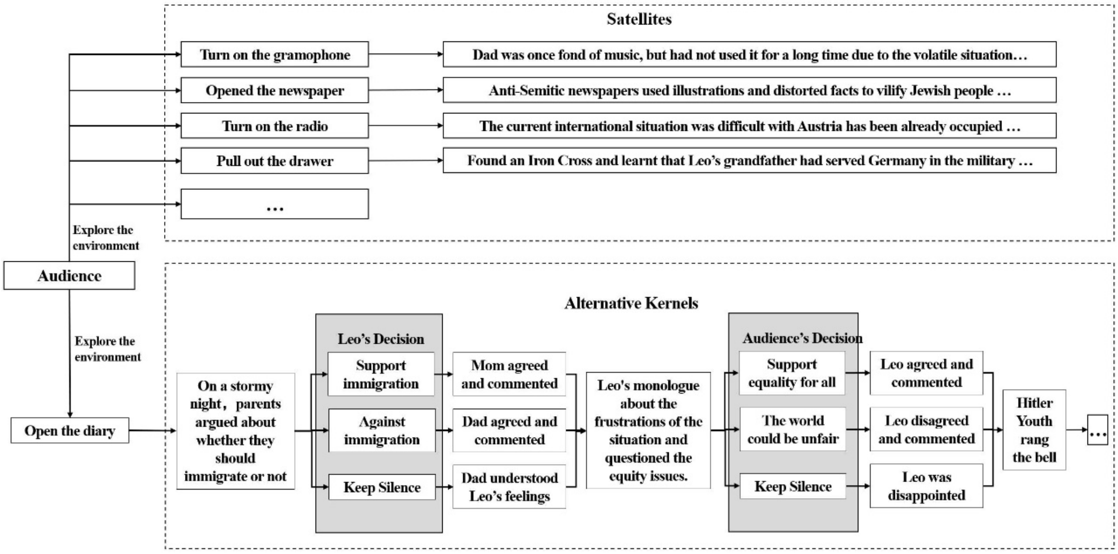


Fig. 3.12 The storylines of *The Extended Journey*

3.3.2. Narrative strategy

Koenitz and Chen (Koenitz & Chen, 2012) summarised a model of interactive narrative strategy using a sample of 60 interactive digital narrative projects. Their model consists of five elements: introduction, narrative world, narrative path, narrative presentation, and PoV. Based on this model, the narrative strategy used in this project was proposed as follows (see solid line in Fig. 3.13):

- A mixed introduction type was chosen for this project for the introduction section. *The explorative introduction* was the default mode that required the audience to find their own way into the narrative world. If the audience could not access the story after a specific time or encountered difficulties using the new device, an introduction would be activated to offer a clear guide to utilise the program. As using the latest VR or AR device is a potential barrier for people unfamiliar with this technology, a consecutive introduction is helpful to draw the audience into the plot gradually and familiarise them with the devices and the virtual environment in a friendly step-by-step way. On the other hand, immersive interactive environments in HMD-based VR/AR/AV are well-known to have inherently allowed users the agency of interaction, such as freely viewing, walking around, searching, and discovering the virtual by interacting with items and more. This explorative introduction takes advantage of the immersive interactive environment by stimulating the audience's curiosity.

- For the narrative world, an *interwoven world* type was used for this project. In an interwoven world type, an overarching narrative exists, while several sub-narratives also exist in a parallel world type. In this project, the only important plot is the clear central story of Leo, utilising the parallel world type is not suitable in this case.

- For the narrative path, the *conditional path* was selected for this project. A conditional path means that the consequences of the user's choices are influenced by the audience's decisions made within the story rather than being entirely pre-determined by the author in a fixed-path. As discussed in the last section, the conditional path is promising for a more appealing and engaging experience while maintaining the narrative continuity and cause-effect connection.

- For narrative presentation, to maximise the display capability of the immersive medium, including stereoscopic vision and spatial sound, which involved a mixed approach of graphics-based and voice-based presentation, was adopted. A mixed approach is also helpful in reducing and controlling costs. On the one hand, graphics-based presentations such as *Detroit: Become Human* require more development and stronger technical support. On the other hand, text-based and voice-based presentations, such as *Zork* and *Unheard*, can tell more complex stories with the same budget.

- PoV is an interesting topic for narratives in HMD-based immersive media. Due to the limitations of technology in an HMD device, a user cannot view a program from the perspective of an omniscient viewer but instead they must experience the story from the perspective of an invisible observer (*third-person view*). A user may also act as one of the characters in the story (*first-person view*) or act as a visible observer (*second person view*). If a user plays in the third-person perspective as an invisible observer, it would be hard to interact with other characters in the story and as such they would instead simply watch and listen in silence. However, if a user chooses to play in the first-person perspective as a member of the story, it would require some prior background knowledge of the story. If the audience plays in the second person view as a visible observer, the virtual character could "see and interact" with the audience, including those unfamiliar with the story.

According to existing research, however, the first-person view enables more accurate interactions in VR (Gorisse, Christmann, Amato, & Richir, 2017).

- In contrast, Larsen and Mads argued that the second person view, where the viewer is the protagonist's sidekick, is more advantageous since it requires less background knowledge and has more effectively controls within the narrative (Larsen, 2018). Existing studies also revealed that the second-person-view stimulates a greater sense of presence and participation than third-person narration (Rembowska-Płuciennik, 2018; Vosmeer, Roth, & Koenitz, 2017). Given this research background, the *second-person view* was selected as the PoV of the narrative in this project after a comprehensive evaluation.

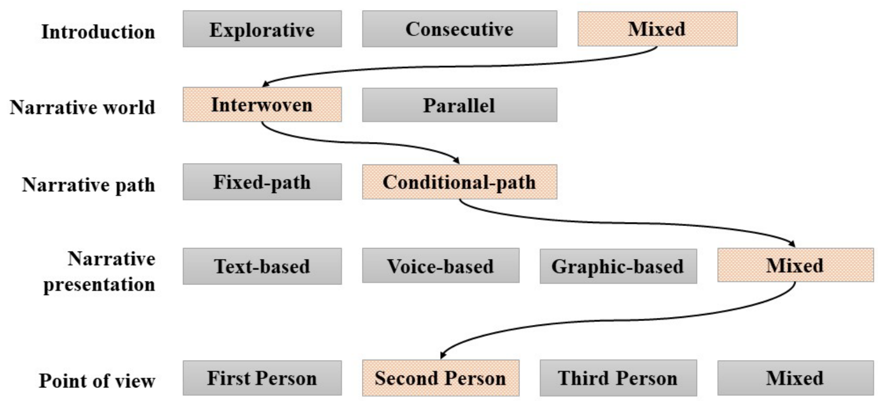


Fig. 3.13 Interactive narrative strategy. The solid line represents to the path this project adopted

In conclusion, the audience will experience *The Extended Journey* from the second-person view as they are introduced into the story in a mixed explorative-consecutive way. Accompanying an overarching narrative about Leo are some complementary story fragments about his family, and the audience can influence the plot to a certain extent via their choices. The story will be presented alongside immersive visuals and audio.

3.3.3. **Narrative structure**

The literature review highlights that branching structure is a solution for mediating narrative coherence and user control. As a result, branching structure is a commonly used strategy for interactive storytelling that is utilised to achieve the alternative kernels discussed in 3.3.1 and conditional path mentioned in section 3.3.2. Ashwell gave an exhaustive review of the various structure that narratives can take, including Time Cave, Gauntlet, Branch and Bottleneck, Quest, Open Map, Sorting Hat, Floating Modules, Loop and Grow, and more (Ashwell, 2015). Among these, branch-and-bottleneck structures refer to the narrative branches that regularly rejoin, particularly around events common to all versions of the story (see Fig. 3.14). To avoid obliterating the effect of past choices, branch-and-bottleneck structures almost always rely on the heavy use of state-tracking patterns. In addition, the bottlenecks may be rendered invisible with careful design strategy, as the plot branches may never reach an explicit rejoining node even though the choices at the end of each branch remain the same or similar. In this way, the audience can feel that they are really in free and in control of the plot while the developers can avoid too many branching stories and uncontrolled development. Therefore, the branch-and-bottleneck structure was also adopted in this project.

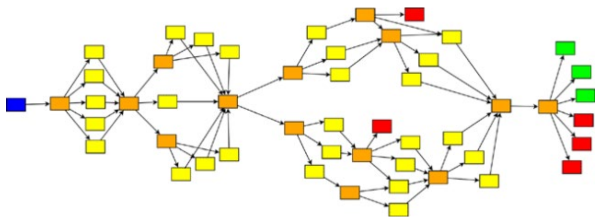


Fig. 3.14 Diagram of the branch-and-bottleneck structures

The central focus of the story is a debate between Leo's parents that happens in the living room. There, the audience can experience the story in a second-person view and make choices for the protagonist Leo. The narrative of *The Extended Journey* was mainly designed to exploit the branching structure in combination with a video game exploration mechanism. Specifically, the audience can explore the story fragments by examining different items, and finally, trigger the main story by interacting with the key item. After this, they can go through the branched main story by making decisions (see Fig. 3.15).

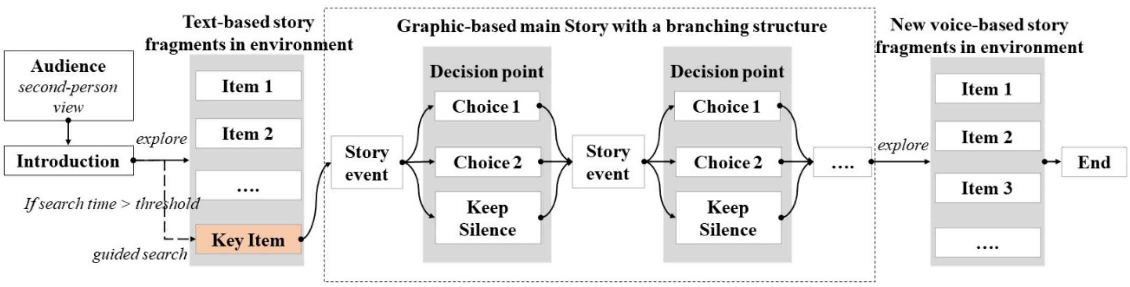


Fig. 3.15 Flow diagram of Narrative Structure

To ensure historical accuracy, the script and dialogue were rewritten in collaboration with a historian at the NHCM to mirror an existing script from the parallel project *The Journey* application. The dialogues and plots were designed based the testimonies of real survivors' and true facts about the period. In *The Extended Journey* experience, after a brief introduction to the story's time and place, the audience is free to explore the room by closely observing each of the items, opening the drawers, and reading the floating text descriptions located throughout the rooms. The main story is also told in a fractured way through the floating text segments. The audience is meant to search the living room until they locate the key item, Leo's diary in a drawer, thus triggering the main narrative. If a user is unable to locate the diary, they will then be guided by the text bubbles and off-screen voices until they find it. Upon finding Leo's diary, the audience can experience the story of Leo's family's debate as it is recorded in the diary in the immersive environment through the HMD device. The audience can see vivid virtual characters, including Leo and his parents, talking, arguing, and reassuring each other before them in the room (see Fig. 3.16). Since the story has a branched structure, the audience can investigate different branches by making choices via a second-person view, indicating that the audience is a visible observer, and protagonist Leo can "see and find" the audience to raise questions to them as suggestions that lead to branching narratives. The three decision points in the story are: (1) the decision to supporting which side in the debate between Leo's parents; (2) a reflection on whether everyone should be equal or not; and (3) the decision to raise either the question of the Hitler Youth or the unemployment of Jewish people. When the main storyline is over and the users have followed the narrative throughout the rooms, all the virtual characters will disappear except Leo, and the audience will return to the living room environment. At this time, new story fragments embedded in the items in the room will be activated. These items include a telephone, a radio, a suitcase, a newspaper, the Iron Cross, and a gramophone (see Fig. 3.16). By interacting with these items, the audience hear the stories they represent through Leo's narration and access more details. For example, by interacting with The Iron Cross, users can learn that Leo's paternal grandfather was awarded this medal for his bravery in a battle in World War I fought for Germany. The Newspapers, titled *Der Sturmer*, includes offensive stereotypes of Jewish people that can be explain in further detail by interacting with it. Finally, by choosing the gramophone, users can learn that Leo's father used to love listening to classical music, but now he has not been in the mood to listen to it for a long time. Each new item adds a new layer of complexity to Leo's story.

Through these fragments of daily life and the items in the room, the narrative paints a picture of the challenges that Jewish people in Germany faced before World War II. By exploring various items and making decisions, the audience can follow the story in an exploratory, participatory, and active manner.

Fig. 3.16 Layout of the Props (Left), Concept Image for *The AR Journey* in Living Room (Right)

Chapter 4: Methodology and Development of *The Extended Journey*

This chapter focuses on the methodology. Section 4.1 firstly introduces the design science research methodology used in this study and the proposed models and hypotheses will be validated via controlled experiments. The following sections then introduce the design and development of *The Extended Journey* project. The project includes a HoloLens application, *The AR Journey* and VR application *The Virtual Journey* that can be deployed on VR headsets like HTC Vive and AR headsets like HoloLens. The project context, interaction design, and user interface design are described in section 4.2 and 4.3. Finally, the development of the applications covering the system architecture, asset development, system integration and deployment are further illustrated, and lessons learned during the process are summarised in section 4.4.

4.1. Design Research Methodology

As Fig. 4.1 shows, the process of design science research involves three closely related cycles of activities (A. R. Hevner, 2007). 1) The relevance cycle provides an application context of the research question, and the context contains requirements for the research and the acceptance criteria for the final assessment. 2) The rigour cycle provides a knowledge base including scientific theories, experience, expertise, etc. It is essential that the design offers innovative contributions rather than applying well-known processes. 3) The central design cycle iterates between the core activities of building and internal evaluating the design artefacts and processes of the research (A. Hevner & Chatterjee, 2010).

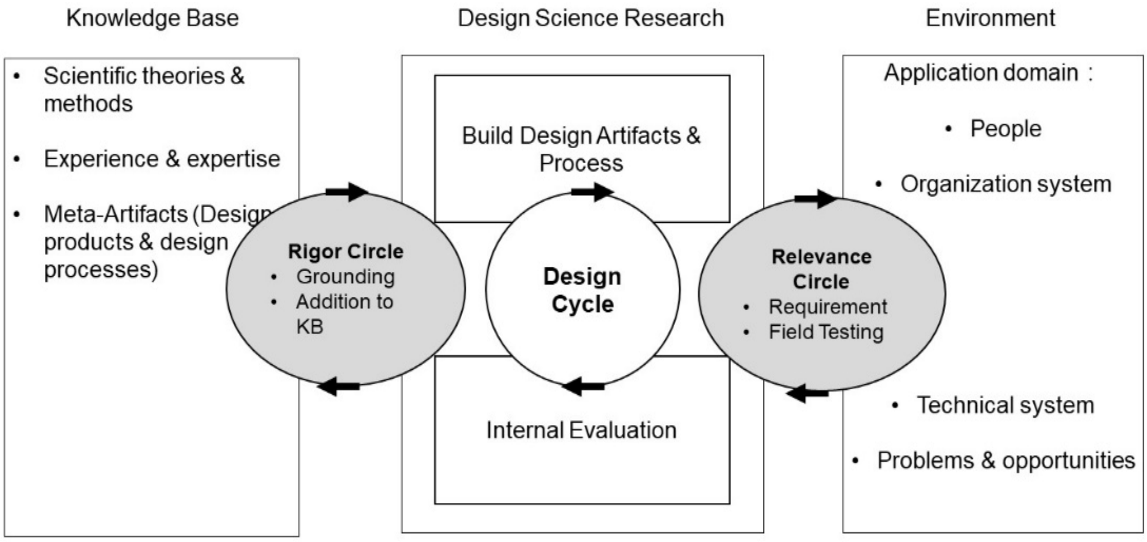


Fig. 4.1. Three cycles of design science method

The study utilised the Design Science Research Method, which is proved as a reliable method for Human-Computer Interaction (HCI). As shown in Fig. 4.2. Three cycles of This Study, the initial design iterates during the development stage through internal evaluation. In order to answer the research questions in Chapter 1 and explore guidelines for narrative in immersive media, an interactive AR narrative experience for museum visitors entitled *The AR Journey* and an interactive VR narrative application for a virtual museum experience entitled *The VR Journey* were developed, in collaboration with the NHCM using Microsoft HoloLens and HTC Vive Pro.

Building on HMD-based immersive media, these two applications adopted the interactive narrative to deliver the story of Leo, a fictional Jewish boy and were dedicated to promoting Holocaust education, improving young people's emotional engagement and encouraging a passion for learning about the history. The design of *The AR Journey* is intended to enhance the museum's on-site exhibition experience, while the design of *The VR Journey* aims to heighten the virtual museum's remote-site experience. The design and development process were based on interaction design theories, user experience theories, interactive narrative models, and computer graphics and animation principles. During the development process, several internal evaluations were carried out. Experts from the NHCM evaluated the script and story, experts from the animation and game department assessed interaction design and user interface, and a small group of young people gave feedback on user experience. Finally, within-subjects and between-subjects experiments were conducted to explore the three research questions and made several contributions to the relevant field, including Uncanny Valley theory, theory of Multimodal interaction, natural user interface, User experience in an immersive environment, and design guidelines for HMD-based narrative.

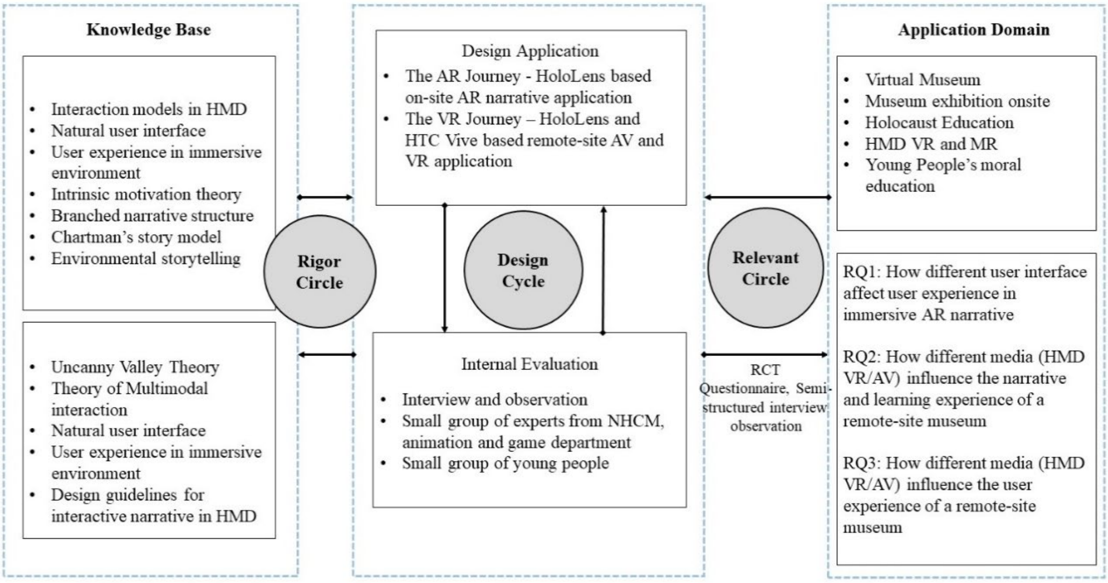


Fig. 4.2. Three cycles of This Study

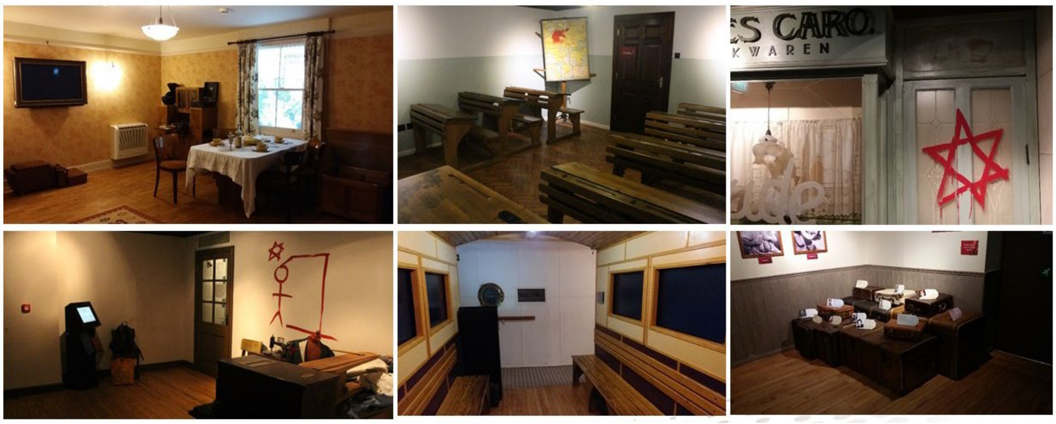
4.2. Introduction and Project Context

This section introduces the background and narrative context of *The Extended Journey* project, which is a fictional story based on an existing exhibition at the National Holocaust Centre and Museum. The story is intended to depict a typical example of Jewish children's experiences in pre-World War II Germany. The objective of this project is to improve the accessibility and attractiveness of the museum's exhibits by utilizing modern HMD-based immersive technologies.

4.2.1. Narrative context

Narratives are a powerful tool for empathy, as they encourage perspective-taking and emotional engagement (Busselle & Bilandzic). According to previous literature, there is a positive association between empathy and prosocial behaviours (Hoffman, 1984; Saarni & Crowley, 1990). Additionally, according to Jin et al. (Yunshu Jin et al., 2017), the empirical evidence on the topic demonstrates that prosocial video games benefit the moral development of young people. These findings reveal the immense impact that narrative devices can have on one's moral education.

The National Holocaust Centre and Museum (NHCM) has many conventional exhibits which present artifacts collected from the Holocaust in a traditional manner. Additionally, as the museum hopes to reach a younger demographic as well, it also utilises various narrative techniques to allow younger generations to fully experience history while simultaneously commemorating and learning from the tragedy of the Holocaust. A physical exhibition named *The Journey* in NHCM was specifically designed to guide young people's moral development and citizenship education. It follows the story of a fictional Jewish boy named Leo as he is faced with the choice to board *Kindertransport*[33] by restoring various scenes of his life. These scenes take place in six restored rooms: Leo's family living room, Leo's school, the street after the Night of Broken Glass, the family tailor shop business, a train carriage for *Kindertransport*, and a refuge in the U.K. (see Fig. 4.3). Leo is a fictional character, but his story is representative of that of a typical Jewish child in pre-World War II Germany. These restored scenes demonstrate what life was like for Jewish people at that time. In each room, the audience can watch a short video of Leo giving a monologue of what he saw, heard, experienced, and felt in each scene. The visitors can experience the complete story gradually by going through each room and watching the available videos.



33 Kindertransport was the title for historical events that the British government made efforts to bring Jewish children out of Nazi Germany, occupied Austria and Czechoslovakia before World War II .

Fig. 4.3. Six rooms of *the Journey* exhibition: living room (top left), classroom (top middle), the street after Night of Broken Glass (top right), the family's tailor shop (bottom left), the train carriage for Kindertransport (bottom middle), a refuge in the U.K. (bottom right)

The Journey is a text free and tactile exhibition designed mainly for younger audiences. One objective of this PhD project is to enrich the museum experience and convey the story to young people in an appealing way. The author will achieve this by developing an interactive storytelling app for Leo's story using digital technologies including games, VR, AV, and AR. The project is entitled *The Extended Journey* because it extends the physical exhibition to VR, AR, and AV. This study also includes a comparative study of the interactive narrative in VR and AV.

4.2.2. The aim of The Extended Journey

The NHCM is located far away from the city centre and is not accessible via public transportation. For this reason, it is difficult to make the learning experience widely accessible to new audiences and young people. Furthermore, the current primary interactive experience relies on Q&As with virtual Holocaust survivors. However, most survivors are now in their 90s, and there is some concern over missing out on the richness of their experiences. Therefore, modern elements should be introduced to bring their stories to life.

According to the authors' on-site observations and interviews with NHCM experts, the following major challenges of *the Journey* exhibition were identified:

- Accessibility: the NHCM is far from the city centre and inaccessible via public transportation. It is difficult and time-consuming for potential visitors to come to the museum. At the same time, due to lockdowns and travel restrictions during the COVID-19 pandemic, the demand for remote visitation options is rapidly increasing. Given the global situation and the availability of technology, it is reasonable to believe that the trend of visiting remotely will only continue to increase. As a result, improving the accessibility of the museum's exhibitions has become a top priority.

— Attractiveness: as the younger generations' preference for modern interactive methods grows due to their evolving access to technology(Best, 2012), interactive experiences through digital media have become increasingly important for appealing to young people's emotions. However, the existing interactive experience at the museum, touch screens and recorded interviews or testimonies, is limited. It is therefore necessary to develop a new and interactive storytelling approach to inspire young people to study and absorb this meaningful period of history.

As part of *The Extended Journey* project, the bespoke AR narrative application entitled *The AR Journey* was initiated to improve the overall attractiveness of the exhibition. Additionally, the bespoke VR/AV narrative application entitled *The Virtual Journey* was launched to expand the accessibility of the exhibition.

The AR Journey was developed using Microsoft HoloLens, an immersive HMD-based AR device, which can seamlessly integrate the virtual holographic characters (e.g., Leo and his parents) and the virtual props with the physical environment via its see-through holographic lenses. With the addition of this technology, the audience would be free to walk around and interact with the holographic characters and props in this mixed reality world. Unlike a conventional hand-held, non-immersive AR device, this HMD-based AR device can create a uniquely immersive AR experience by giving the users hands the freedom to explore, thus bringing more possibilities to the user interface. However, there is yet to be an empirical study of how different user interfaces could influence the user's narrative experience. Immersive HMD-based AR for HoloLens has only been released for wider consumption a short time. Therefore, the author intended to design different user interfaces for *The AR Journey* and further examine their effectiveness in furthering the narrative experience of immersive AR.

Moreover, to improve the accessibility of the exhibition for the intended audience, *The Virtual Journey* was developed to deliver a remote-site visit and convey a sense of teleporting for the audience. In other words, the audience can have a fully-immersive visiting experience of *The Journey* exhibition and Leo's story all from the comfort of their own home or office. There are two approaches for achieving an effective remote immersive visit: HMD-based VR and HMD-based AV. Unfortunately, there has yet to be a study comparing the effectiveness of immersive VR and AV regarding the implementation of interactive narratives. Thus, the author developed and compared two versions of *The Virtual Journey*: a VR version using HTC Vive and an AV version using HoloLens.

In summary, the objectives of *The Extended Journey* are as follows:

1) To explore potential approaches to moral education in museums using digital technologies which promote a more attractive and accessible experience.
2) To investigate the advantages and disadvantages of different user interfaces for narratives in immersive AR.
3) To investigate the strengths and weaknesses of interactive and immersive narratives in VR and AV, particularly in the context of remote-visitation for museums and heritage sites.

In addition, the limitations of this study should not be overlooked. Except for the limitations mentioned in section 1.1.2 regarding HMD AR devices, the experiments which could not be conducted in the NHCM on-site but in a simplified, simulated environment in China, may affect the data and results to some extent. Meanwhile, the comparative study of HMD VR and HMD AV is limited by the currently available hardware, for example, future Video See Through (VST) AV technology can effectively solve some known issues of HoloLens like translucent display and narrow FOV. With the development of VST headsets in the near future, some of the conclusions in the thesis on HMD VR and HMD AV may be invalid and need to be revisited.

4.3. Interaction and User Interface Design

The audience triggers the storytelling branches through interaction. They do this by choosing branches of the story or discovering story fragments by interacting with 3D items in the room via an input interface. The interface is essential for the narrative experience. However, this particular HMD VR device has only been available to the market since 2015, and their input device will continue to advance as time goes on. Thus, the interface for HMD devices is a largely unexplored area. One focus of this study is to investigate the interface of these devices, especially for HMD AR. This section first reviews the currently available input types and input models for HMD devices. Following this, it proposes the optimal user interface design for HMD AR in HoloLens and VR/AV in HTC Vive Pro and HoloLens, respectively. Finally, it summarises the knowledge and the insights gained from the design process.

4.3.1. Input type and input model for HMD-based immersive environment

The input for an HMD-based interactive, immersive environment can be decomposed into the input type and the input model. The input type refers to the fundamental input genre in HMD-based immersive narrative, including gaze, manipulate/point/commit, and voice. The audience can perform the same input type using different apparatus, e.g., the gaze can be performed via head gaze or eye gaze, and the action of pointing and manipulation can be executed via hands or controllers.

Table. 4.1 compares the merit and limitation of different apparatus aiming at the same input type. As to gaze, it reveals that eye gaze and head gaze are different. Eye gaze is more implicit, inaccurate, faster, easier, and usually is used as an alternative input channel, while head gaze is more accurate and reliable but slower and discomfort. For manipulation/point/commit, there are several possible apparatuses, including direct manipulation by hand, symbolic hand gestures, and the controllers (the *motion controllers*[34], the *HoloLens clicker*[35], the Vive/Oculus controller, etc.) Direct manipulation by hand, which is only supported for advanced headsets like HoloLens 2nd generation, Oculus Quest 2 and HTC Vive Pro, is the ideal choice as it is natural, institutive to use and consistent with real-world manipulation (Microsoft, last accessed 20120/1/31c). The motion controllers are more precise and stable with tactical feedback but draw a clear line between virtuality and reality (Microsoft, last accessed 20120/1/31f). Hand gestures are not recommended in most cases as

[34] The motion controllers are hardware accessories developed by Microsoft that extend the user's physical capabilities by providing precise 6DoF tracking, several buttons and tactile feedback while using one or both hands. They are compatible with all mixed reality headsets with Bluetooth.

[35] The HoloLens Clicker (clicker for short) is the peripheral device built specifically for HoloLens 1 & 2. It is a miniature controller that lets the users click on whatever they are looking at. A motion sensor is inside to check the clicker's up, down, left, and right.

they are inconvenient to learn and remember, and fatigue users easily (Microsoft, last accessed 20120/1/31e). Voice command has excellent potential as it is a hand-free, natural and low effort but is still unreliable at present, especially in non-English or noisy environments (Microsoft, last accessed 20120/1/31a).

Table. 4.1 Comparison of different input types and their apparatus

Input Type	Apparatus	Merit & limitation
Gaze	Eye gaze(Microsoft, last accessed 20120/1/31d)	Merit: — High-speed pointing — Low effort — Implicitness — (can always be) Alternative input channel
		Limitation: — eye-gaze is "always-on" — Leave before click issue — Difficulty in small targets — Ragged eye-gaze movements — Tracking unreliability
	Head gaze	Merit: — Accurate and explicit — Reliable
		Limitation: — Slower pointing — Possible discomfort (e.g., neck strain)
Manipulate /Point /commit	Hand (Direct Manipulation, hand gesture, hand pointer)	Merit: — Institutive for direct manipulation — Fast learning curve — Consistent with real-world manipulation — No need to hold a controller all the time
		Limitation: — Hand gestures and pointers are not natural and not easy to learn — Hand gestures tend to fatigue users — More effort — Direct manipulation is only supported by some devices — The false triggering issue for direct manipulation

	Controller (Motion controller, clicker, Vive/Oculus controller)	Merit: — Precise and allowing for fine-grained interaction — Stable tracking — Low effort for commit — Consistent with standard game consoles' manipulation like Xbox controllers — Embed with buttons to facilitate complex interactions and menu navigation — Some tactile feedback — Good compatibility (with Bluetooth)
		Limitation: — A visible and tangible interface/barrier between the user and the world — Hands are always occupied — Some, e.g., clickers, can only track simple and limited movement — It takes time to learn for complex controller
	Real-world items	Merit: — Institutive for function. The user already knows the function of the interface by knowing the physical objects' function. — Multi-sensory feedback. — More friendly for multi users and face-to-face collaborative activities
		Limitation: — Usually, built for one specific application area or function — May suffer from poor recognition and inaccurate control
Voice	Voice Command	Merit: — It's the routine and natural way — Hands-free — Low effort, especially good at traversing complex interfaces
		Limitation: — Unreliability issue (of input detection) — Bad performance with non-English input — Take time to learn — Interference in shared spaces & privacy issues — Challenge for dictation recognition

		— Weak in the continuous input control

For an HMD-based immersive environment, different input types can be combined or used alone with their conventions to form an input model, which is listed as followings (Microsoft, last accessed 20120/1/31b) :

— *Direct manipulation* is an input model that involves touching holograms/real-world objects directly with one's hands, real-world items, or controllers.
— *Point and commit* is a 'far' input model that enables users to target, select and manipulate 2D content and 3D objects that are out of reach using hand gestures, real-world items, or controllers.
— *Gaze and commit* is a far input model using eye/head gaze and committing action via hand gestures, real-world items, controllers or voice command.
— *Gaze and dwell* is a hand free input model. The user keeps gazing (with their head or eyes) at the target and lingers for a moment to activate it.
— *Voice input* is a hand free input model by using one's voice to command and control an interface, e.g., the user can read a button's name out to activate it.

From the function aspects, there are two requirements of interaction in the narrative of *The Extended Journey*, namely, 1) targeting and selecting choices like answering Leo's question to choose from an interface, and 2) manipulating with props like opening a drawer, grasping a telephone, turning on a radio, etc. Table. 4.2 lists the main functions and typical scenarios of different input models as well as their apparatus and devices.

The AR Journey, which is developed based on the HoloLens 1st generation, head gaze and commit, and head gaze and dwell, are potentially appropriate input models. HoloLens 1st generation does not support hand capturing for direct manipulation. Eye gaze is filtered out because it is only supported by HoloLens 2nd generation. Voice input is also excluded as the Chinese voice input is poorly supported, and hand gestures have proved problematic in our preliminary study. Besides, as motion controllers are not natively supported by HoloLens 1st, point and commit is removed from the list. For *The Virtual Journey*, which is developed based on the HoloLens 2nd generation and HTC Vive Pro, all input models are potentially available except voice for the same issues of Chinese voice recognition.

Table. 4.2 Functions and typical scenarios of input models for HMD-based immersive environment

Input Model	Functions	(Typical) Scenario	Apparatus & devices
Direct manipulation	— a near input model, — touch, grab, select, manipulate	— spatial layout and design, 3D items manipulation	• HoloLens 2nd & hand • HoloLens 1st & real-world objects • HTC Vive Pro & hand • Oculus Quest 2 & hand • HTC Vive & controllers
Point and commit	— a far input model, — target, select, manipulate	— 2D slate interaction such as a web browser	• HoloLens 2nd & (hand/motion controller) • HoloLens 1st & motion controller • HTC Vive & controller
Gaze and commit	— a far input model, — target, select, manipulate	— click-through experiences, e.g., 3D presentations, demos.	• HoloLens 2nd & (head/eye gaze) & (controller/ hand gestures/voice) • HoloLens 1st & head gaze& (clicker/ hand gestures/voice) • HTC Vive Pro & head gaze & controller/ hand gestures/voice
Gaze and dwell	— a far input model, — target, select	— user's hands are occupied — tight spaces — hand fatigue — social awkwardness to perform hand gestures	• HoloLens 2nd & (head/eye gaze) • HoloLens 1st & head gaze • HTC Vive Pro & head gaze
Voice Command	— a near/far input model, — select, commit, manipulate, etc.		• HoloLens 1st/2nd & voice command • HTC Vive Pro & voice command

4.3.2. User interface design for *The AR Journey*

The AR Journey project was developed in 2018 prior to the HoloLens 2nd generation's release into the market. For this reason, the HoloLens 1st generation was chosen as the device for the project. In order to investigate the potential of different interfaces to produce immersive narratives through HMD-based AR, a 3DUI and a NUI were designed and developed as two potential interface versions for *The AR Journey*. In section 0, several input models were identified. Additional data from exploratory studies and literature reviews were also collected and analysed. An observational analysis was conducted to uncover the general behavioural patterns of users who had been invited to experience the HoloLens suspense and adventure game, *Fragments*. This process revealed the users' typical behaviour in an immersive environment created by HoloLens, in addition to gathering their feedback about said experience.

— Pattern 1: Most users experienced physical discomfort after wearing the HoloLens 1st generation headset for over 20 minutes.

— Pattern 2: Many users had difficulty learning and implementing the HoloLens 1st generation input gesture, which is known as the air tap gesture.

— Pattern 3: Most users tended to stand still when witnessing different characters interact with one another.

— Pattern 4: Users sometimes were confused when interacting with the gaze and dwell model. They demonstrated a tendency towards wanting to perform an action rather than waiting. This included touching the virtual interface or clicking the HoloLens clicker.

— Pattern 5: most users reported that the narrow FoV issue was distracting.

In response to this negative feedback, the gaze and dwell model and air-tap hand gestures were abandoned for 3DUI. Instead, head gaze and commit via the HoloLens clicker were adopted as the interaction model based on our pilot study (Yunshui Jin, Ma, & Liu, 2020). For NUI design, direct manipulation of physical objects with the users own hands and natural language voice command with virtual 3D characters were adopted as the interaction model (see Fig. 4.4).

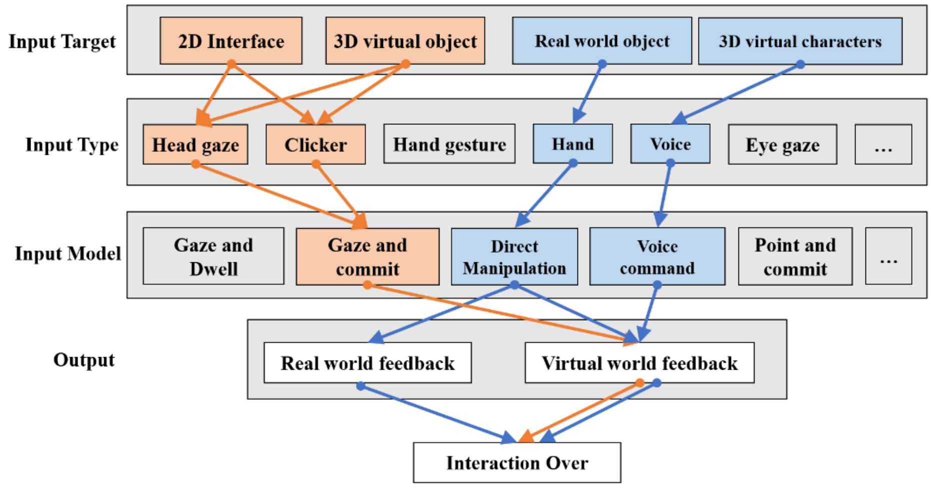


Fig. 4.4 Interaction strategies of the different user interfaces options for *The AR Journey* (Orange line represents the 3DUI design, and the blue line represents the NUI design)

With the 3DUI model, the audience can activate the 3D virtual items via the head gaze function to highlight the item and then perform the desired action via the HoloLens clicker. For example, the user can pick up the virtual holographic gramophone using the head gaze cursor (see step 2 of Fig. 4.5). They can then click the HoloLens clicker to cause the gramophone to play the music, thereby rotating the disk and handler (see steps 3 and 4 of Fig. 4.5).

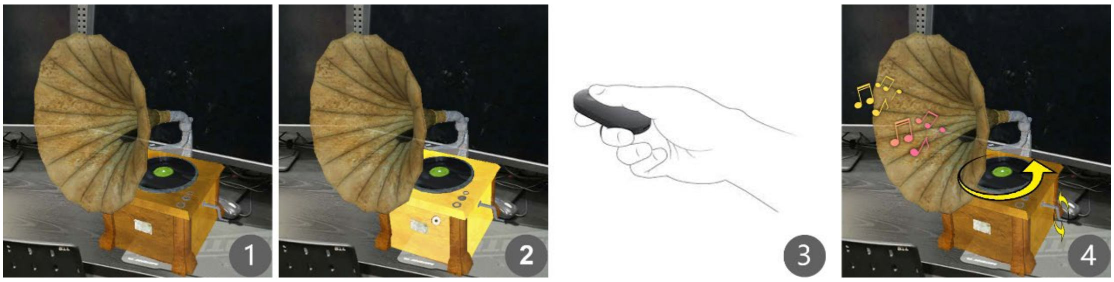


Fig. 4.5 Diagram of 3DUI for props

When using the NUI, when approaching physical objects, a text hint may appear on the object and function as a guide for the audience. The audience can then directly play with a physical object in accordance to the instructions provided by the hint. As Fig. 4.6 shows, based on the text instruction, the audience knows to turn the physical gramophone's crank handle in order to play music from HoloLens.

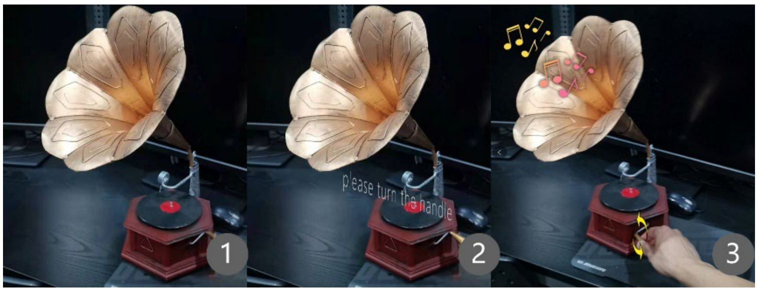


Fig. 4.6 Diagram of NUI for props

As for decision making actions within the interfaces, 3DUI offers a virtual 2D panel which floats in front of the 3D character. This provides two options to choose from and a countdown timer. The user can employ the head gaze function to activate their choice. They can then confirm that choice via the clicker. On the other hand, by offering a simple floating text hint, NUI allows the user to directly talk to the virtual characters when making a choice (see Fig. 4.7).

However, NUI for HoloLens 1st generation is difficult to implement technically. Image recognition with Vuforia[36] on HoloLens 1st generation is subject to severe latency issues, and its Chinese language speech recognition remains underdeveloped. As a result, the Wizard of Oz method was employed for NUI. The Wizard of Oz method refers to the process of allowing a user to interact with the physical object or talk to Leo and receive responses that appear to be generated by a human rather than by a computer. However, this level of authenticity is achieved by assigning someone behind the scenes to control Leo's responses via a Bluetooth keyboard without the user's knowledge.

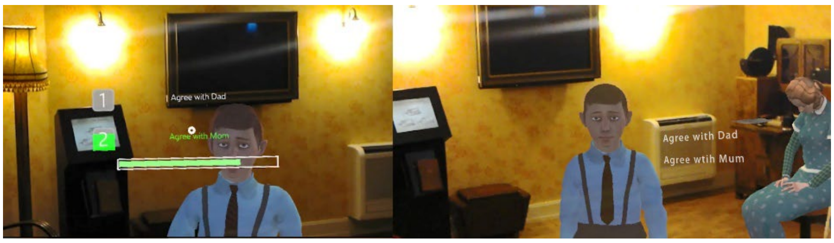


Fig. 4.7 User interface for the decision point (Left refers to the 3DUI, right refers to the NUI)

The following guidelines were implemented to ensure the validity of the comparison

[36] Vuforia is an augmented reality software development kit with world-leading image recognition technology.

between the GUI and NUI designs. The following goals should be achieved by the respective applications:

- deliver identical versions of the story by complying with the same story branch structure;

- offer props which appear visually similar or identical (e.g., gramophone, telephone and radio);

- provide identical (or similar) feedback after using the props. For instance, a piece of 1940's music is played on the phonograph when the virtual gramophone is triggered or the physical crank handle is turned.

- deliver an identical amount of information, such as the number and the type of props are identical.

The AR Journey was designed as an HMD-based, single-user application. Though HoloLens supports a multi-user model, the narrative design is based around a single user. On the whole, visitors of NHCM are typically members of a larger group, so there is a risk that other visitors may interfere with *The AR Journey's* narrative experience. For instance, the holographic virtual characters may collide with other audience members, or surrounding bystanders may cause the user to feel embarrassed. When the app is deployed on-site, it is recommended that groups of visitors be divided. The audience members should experience the AR narrative one at a time, while the other visitors view the other NHCM exhibits, thereby avoiding any potential interference.

4.3.3. User interface design for *The Virtual Journey*

For *The Virtual Journey* project, HoloLens 2nd generation and HTC Vive Pro Eye were chosen as the devices for the AV and VR offered by the exhibition, respectively. As mentioned in Chapter 2, HoloLens 2nd generation was released in February 2019, making it the most advanced AR/MR device on the market. Similarly, HTC Vive Pro Eye is known as the most advanced HMD VR device before 2021 for its large space tracking feature (more than 100 square meters), low-delay video-audio streaming capability with wireless adapter and high resolution. Both devices have decent hand-tracking and eye tracking capabilities, as well as quality voice recognition features. This allows users to directly manipulate virtual items by hand (without any symbolic hand gestures) and perform dictation recognition offline.

In order to investigate the difference between VR and AV for a remote-site immersive narrative, the interface needs to be designed with the intention of eliminating potential influence caused by the difference in the interface. While all kinds of input models are supported by both HoloLens 2^{nd} generation and HTC Vive Pro Eye, direct manipulation, which is generally accepted as the most intuitive approach, was chosen. Additionally, the direct manipulation feature encouraged the users to fully explore the immersive environment, as the near input model required users to get close to various features and props to perform actions (see Fig. 4.8).

Fig. 4.8 Direct manipulation in HoloLens 2^{nd} (Left), direct manipulation in HTC Vive Pro Eye (right)

Thanks to both devices' excellent hand recognition capabilities, direct hand manipulation is a feasible interaction input method (see Fig. 4.9). For the interaction design and development of *The Virtual Journey*, I have adapted the lessons learned from the successes and failures in the development of *The AR Journey*. The improvements include four aspects:

1) Use direct hand manipulation to replace the HoloLens clicker as the interaction method for prop interaction. In experiment 1, the interviews revealed that the direct hand manipulation version brought a more novel and attractive experience to the participants than the HoloLens clicker version.

2) Use direct hand manipulation on a floating choice panel for the interaction with the CG character instead of using voice command. In the interviews of experiment 1, I found that the voice command interface enabling users to talk to the CG characters was difficult to understand and use for many participants. They complained that they were embarrassed to talk to CG characters in public and sometimes were confused about what to say.

3) A multi-layered interaction feedback is used for a richer interaction experience instead

of straightforward interaction feedback. In experiment 1, some participants thought the placement and activation of interactive props were simple and deliberate. Therefore, the multi-layered interaction feedback is designed to allow the result of an interaction with a prop to trigger the appearance of new interactive props. For example, users need to open the virtual drawers first and then find the interactive diary book lying in the drawer.

4) Highlight the interactive part's outline of the prop as the visual cues for props interaction instead of using floating text. In experiment 1, many participants complained the text hints broke the immersion of the scene. In addition, the eye gaze on the props replaces the head gaze to trigger the visual cues, allowing for a more responsive and natural user experience.

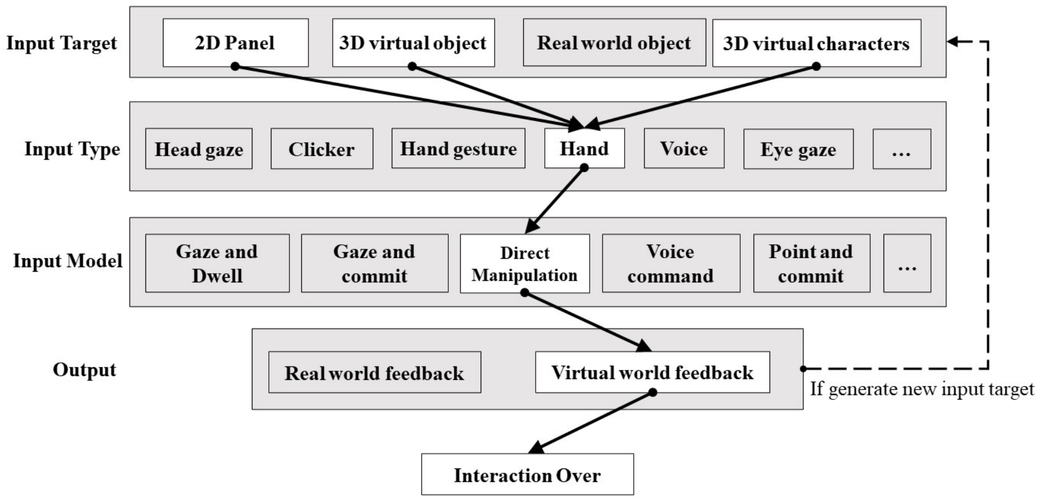


Fig. 4.9 Interaction strategies of the user interface for *The Virtual Journey* (see the solid line with arrow for the progression)

In summary, a 3DUI was implemented for VR and AV that uses direct manipulation. There are three types of interfaces: text-based instruction, the 3D props interaction interface, and the option selecting interface. The text-based instruction is a text label which uses neo-classical typeface and decoration. This label will fade in and out according to the distance between the users and the corresponding props. For instance, once a user approaches the photos on the desk, a text label saying, "This is the photos of my parents, me, my little sister Hanna, and my grandpa" will appear (see Fig. 4.10).

Fig. 4.10 Text label fades in when the user approaches the items.

The 3D prop interaction interface is embedded with the 3D virtual objects. Once the user's gaze meets the object, the interactive part of the prop is highlighted, which serves as a hint to the user. The relevant animation and audio can be triggered when the user's hand touches the correct part of the prop. For example, if the user's gaze settles on a telephone, the telephone's handle will then light up as a hint. After the user has grabbed the telephone with their hand and picked it up, the telephone will be suspended in the air and a message from Leo's father's friend will play (see Fig. 4.11). In order to make the interaction as natural as possible, the portion of a prop that is highlight will based on its real life usage. For example, the handle of some drawers, the crank handle of a gramophone, the latch of a suitcase, the knobs of an old radio, or the cover of a diary may be highlighted.

Fig. 4.11 When the user gazes at the telephone, the interaction part (the telephone handle) will be highlighted (middle). The user can then grab the handle directly using their hand to trigger the animation and the phone message (right)

As for the interface of choices, a virtual 2D panel appears with two options and a countdown timer which floats in front of the 3D character. The user needs to walk up to the panel and hit the option directly with their hand to make a choice (see Fig. 4.12). After a selection is made, the panel will fade out. Afterwards, a floating text describing the user's choice will quickly appear and then disappear.

Fig. 4.12 The user can hit the second option titled “supporting mom” (middle). The second option is then selected, and the system will give feedback to the user with a floating text saying they have supported mom (right)

HoloLens 2nd generation has better hand recognition performance than HTC Vive Pro Eye and includes special depth sensors, allowing it to support precise hand manipulation. However, unlike typical modelling software, the interactive narrative does not usually require complicated hand interaction. Therefore, the experience of hand interactions in VR (HTC Vive Pro Eye) and AV (HoloLens 2nd generation) should be somewhat similar.

4.3.4. **Lessons learnt**

Firstly, interaction in Immersive Extended Reality Environment (IXRE) is important not only to the natural experience of the story but also to the *suspension of disbelief.* [37]. “Presence”, in IXRE, is similar to the concept of the suspension of disbelief. It refers to the experience that results from combining a virtual environment with the real world in a way that transcends the idea of physical location. Witmer (Witmer & Singer, 1998) found that responsive and controllable interaction is critical to producing presence in a virtual environment. As a result, simple interactions with straightforward feedback like turning on/off a virtual light, opening/closing a virtual drawer, and pulling/closing a curtain can help to suspend the audience’s disbelief. That being said, triggering an event or introducing a story piece after every interaction is not necessary. Meanwhile, interactions with complex feedback, such as

[37] A film terminology refers to the temporary acceptance as believable of events or characters that would ordinarily be seen as incredible. This acceptance usually allows an audience to appreciate works of literature or drama that explore unusual ideas.

determining the story branch, triggering a voice recording, or reading a diary, can help the audience to understand the narrative and start assembling the different story fragments.

Secondly, it is essential to design secondary interactions that can generate (unlock) new input targets to trigger subsequent interactions (see Fig. 4.9). For example, a user opens a drawer and then finds a diary in the drawer. After the user has opened the diary, a postcard slips out on to the floor. The user then picks up the postcard and reads the words on it. In this case, picking up the postcard is the secondary interaction of both opening the diary and pulling open the drawer. Secondary interaction in IXRE is significant because it can create a convincing environment for the audience due to its similarities with the real world. The idea of natural interaction differs from many user interaction design concepts, which tend to feedback the information as directly as possible.

Thirdly, the audience interacts within IXRE through input-on-input targets and output. It is important to recognise that input targets in IXRE could be both real-world targets and virtual world targets. The output works in the same way. Meanwhile, input on virtual input targets can output real-world feedback, and vice versa. For example, turning off the light in the real world can change the lighting on virtual characters, while flipping a virtual switch can turn on a floor lamp in the real world. These tactics help to further blur the boundaries between the virtual and the physical world. However, to bring focus back to the research questions and ensure the accessibility of *The AR Journey*, this study focuses on how input on virtual targets can result in output in the virtual world.

Lastly, dilemma choices, open questions, and tasks lists are three branching strategies used for the interactive narrative in this project. All three have shown evidence of being effective. For example, at the beginning of the story, the audience faces a dilemma on whether they should support Leo's mother or father. At the same time, the audience needs to complete the task of choosing and finding stuff to pack into Leo's suitcase. A task list can help bring the audience and the character closer by letting the audience interact with the character.

4.4. The Development of The Extended Journey

The development has three phases: the system architecture prototype without the final asset to quickly implement the above narrative and the interaction design; the production phase referring to the final asset development; the publish and deployment phase, including deploying the program to the devices and debugging.

4.4.1. System architecture

The programming was developed in the Unity3D game engine. As the audience is supposed to interact with the virtual characters and the props, the main challenge for programming was to design the character behaviour module and the interactive props module. There is two existing animation system in Unity3D, the *timeline* system and the *animator* system. The timeline system is easy to cut, edit, and match different animation clips together with audio, is suitable for non-interactive character animation. The animator system, a finite state machine that contains different animation clips (states) and switches between different clips if the predefined conditions are satisfied, is suitable for interactive character animation. There are a lot of complicated non-interactive characters animations, e.g., Leo, his mother and father hugging together, and interactive character animations, e.g., Leo can find and walk towards the audience, facing the audience and having eye contact with them. Therefore, it is important to combine the timeline and animator system. As Fig. 4.13 shows, a character behaviour module mixing the timeline and finite-state machine was designed. The main idea was to put timeline animation and the finite state machine animation into three channels, known as *Playables* in Unity3D, and use an animation mixer to mix the above three playables with adjustable weight. The three playables are two timeline playables, which can dynamically load timeline animation assets and blend from one to the other seamlessly by animating the weight value, and a playable of animation layer mixer, which is the output result of the finite state machine animation. For the finite state machine part, separate control of the upper body, lower body and expression was achieved with *an avatar mask* in Unity3D. In this way, the system can extract the lower body part of a walk cycle animation, the upper body part of a dancing animation, the expression animation of a greeting animation and put them together. Besides, a layer of Inverse Kinematics (IK) animation with weight value is added before the final output of the finite state machine part, which allows using a real-time changing target to drive the character's animation. There are six IK goals, including eye, head, chest, hip, hand and foot, the weight value of which can be assigned separately. In order to achieve a natural eye contact gazing animation of a character, the IK weight value of the eye, head, chest and hip can be set to 100%, 70%, 40% and 20%. Moreover, the 'hub and spoke' pattern with an empty hub node is used as the main pattern to connect different animation clips. This pattern design can seamlessly blend any two animation clips of all clips.

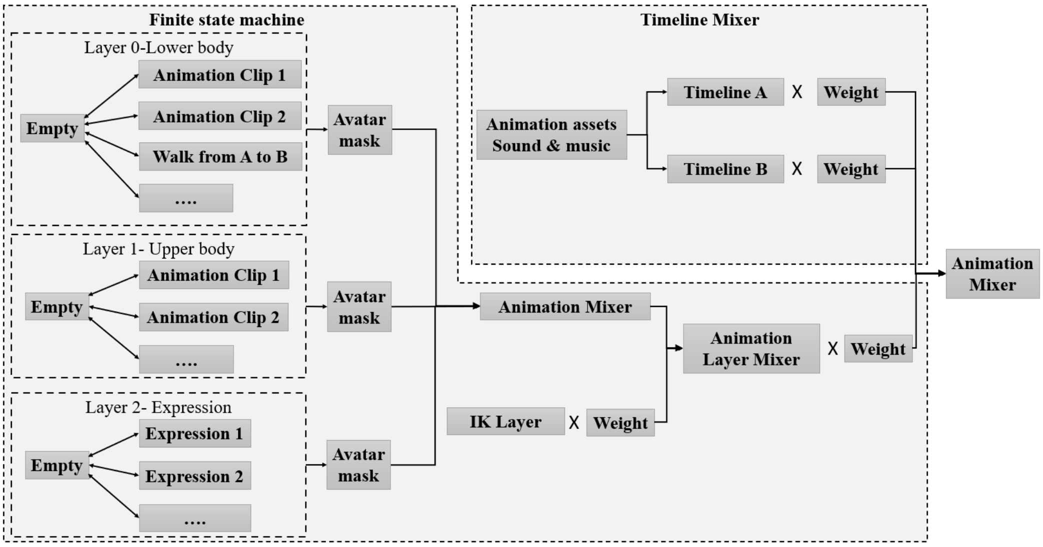


Fig. 4.13 The diagram of the character behaviour module

Props interaction is a crucial part of the overall user experience and the narrative, and there are many different kinds of user interaction, such as opening the virtual newspaper, picking up the virtual telephone, listening to the virtual human figure icon, etc. In order to develop and manage the interactive props efficiently, a general module for interactive props was developed (see Fig. 4.14). There are four states for interactive props: inactive, standby, active, activated. The inactive state is the default state to avoid false triggering, and the standby state can only be activated when the distance between the prop and the audience is less than a threshold value, and the prop is being gazed. In the standby state, hint animations, including glowing highlight, floating text and sound effects, and active state, can be activated if the audience further performs input on the prop. In an active state, the prop animations like unfolding newspaper, rotating vinyl of a gramophone, opening a suitcase are played with audio. Meanwhile, it may also trigger other secondary animations, including character animation and special effects animation. For example, after the gramophone begins playing music, Leo can turn to the audience and introduce how his mother and father danced in the living room with the music in the old days. When all the animations end, the prop automatically enters into an activated state. In this state, a new interface may emerge, e.g., headline, paragraph and illustration on the newspaper are the new interaction interface after the newspaper is spread; a new prop may show, e.g., a diary appears when the suitcase is open, or it may trigger the close animation automatically or manually and set the state back to inactive.

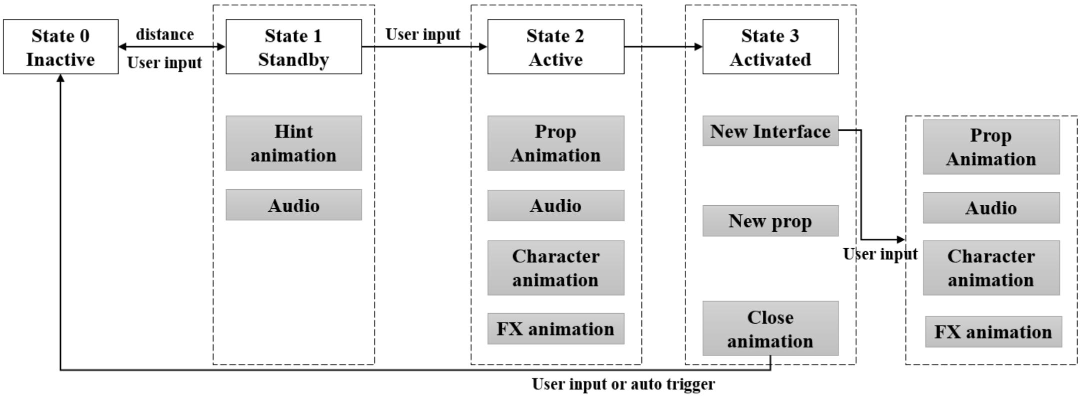


Fig. 4.14 The diagram of the interactive props' module

As discussed in section 3.2, there are two input models in our design: *gaze and commit* with a clicker, a built-in module in HoloLens API, and *gaze and dwell* module, which was developed.

4.4.2. Asset development

Four characters, totally about 40 minutes full-body character animation, several props animation, several partial effects and around 20 User Interface (UI) elements have been created for this project. The visual asset development follows the same rule as script development regarding historical accuracy. Most references came from the National Holocaust Centre and Museum and the online United States Holocaust Memorial Museum.

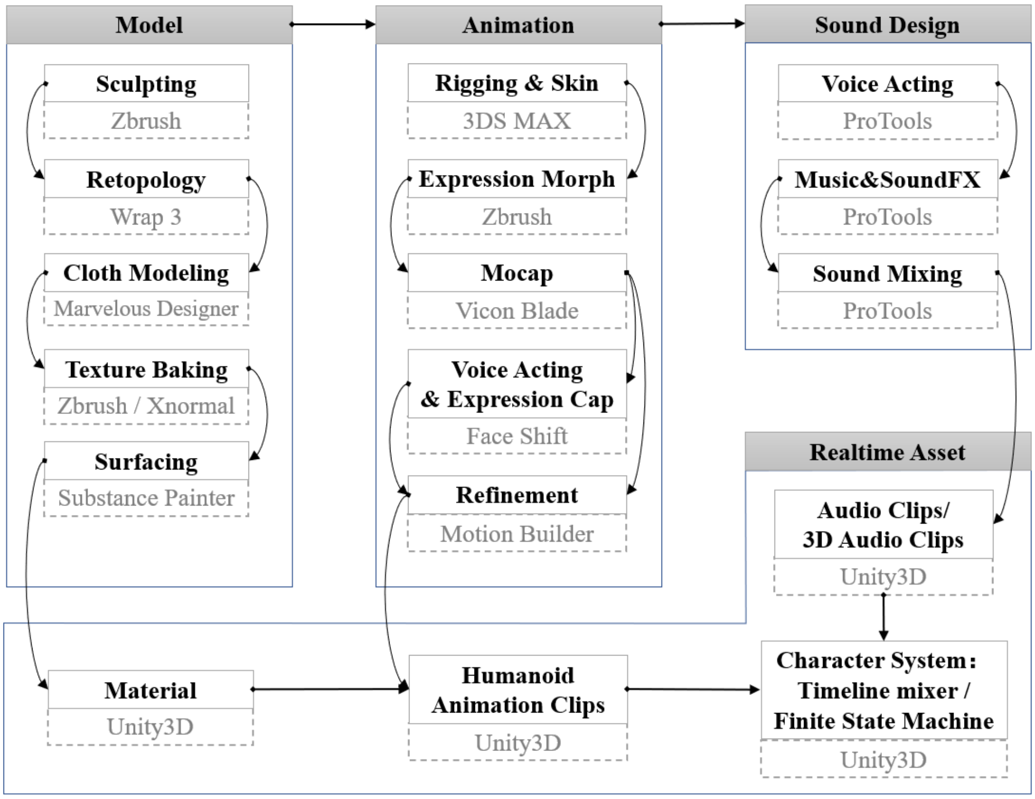


Fig. 4.15 The pipeline of character asset development

Character models and animation are the biggest part of asset development in this project. The character asset development consists of modelling, animation, sound design, and realtime assets (see Fig. 4.15). The realtime asset refers to the assets that are imported and adjusted in Unity 3D, ready for the system architecture. For example, developers need to import the character animation (usually. fbx format) and carefully edit parameters of the imported animation using humanoid functions to get the correct motion clips (.anim file) for character systems in Unity 3D. The visual asset development follows the same rule as script regarding historical accuracy. Most references came from the National Holocaust Center and Museum and the online United States Holocaust Memorial Museum (see Fig. 4.16).

Fig. 4.16 Reference images from Holocaust museums

There are four characters (see Fig. 4.17), about 40 minutes of character full-body animation, around ten props, several partial effects and around 20 UI elements required to be created. The model part follows the latest Physically Based Rendering (PBR) pipeline in the game industry, including collecting references, sculpting in Zbrush, retopology in Wrap 3, cloth modelling in Marvelous Designer, normal map baking with Zbrush and Xnormal, texture painting in Substance Painter, and finally adjusting material in Unity3D (see Fig. 4.18).

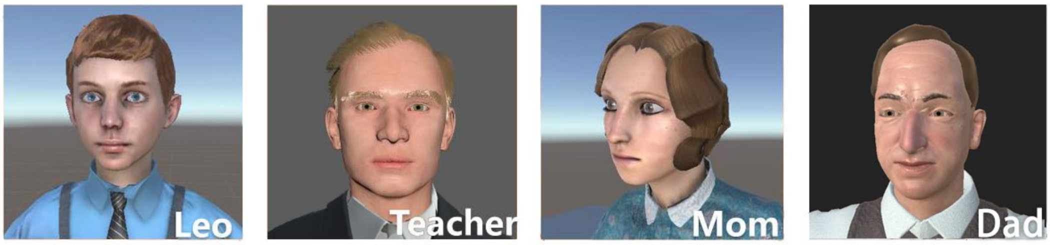


Fig. 4.17 Head models of each character

This pipeline is accessible and effective. It separates the shaping process into two independent steps, sculpting and topology, instead of mixing them as the traditional way does. Moreover, Wrap 3 can efficiently complete the topology task as it can map a standard-topology character model onto the sculpting model instead of retopology manually. Cloth with natural folds is important to make a character visually believable, and Marvelous Designer is the best tool that can precisely create cloth folds quickly. Substance painter is the most popular PBR texture painting tool, however, skin shader is different between Substance Painter and Unity3D. Standard material in Unity3D does not support the Subsurface Scattering (3S) effect, and some third-party materials like LUX 3S material are not supported by HoloLens hardware. Consequently, to make the skin as natural as possible, extra tweaking and adjustment need to be done for standard material in Unity3D.

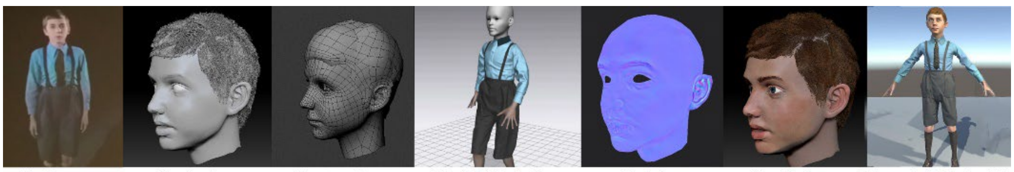


Fig. 4.18 Pipeline of Leo’ s model creation

Three different Motion Capture (Mocap) systems have been evaluated in this project —

Vicon T-series optical Mocap system (12 cameras of 12 megapixels each) with Blade 3.0, Noitom perception neuron sensors-based Mocap system and Nokov optical Mocap system. In the end, it was proved that the Vicon Mocap system had a distinct advantage over the other two. In a word, Vicon can capture three people simultaneously and accurately, while Noitom had a severe bias issue capturing multiple characters. In addition, Vicon Blade can fix the Mocap data efficiently, which is an impossible task for Nokov as there are too many occluded marker points when capturing three people together using only 12 cameras. Fortunately, Vicon has a built-in *Quick Post* function to calculate point cloud data, generating a human skeleton's animation and intelligently filling the missing part of the animation.

Finally, full-body animation was captured with Vicon Mocap system in the Mocap Lab at Tongji University, where we restored the layout of the rooms in the Holocaust Centre to ensure the holographic virtual character could dovetail the real-world space (see Fig. 4.19).

Fig. 4.19 Motion capture for scene 1(left), concept composition of mocap animation and living room (right)

All the animation clips are controlled via an animation state machine. The states include idle, sitting, standing (direction), turning and walking. Specifically, the 'The hub and spoke' pattern is adopted for the animation state machine (see Fig. 4.20). This pattern consists of a central empty state connecting all other states, enabling blending within any two states inside the state machine. In this way, the character could transfer to any given position via natural body movement in real-time.

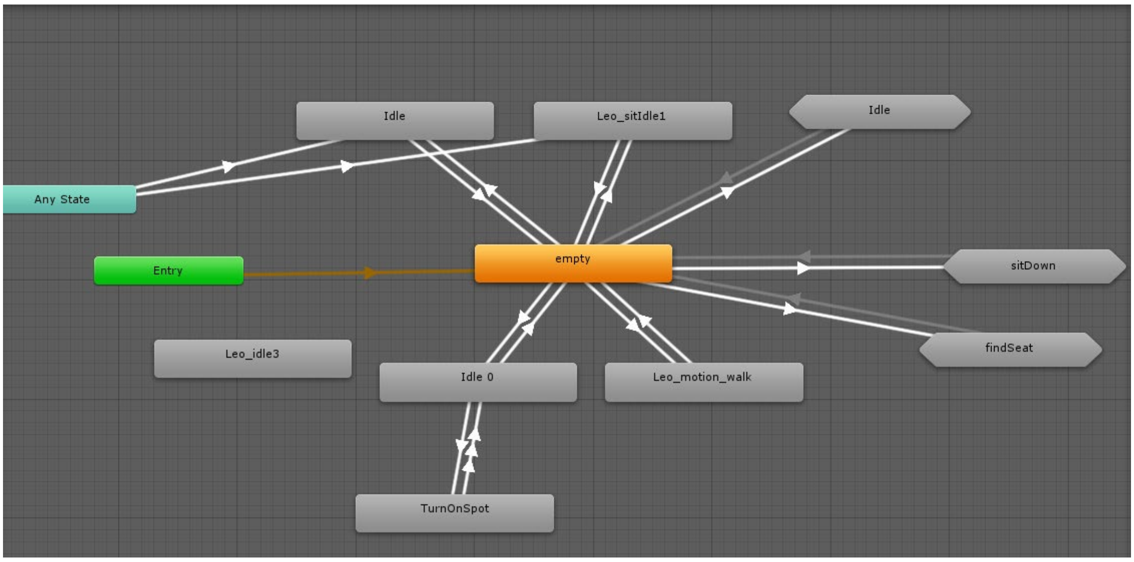


Fig. 4.20 'The hub and spoke' pattern in animator controller

The facial expression capture has been implemented with PrimeSense 1.0, a depth camera and Faceshift software. In order to use Faceshift, 51 expression morphers need to be made to meet the requirement of the internal expression manager of Faceshift (see Fig. 4.21). Students from the acting department of Staffordshire University performed for facial motion capture to match the existing body animation.

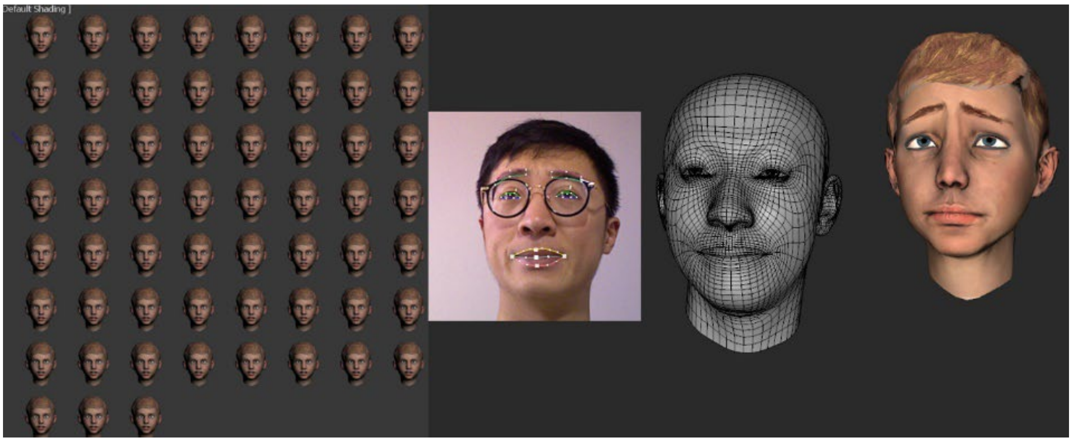


Fig. 4.21 Using Faceshift to perform facial expression capture

The sound design includes ambient sound effects of the environment (e.g., wind, rain, car horns), character sound effects (e.g., breath, cloth friction, contact), sound for props (e.g., radio, newspaper), sound effects of the interface, background music and off-screen voice. In order to make the sound more credible, the voice acting was implemented by actors who speaks English with a German accent. HoloLens headphones can achieve spatial sound via Head

Related Transfer Function (HRTF) technology, making the position and direction of an audio source recognisable in a real-world space. Spatial sound can strengthen the fidelity and direction of the sound effect, character's voice and sound of props. Built-in 3D sound module in Unity3D and Microsoft HRTF Spatializer plugin can deliver the audio into headphones of HoloLens as spatial sound.

4.4.3. **Deployment, optimisation and lessons learnt**

There are two ways to deploy the program from Unity3D to HoloLens: through a USB cable or WIFI. To deploy with WIFI, firstly, HoloLens and the computer for development must be connected to the same LAN, and then Unity3D can publish a .sln file for Visual Studio. Finally, Visual Studio can resolve the .sln file to deploy the program to HoloLens's IP address through remote machine mode. It is important to deploy the program with release mode and X86 solution platform; otherwise, it would lead to a low Frame per Second (FPS) or a failed deployment. In addition, with the same WIFI connected, Unity3D and HoloLens have a feature for quick tests named *Holographic Remoting*. This feature enables the program to run on the computer sending the calculated rendering frame to HoloLens, letting developers see how the program looks in HoloLens in a few seconds. It is much faster than deployment, which may take over 20 minutes, however, holographic remoting is not stable and suffers from a drifting issue but still a good way for a quick preview. In a word, it is recommended to use the holographic remoting feature for preview and to deploy the program with WIFI.

In terms of asset development, due to feedback from interviews for The AR Journey in Experiment 1, the virtual environment's and CG characters' visual qualities were insufficient. I have modified the models and textures of the environment and furniture in the AV/VR version, including increasing the number of furniture props and items such as carpets, walls and ceilings, enhancing the quality of diffuse textures and environment lighting and using a light probe (see Fig. 4.23). For CG characters, I improved the character's skin material and shader by adding a subsurface scattering effect and reducing the ambient occlusion effect, changing the protagonist Leo's hair shader with an anisotropic specular. In addition, I upgraded the randomised idle animation algorithms for Leo. With the new algorithm, Leo can automatically blend among six different idle animations more smoothly. Consequently, Leo behaviours more naturally by occasionally looking at the audience and blinking his eyes. Fig. 4.22 shows the screen captures of the three versions on different devices.

Fig. 4.22 Screen captures of *The Extended Journey*: AR version (left), AV version (middle), VR version (right)

Many experiences and lessons were gained during the challenging development process. The key lessons learned are as follows:

- Character animation merging and refinement issues. Motion Builder is the key tool to process the Mocap data. Motion Builder is optimised for rendering and modifying real-time character animations. For example, Motion Builder can easily handle a 15-minutes shot containing three characters' animation and over 100,000 keyframes, leading to other software crashes or stuck. Besides, its built-in story mode can edit multiple character animation clips and audio using a layered track structure as film editing software. The position and rotation of different animation clips can be automatically re-aligned based on the same bone, such as hip, foot, hand, etc. Animation clips can be blended by overlapping with each other on the track. Therefore, Motion Builder can quickly merge and match the expression animation and body animation and voice acting. Lastly, Motion Builder has a better integrated Forward Kinematics (FK) and Inverse Kinematics (IK) character rigging system, which can adjust the animation faster.
- Expression animation issues. The expression animation captured with Faceshift is not satisfactory for the expression development. Though mouth synchronisation and eyelid animation are acceptable, the eyebrow part, the crucial to express emotions, is inaccurate and obscure. Especially, Asian actors are usually not suitable for expression capture with Faceshift as their faces are usually flat and facial muscles are thin. More advanced facial capture systems like Cara system should be considered if high-quality expressions are requested.
- Interactive pathfinding issue. Pathfinding is a common demand for the interactive

character. In this project, protagonist Leo needs to find the audience and talk to them face to face. Unity3D has a *Navmesh* module for pathfinding, which can dynamically generate a ground surface for navigation based on the 3D scanning data from HoloLens, and the character can avoid the obstacles and find the target on the generated ground surface. Though navmesh offers good results, it is not a perfect solution requiring extra computing. In order to save computing power, a simplified pathfinding module was developed using *animator*. It consisted of turning into the target, walking towards it, and stopping in front of it.

- Real-time shading issue. As HoloLens has limited computing power, it is impossible to use a complicated shader for interior scenes and props. However, it doesn't mean that a realistic image can't be achieved with simplified shaders that are only diffuse and specular. Lighting, baked Global Illumination (GI) and post-process like bloom effect can help to build a realistic atmosphere with a simple diffuse shader (see Fig. 4.23).

Fig. 4.23 The real-world exhibition room(left), the real-time one rendered in Unity3D (right)

- Stabilisation of the hologram in HoloLens issue. Hologram's stability is a common issue in AR. Microsoft has developed and defined several terminologies to describe the hologram's instability, including jitter, judder, drift, jumpiness, swim and colour separation. In order to avoid the above issues, frame rate and frame-rate consistency is the first pillar of hologram stability. 60 FPS is the ideal and maximum frame rate for HoloLens, and 30 FPS or below can lead to obvious drifting or jitter issues according to our tests. Besides, a constantly fluctuating framerate is a lot more noticeable to a user than running consistently at lower frame rates. Furthermore, it's important to choose the right spatial coordinate systems: Stationary Frame of Reference (SFoF) and spatial anchors.

SFoF is a single rigid coordinate system suitable for a small room-scale experience within a 5-meter diameter or moving objects like walking characters and floating UI. Spatial anchors are a multiple coordinate system suitable for world-scale experiences beyond 5 meters, which can mark the important point in the real world, and each anchor stays precisely where it was placed relative to the real world. In this project, spatial anchors coordinate systems are used to stabilise the hologram, and these anchors can be persistent, which are stored and loaded back even when HoloLens restarts. Lastly, HoloLens performs a sophisticated hardware-assisted holographic stabilisation technique known as reprojection. For HoloLens, *Automatic Planar Reprojection* technology is usually used to set a stabilisation plane using the information in the depth buffer. On Unity, this is done with the "Enable Depth Buffer Sharing" option in the Player Settings pane.

- Optimisation for FPS issues. There are many possible reasons to slow down the program. The most effective treatments during our development include: 1) use release mode to deploy the program instead of debugging; 2) set blend weight of skin to 2 bones if possible; 3) keep pixel shader as simple as possible (avoid using standard shader) and use unit or vertex lit if possible; 4) use prebaked textures for shadows and lights instead of real-time; 5) keep texture size under 2048 and generate mipmaps; 6) turn off anti-aliasing and use bilinear filtering; 7) use instancing when ring multiples of the same mesh.

Chapter 5: A Comparison of User Experience through GUI and NUI in HMD-based AR Museum

Experiment 1 was designed to answer RQ1 (see section 1.2) and validate hypotheses 1 and 2 (see section 3.2.5). A mixed approach of the quantitative and qualitative methods was used to find the influence of prior game experience and user interface on the presence and narrative engagement in an HMD-based AR museum. Additionally, in order to finalize the guidance in the interactive narrative design (objective 6), in-depth interviews were conducted, after which the participants' answers were coded and analysed. In this section, the consensus, suggestions and insight that emerged from these interviews regarding sensory experience, interaction experience, and narrative experience are discussed. Finally, the merits and disadvantages of the NUI and the GUI for HMD-based AR museums are evaluated according to the quantitative and qualitative analysis in experiment 1.

5.1. Experimental Protocol

NUI and the GUI (or 3DUI) version of *The AR Journey* developed in chapter 4 were exploited as test materials. Both applications implemented on Microsoft HoloLens 1st generation, offering a FoV of 35° and mass of 579 g, were adopted as the HMD equipment. For the NUI version, physical props were brought and arranged in the space, including a gramophone, a hand-crank telephone, a newspaper, an old radio, a suitcase and a diary book.

The experiment was performed at Tongji University in China, following the procedure described in Fig. 5.1. Participants were randomly assigned to two groups, balancing the gender and RPG experience within each group. Participants were asked to enter the room one by one and go through the experimental procedure individually. Participants in group A experienced the 25-minutes narrative in HoloLens with a virtual interface design, while participants in group B experienced the same narrative in HoloLens with a natural interface (see Fig. 5.2). After the AR narrative intervention, participants were required to complete the post-questionnaire and have an in-depth semi-structured interview.

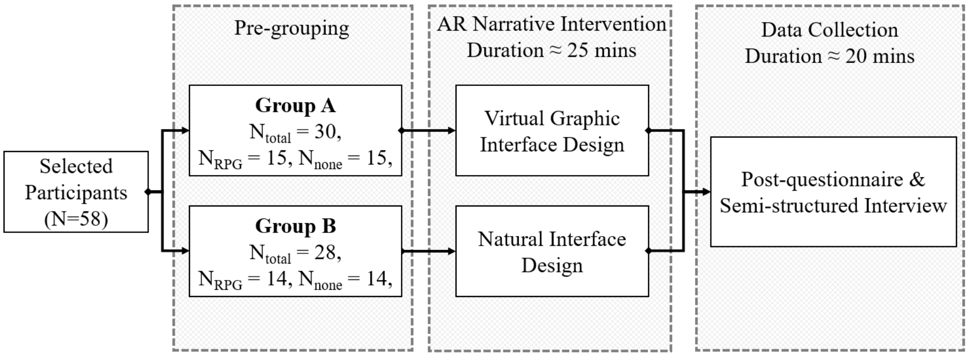


Fig. 5.1 Experimental Procedure, N_{RPG} refers to participants with RPG experience before, N_{none} refers to participants without RPG experience.

Fig. 5.2 Participant was taking part in the experiment in China (left); the hologram mixed into the practical space participants can be observed with HoloLens (right)

5.2. Participants and Design

Due to the impact of the current pandemic of COVID-19, it was not possible to deploy and evaluate the AR narrative app on-site at the NHCM as initially planned. A decision was made to deploy it off-site in China for the experiments and evaluation. Eighty-one university students from Tongji University in Shanghai, China, were recruited and completed the pre-survey for the experiments. Since the intended audience for this narrative experience are young generations, university students can represent part of the generation. Sixty students from various subject areas, e.g., film production, computer science, design, engineering, journalism and telecommunications, were randomly selected based on the balance of gender, subject and previous 3D RPG experience. All the 60 students who volunteered to participate received 10 dollars for each.

As revealed from previous studies, gamers and non-gamers may have different perceptions of virtual environments in terms of immersion, emotions of fear, adaptation to interaction methods (Geslin et al., 2011; Sargunam, Moghadam, Suhail, & Ragan, 2017; S. P. Smith & Du'Mont, 2009). As a result, the 3D RPG experience acted as an independent variable to filter the potential influence of previous gaming experiences.

Two students quitted for equipment failure; both were in group B, i.e., the natural interaction design group. Fifty-eight participants completed the experiment. Table. 5.1 lists the information on their demographics and educational background.

Table. 5.1 Demographic data and RPG experience of the participants

Gender		Age			3D RPG experience	
male	female	min	max	avg.	Yes	No
29	29	19	29	22.07	29	29

5.3. Control Variables and Measures

Three constructs were adopted to assess the user experience from different perspectives, i.e., *presence*, *narrative engagement* and *reflection*.

Witmer and Singer's *Presence Questionnaire (PQ)* (Cronbach a = 0.88,see Appendix A1) (Witmer & Singer, 1998), aiming at virtual environments, was taken to measure *presence*, consisting of 20 *Likert Scale* affirmations with the answers ranging from 1 (totally disagree) to 7 (totally agree). It contained factors of control, sensory, distraction and realism. Two relevant subscales of PQ referred to *Involvement/Control* and *natural*.

The *Narrative Engagement Scale* (Busselle & Bilandzic, 2009) (Cronbach a > 0.8, see Appendix A2) was exploited to assess participants' subjective experience of engaging with a narrative and enjoyment. 11 items were included from 4 dimensions of narrative, i.e., narrative understanding, attentional focus, emotional engagement, and narrative presence.

Since this AR narrative aims at moral development for young people, the educational gain is the attitude and reflection instead of knowledge. A scale was developed to assess the extent to which participants felt empathetic and connected to the protagonist and were provoked to consider meaningful subjects. The connectedness part was adapted from Bartsch's emotional engagement with the characters scale (Bartsch, 2012), and the reflective thinking part was modified from a contemplativeness scale developed in existing studies (Bartsch, 2012; Bartsch, Kalch, & Oliver, 2014). 10 scale items were selected in total, and the wording of the scale items was amended to be relevant to AR experience rather than to film and television, which the scale was initially designed for. All measures complied with a high-reliability rating (Cronbach a > 0.8, see see Appendix A3).

- I had a connection to the people presented in the AR experience;
- I understood how the people in the story were feeling;
- I was able to put myself 'in the shoes' of those depicted in the HoloLens;
- I was able to relate to those depicted in the story;
- I cared about what happened to those shown in the story;
- I was inspired to consider meaningful issues (e.g., equality, wars and race);
- I was inspired to gain novel insights;
- I thought about meaningful or relevant events in today's society;
- I thought about myself in relation to others;
- I found the task thought-provoking.

The scales were translated into Chinese to cater to the participants.

5.4. Quantitative Data Collection and Analysis

A two-way Analysis of Variance (ANOVA) was used to analyse the dependent variables, including presence, narrative engagement, and reflection. Then the interview results were further analysed on sensory experience, interaction, narrative experience and user suggestions.

Participants rated the statements on the questionnaires with seven-point Likert Scales with 7 indicating total agreement. The final score of a scale or subscale was the total of all the ratings in the scale. Shapiro-Wilk test and Levene's test were performed to check normality and homogeneity of variance. As indicated from the result, presence, narrative engagement and reflection data were well-modelled by a normal distribution and exhibited identical variance. Moreover, the subscale control/involvement and natural data of presence were normally distributed on the Q-Q plot. Since there were two categorical independent variables in this study, a two-way analysis of variance (two-way ANOVA) was conducted for the statistical test.

5.4.1. **Presence**

First, a 2 × 2 ANOVA was conducted to assess the presence effects of interaction strategy and previous RPG experience. The analysis yielded several results: a statistically significant main effect of interaction strategy, $F(1, 54) = 5.06$, $p = .029$, $\eta 2 = .086$, a statistically significant main effect of previous RPG experience, $F(1, 54) = 4.30$, $p = .043$, $\eta 2 = .074$, as well as a statistically significant interaction between interaction strategy and previous RPG experience, $F(1, 54) = 12.78$, $p = .001$, $\eta 2 = .191$. As suggested from the examination of Fig. 5.3, the NUI design invoked a better presence for participants without previous RPG experience (P_{none}) than virtual GUI design. In contrast, NUI reduced presence for participants with previous RPG experience (P_{RPG}). P_{none} achieved a mean presence of 93.6 under GUI condition and a mean of 110.79 under NUI condition, representing an unstandardised difference of 17.19 and a Cohen's d of 1.49, respectively. Such a difference was of statistical significance ($p < .001$). P_{RPG} had a mean presence of 110.27 in the GUI and a mean of 106.36 under NUI condition, indicating an unstandardised difference of 3.91 and a Cohen's d of .33, respectively. This difference was of no statistical significance ($p = .36$). This study inferred that the NUI worked for P_{none}, instead of for P_{RPG} regarding presence. Besides, P_{RPG} gained a mean presence of 110.27 under NUI condition and P_{none} had a mean of 93.6 under the identical condition, representing an unstandardised difference of 16.67 and a Cohen's d of 1.54, respectively. This difference was also of statistical significance ($p < .001$). It was concluded that participants with previous RPG experience could have a better presence under the GUI condition than those without such experience.

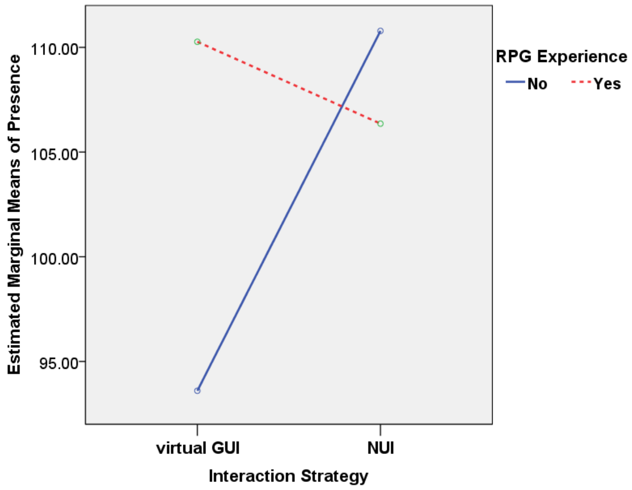


Fig. 5.3 Interaction plot of interaction strategy and previous RPG experience for presence

Further, 2×2 ANOVA was conducted to analyse the two subscales of presence, i.e., *control/involvement(*C/INV*)* and *natural*. Specific to control/involvement, the analysis yielded a statistically significant main effect of previous RPG experience, $F(1, 54) = 4.41$, $p = .041$, $\eta 2 = .075$, as well as a statistically significant interaction between interaction strategy and previous RPG experience, $F(1, 54) = 8.43$, $p = .005$, $\eta 2 = .135$. The main effect of the interaction strategy was slight, p=.35. As indicated from the examination of Fig. 5.4, P_{RPG} achieved a better sense of control/involvement in GUI than $P_{none,}$ whereas it had less control/involvement feelings in NUI. P_{RPG} had a mean C/INV of 36.73 in the GUI condition, and P_{none} achieved a mean of 31.4 under the identical condition, representing an unstandardised difference of 5.33 and a Cohen's d of 1.42. This difference was of statistical significance ($p = .002$). P_{RPG} had a mean C/INV of 34.64 under NUI condition, and P_{none} achieved a mean of 35.5 under the identical condition, representing an unstandardised difference of .86 and a Cohen's d of .23. This difference was of no statistical significance ($p = .56$). It was concluded that the participants with previous RPG experience had more sense of control/involvement than those without the experience under the GUI condition instead of under NUI the condition.

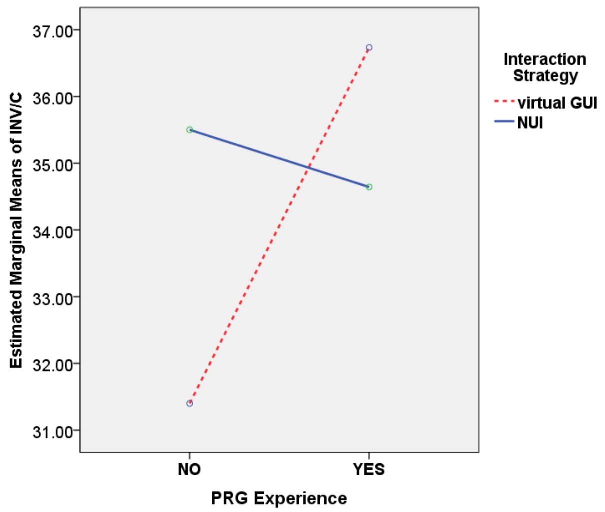


Fig. 5.4 Interaction plot of interaction strategy and previous RPG experience for feelings of control/involvement

Specific to natural feeling, the analysis yielded a statistically significant main effect of previous RPG experience, $F(1, 54) = 4.28$, $p = .043$, $\eta2 = .073$, a statistically significant main effect of interaction strategy, $F(1, 54) = 3.90$, $p = .05$, $\eta2 = .067$, as well as a statistically significant interaction between interaction strategy and previous RPG experience, $F(1, 54) = 8.48$, $p = .005$, $\eta2 = .136$. As indicated from the examination of Fig. 5.5, P_{none} had better natural interaction feelings under the NUI condition. In contrast, P_{RPG} had better natural interaction feelings under the GUI condition. P_{none} had a mean natural feeling of 7.8 under the GUI condition and a mean of 10.29 under the NUI condition, representing an unstandardised difference of 2.49 and a Cohen's d of 1.34. This difference was of statistical significance ($p =.005$). Besides, P_{RPG} gained a mean natural feeling of 10.33 under the NUI condition, and P_{none} had a mean of 7.8 under the identical condition, representing an unstandardised difference of 2.53 and a Cohen's d of 1.55. This difference was also of statistical significance ($p = .002$). Thus, this study concluded that the participants without previous RPG experience had better natural interaction feelings under the NUI condition than GUI, and participants with previous RPG experience had better natural interaction feelings under GUI than NUI.

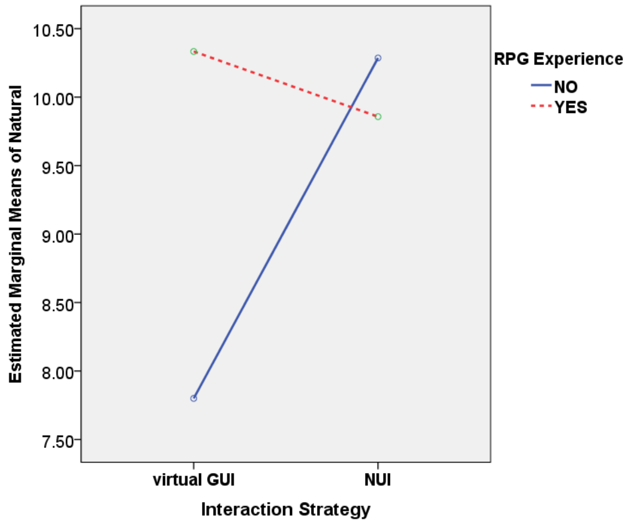


Fig. 5.5 Interaction plot of interaction strategy and previous RPG experience for feelings of natural interaction

5.4.2. **Narrative engagement and reflection**

Moreover, a 2×2 ANOVA was conducted to assess the interaction strategy's narrative engagement and reflection and previous RPG experience. For narrative engagement, the analysis yielded a statistically significant interaction between interaction strategy and previous RPG experience, $F(1, 54) = 6.87$, $p = .011$, $\eta 2 = .113$. The main effect of both independent variables was slight, $p > .05$. As indicated from the examination of Fig. 5.6, the NUI made the narrative more engaging than GUI for participants without previous PRG experience. In contrast, participants with RPG experience were more engaged in the narrative under the GUI condition than those under the NUI condition. P_{RPG} had a mean narrative engagement of 65.93 under the NUI condition, and P_{none} had a mean of 58.8 under the identical condition, representing an unstandardised difference of 7.13 and a Cohen's d of .93. This difference was statistically significant ($p = .027$). The conclusion is that the participants with previous RPG experience have better narrative engagement under the GUI condition than those without such experience.

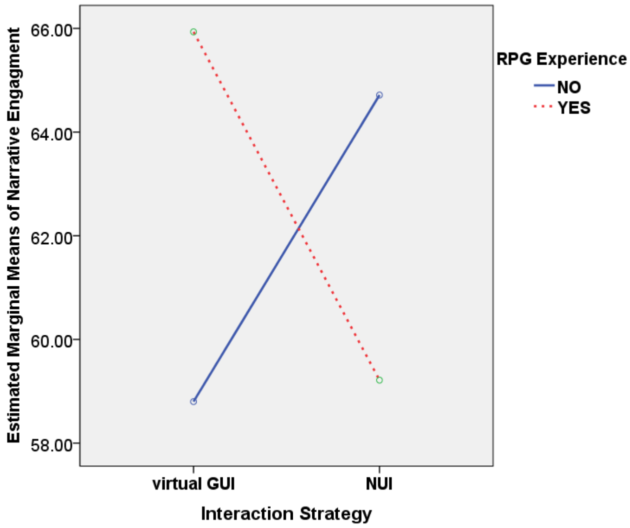


Fig. 5.6 Interaction plot of interaction strategy and previous RPG experience for narrative engagement

With regard to reflection, the analysis also yielded a statistically significant interaction between interaction strategy and previous RPG experience, $F(1, 54) = 5.17$, $p = .027$, $\eta 2 = .087$. The main effect of both independent variables was slight, $p > .05$. As suggested from the examination of Fig. 5.7, the NUI generated more reflection than GUI for participants without previous PRG experience; as opposed to such a result, participants with RPG experience had more reflection under the GUI condition than those under the NUI condition. However, after comparing the mean reflection of four sub-groups, no statistically significant difference was identified ($p > .05$). Accordingly, the conclusion of the relationship between reflection, interaction strategy and previous RPG experience could not be drawn.

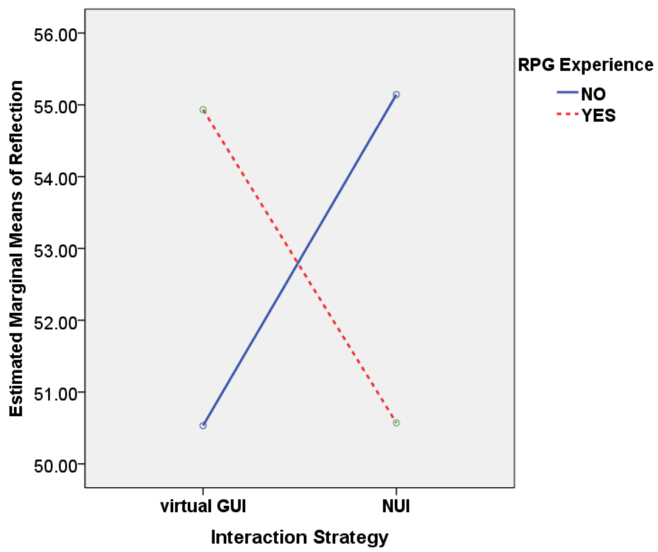


Fig. 5.7 Interaction plot of interaction strategy and previous RPG experience for reflection

5.5. Qualitative Data Collection and Analysis

The present section presents a descriptive analysis of the interview results, which is also expected to underpin the later discussion of design guidelines for AR narrative. Interview questions stressing three main aspects of the user experience of HMD-based AR museum, i.e., sensory experience, interaction experience and narrative experience, are elucidated below:

Q1: Was the overall sensory experience acceptable during this activity?

Q2: How do you like and dislike the sensory experience? Please describe in detail.

Q3: Do you think the interaction methods were fine and easy to use?

Q4: How do you like and dislike the interaction experience? Please give details.

Q5: Did the interactive story make you curious?

Q6: Please describe the narrative experience you felt good and bad.

Q7: Did the AR narrative experience engage you? Will you recommend it to your friends?

Q8: Do you have any other suggestions about improving the interactive AR narrative?

As Q1, Q3, Q5 and Q7 were generally yes or no questions, the interview results could be coded according to participants' choices.

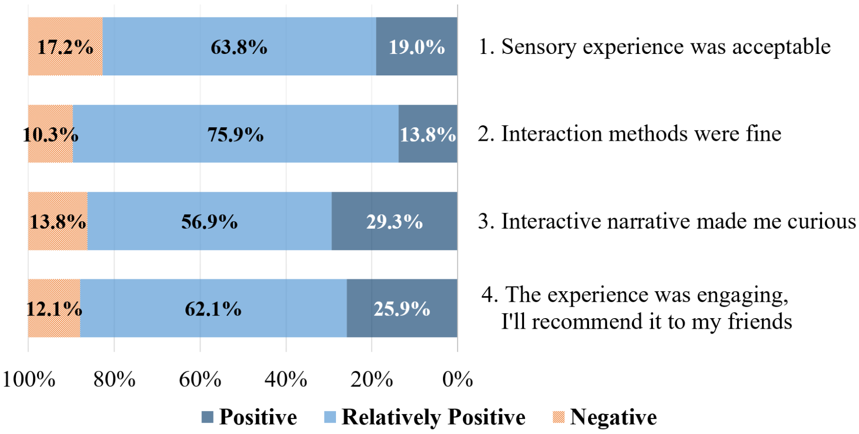


Fig. 5.8 Results for Experience of Sensation, Interaction, Interactive Narrative Design and Overall Feelings

A rough consensus was reached among participants that the AR narrative experience was relatively positive for sensation, interaction, interactive narrative design and overall feelings. Forty-eight participants (82.8%) claimed that the overall sensory experience was acceptable, 52 (89.7%) considered the interaction methods were adequate and easy to use, 50 (86.2%) reported that they were curious about other branches of the story, and 51 (87.9%) said that the experience engaged them so that they would like to recommend this experience to their friends (see Fig. 5.8). In addition, three participants did recommend it to their friends, who later requested this experience from the author. However, as indicated from the in-depth data, only 11 participants (19.0%) agreed the overall sensory experience was attractive, 8 (13.8%) considered the interaction methods to be natural and exciting, 17 (29.3%) generated high interest in exploring other branches of the story, and 15 (25.9%) would highly recommend the AR narrative for both the new medium and content. In contrast, 36 (62.1%) recommended it mainly for the novel experience with HoloLens (see Fig. 5.8). As revealed from the mentioned finding, the experience of AR narrative in HoloLens was okay but not satisfactory.

The remaining four interview questions (Q2, Q4, Q6, Q8) aimed to uncover the problems and merit of the AR narrative, forming a guideline for future designers and discovering the possible reasons behind the previous findings. Unlike the previous four questions, these were formulated as "how" questions. A two-cycle, simultaneous coding procedure was applied to analyse the results. The first cycle established an initial, in vivo coding. The second cycle used a holistic pattern coding method to summarise the content and a point of reference for discussing specific quotes (Saldaña, 2015). Two researchers coded the interview separately, and the results of the two coders were tested for consistency, and the Cronbach coefficient was 0.913.

5.5.1. Sensory experience

In Q2, the participants were asked to describe the positive and negative sensory experiences during the experiment. The second cycle codes and results were analysed according to group type and RPG experience. There was no finding in group type, and the analysis based on RPG experience are presented in Fig. 5.9, in which the horizontal axis shows the percentage of participants who mentioned these in their responses to the total number of all participants.

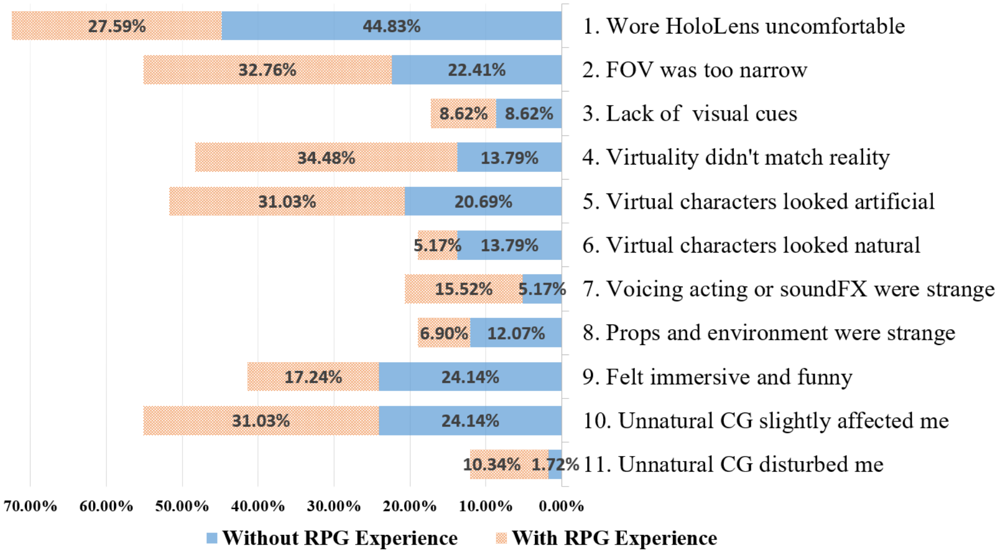


Fig. 5.9 Codes of Question 2

The Code 1 rate of 72.42% indicated that 42 participants reported HoloLens were too heavy or uncomfortable to wear, and 32 (55.17%) reported Code 2, indicating that the FoV was too narrow. Fig. 5.9 also indicated that participants with RPG experience had less trouble wearing HoloLens and less tolerance for the narrow FoV issue than those without such experience. Some comments are presented below:

Participant # 23: "…I couldn't comfortably wear HoloLens, I had to hold it by my hand during the experiment…"

Participant # 14: "…The FoV was far too narrow. I could only see Leo's head when he was in front of me. I had to put my head down to see Leo's legs…"

The statements for Code 3 (17.24% of participants) indicated that the proper visual cue design could potentially alleviate the issue of narrow FoV.

For Code 4, Code 5 and Code 6, 28 participants (48.28%) noticed the CG virtual objects did not match the physical world perfectly, and over half (51.72%) reported the virtual CG characters were artificial and unnatural. 11 participants (18.97%) considered the CG characters to be natural and alive, and 8 of them had no RPG experience. Code 7 further demonstrated that 12 participants (20.69%) thought the voice acting or sound FX were disturbing, and 11 (18.97%) highlighted that the CG props and furniture were arranged or looked strange (Code 8). Fig. 5.9 suggested that participants with RPG experience were more sensitive and stricter to the authenticity of CG characters and the mixture of virtuality and reality. Some statements are detailed below (see more comments in Appendix C1):

Participant # 6 "…the number of the props and furniture was too little. It did not look like a living room…"

Participant # 24: "…When I approached the CG characters and props, they were shifting a little…"

Though many participants reported the unnatural feel of the CG content, Code 10 revealed that over half of participants (55.17%) claimed the unnatural CG content only slightly impacted them during the experiment. Only 7 participants (12.07%) agreed that the unnatural CG content had a negative impact (Code 11), and 6 of them had RPG experience, which was inconsistent with the previous finding that participants with RPG experience tended to be stricter with CG content in AR. Some comments are presented below:

Participant # 6 "…It affected me slightly, as my main focus was on the plot…"

Participant # 58 "…It had a clear influence on me, as my attention was always drawn away by the unnatural characters…"

Lastly, Code 9 indicated that 24 participants (41.38%) reported immersive and funny feelings. Some statements are detailed below:

Participant # 52: "…It is hard to describe, but I had an urge to approach the characters to watch. It made me feel immersive…"

Participant # 14: "…Compared with a movie, the experience was clearly more immersive while I am just a bystander when I watch movies…

In summary, the analysis for the code of question 2 inferred that the main issue of the sensation aspect were HoloLens hardware issues (e.g., heavy mass, narrow FoV) and a mismatch of virtuality and reality. Over the half of the participants noticed the unnatural characters, however, the majority of them claimed the artificialness only slightly affected them. Moreover, participants with RPG experience were more fastidious about the authenticity of CG characters. Less than half of the participants (41.38%) had a positive impression of immersion.

5.5.2. **Interaction experience**

Through a similar vivo coding procedure in Q2, this study attempted to investigate the detailed process of the interaction (Q4). The second cycle codes and results were analysed by complying with the group types. Fig. 5.10 demonstrats the results and the horizontal axis in the figure refers to the percentage of participants who mentioned these in their responses to the total number of participants in each group

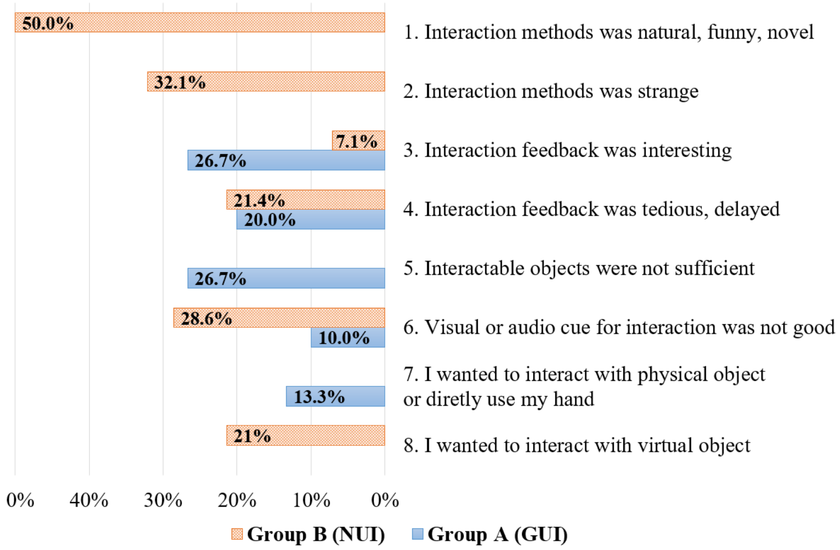


Fig. 5.10 Codes of Question 4

Code 1 and Code 2 indicated a mixed result for the interaction method of GUI. Code 1 demonstrated that 14 participants (50%) reported that interaction methods were natural, funny and novel in group B (NUI), and 10 participants were fond of interacting with a physical object, while 5 participants endorsed talking to virtual characters. However, Code 2 showed that 9 participants felt awkward talking to Leo or uncomfortable interacting with physical objects, and 8 participants denied the design of talking to virtual characters, while 3 participants rejected interacting with physical objects. As revealed from the mentioned finding, NUI could act as a controversial interaction method, probably causing mixed attitudes of users. It is noteworthy that NUI was criticised mainly for natural language design to talk to virtual characters, and interaction through physical objects was more welcome than disapproving. It is also noteworthy that participants in group A (GUI) neither admired nor complained about the interaction methods. Some statements are detailed below:

Participant # 52: "…I like the experience of talking with Leo. Besides, it was also funny and fresh to interact with practical objects …"

Participant # 55: "…It is a very engaging method, especially for opening the suitcase, picking up the telephone…"

Participant # 40: "…I felt distracted to talk with Leo, as you could feel that you were not really talking but answering multiple-choice questions…"

Participant # 43: "…I was afraid what I said couldn't be processed via voice recognition. Therefore, I read the choice word for word. I thought it was silly…"

For Code 3 and Code 4, 8 participants (26.7%) of group A and 2 (7.1%) of group B reported Code 3, indicating that the interaction feedback was interesting; 6 participants (20%) of group A and 6 of group B (21.4%) reported Code 4, suggesting that the interaction feedback was either slow or tedious. Some comments are presented below:

Participant # 12: "…I liked to explore the props. The unfolding animation of the newspaper was amazing…"

Participant # 42: "…It is interesting that the physical objects are capable of generating sound and music…"

Participant # 37: "…Leo's response was too slow…"

Participant # 56: "…The props were extremely simple. Secondary interaction design should be considered and applied in this case. For instance, let the audience open the drawer to find the diary, other than putting the diary directly on the ground…"

Next, only participants (26.7%) of group A reported Code 5, indicating that the number of interactable objects was small and insufficient. Some statements are detailed below:

Participant # 57: "…I would like to interact with more objects…"

Participant # 5: "…I want to open the drawer…"

For Code 6, 9 participants (28.6%) of group B and 3 (10%) of group A, wanted more visual or audio cues for interactable objects. As revealed from the mentioned finding, visual or audio cues were essential and necessary for NUI. Some comments are presented below:

Participant # 48: "...the visual hint was just a line of text floating on the prop. It was too simple..."

Participant # 34: "...I didn't know how to turn on the radio and open the gramophone..."

Lastly, 4 participants (13.3%) of group A hoped to interact with a physical object or directly use one's hand (Code 7), and 6 participants (21%) of group B wished to interact with virtual objects (Code 8). Some remarks included:

Participant # 37: "...I assumed the virtual cabinet could be opened to find a hidden clue..."

Participant # 18: "...If I could interact with practical objects, the experience could be even better..."

Then an analysis based on RPG experience are shown in Fig. 5.11, in which the horizontal axis shows the percentage of participants who mentioned these in their responses to the total number of participants in each group. Code 2 revealed that participants with RPG experience (20.7%) tended to resist NUI more than those without such experience (10.3%). As indicated from Code 4, participants with RPG experience (34.5%) were obviously keener for slow and tedious feedback than those without such experience (6.9%). Besides, according to Code 5 and Code 7, the number of participants without RPG experience who requested more interaction hints and more interactive items was three times those with RPG experience. Moreover, participants without RPG experience generated more interest in a mixture of virtuality and physical object interactions than those with RPG experience.

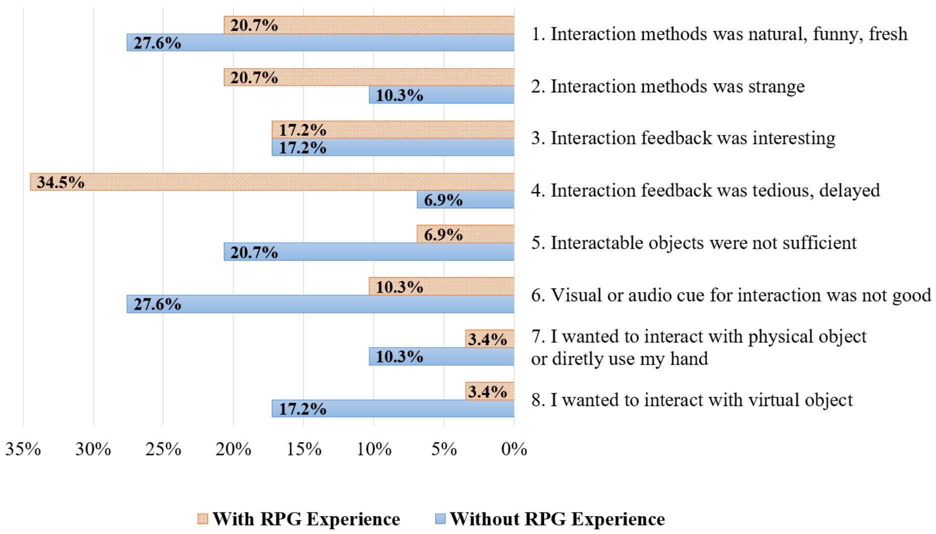


Fig. 5.11 Codes of Question 4

In brief, the current GUI can be concluded as a reliable interaction method that does not cause either unpleasant experiences or pleasant emotions. Besides, the number of interactable objects may impact participants' experience, especially under the GUI condition (Code 5). In addition, NUI is a controversial interaction method that frustrates one-third of the participants for its natural language interaction with a virtual character, whereas it is also praised by half of the participants for its natural and novel experience. Moreover, participants with RPG experience were inclined to oppose NUI more. Besides, good visual or audio cue design might be essential for NUI and participants without RPG experience (Code 6). Slow interaction response should be avoided, and a range of interaction feedback should be designed (e.g., animation, audio and characters' actions), especially for participants with RPG experience. Lastly, though few participants requested, a mixed interaction experience inquiry that users can interact with virtuality and reality should not be neglected, especially for those without RPG experience.

5.5.3. **Narrative experience**

In Q6, the participants were asked to describe their positive and negative narrative experiences. The second cycle codes and results were analysed by complying with group type and RPG experience, and no findings were identified. Thus, the code results were presented as a whole instead of into groups (see Fig. 5.12). The horizontal axis of Fig. 5.12 shows the percentage of participants who mentioned these in their responses to the total number of participants.

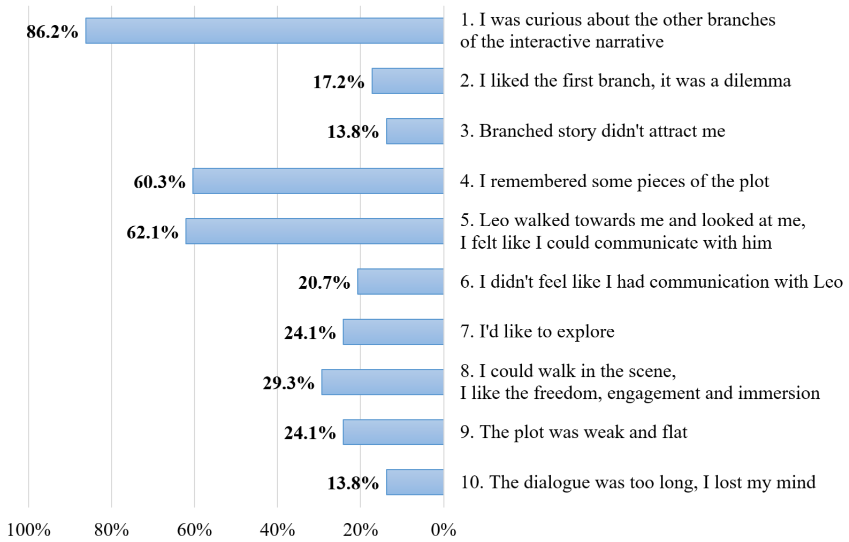


Fig. 5.12 Codes of Question 6

Fifty participants (86.2%) reported that they were attracted by the branching interactive narrative (Code 1), and 10 (17.2%) mentioned that they liked the first branch since it was a dilemma to support Leo's mother or father (Code 2). Besides, only 8 participants (13.8%) stated that the branching story was not attractive. This finding showed that branching narrative design was conducive, and dilemma choice was potentially effective in branch design. Some comments are presented below:

Participant # 22: "…especially the disagreement between mom and dad. It asked you to make a decision. I was gaining insights at that moment…"

Participant # 11: "…I was not curious. No conflict was suggested between different choices for me…"

Participant # 32: "…I had a feeling that the choices I made wouldn't affect the story…"

Moreover, 35 participants (60.3%) stated that they remembered some pieces of the story (Code 4), and 21 (36.2%) remembered the dispute between mom and dad. As indicated from this finding, this AR interactive narrative was relatively positive for storytelling. Some statements are detailed below:

Participant # 22: "…I could basically recall all the plot. I more clearly remembered the quarrelling between mom and dad…"

Participant # 33: "…I could recall the plot through the physical objects in this room. For instance, the telephone reminded me the dangerous situation of Leo's family…"

Furthermore, as demonstrated by Code 5, 36 participants (62.1%) had a sense of communicating with Leo when Leo was walking towards and looking at them. As opposed to the mentioned, Code 6 presented that 12 participants (20.7%) did not have a feeling of communicating with Leo. As implied from this finding, virtual characters' eye contact and finding behaviour were generally valid to improve virtual characters' presence. Some statements are detailed below:

Participant # 22: "…As Leo looked at me and he could find and walk towards me, I gained a strong sense that Leo was communicating with me…"

Participant # 33: "…the feeling was relatively strong…when I saw Leo walking towards me, I stood up to transfer my seat to him…"

Participant # 21: "…It was week. Leo's response was slow. I also tried to move a step. However, Leo did not follow me but stood in place…"

Next, Code 7 and Code 8 suggested the merit of AR interactive narrative. Fourteen participants (24.1%) expressed that exploration in the space was attractive, and 17 participants (29.3%) mentioned that walking in the scene and the freedom of focus was helpful to improve engagement and immersion. Some remarks included:

Participant # 26: "…I thought it was fascinating to explore the props and find clues…"

Participant # 25: "…I could choose what I want to see. I felt I was together with them, listening to them. It was engaging…"

Participant # 17: "…Since I could walk around and interact with Leo, I got the feeling that the story was happening just in front of me…"

Lastly, Code 9 and Code 10 implied the defect of the narrative in this study. Fourteen participants (24.1%) claimed that the plot was weak and flat, and 8 participants (13.8%) complained about the interminable dialogue, which made them absent-minded sometimes.

In summary, branching narrative design was attractive, and eye contact and finding behaviour of virtual characters were proven effective design strategies to generate certain character presence. The narrative experience was positive regarding the short-term memory of the plot. As the evidence was insufficiently strong, exploration, walking around in the scene and the freedom of focus might lead to positive feelings of the participants. Moreover, a flat plot and long dialogue could cause negative feelings in the participants.

5.5.4. Suggestions for improving HMD-based AR museums

In Q8, additional suggestions about improving the experience were asked. The responses were collected and then analysed. The repeated pattern in this response was extracted and listed:

1) The virtual character could call participants by their names to make participants feel more connected to the virtual character.
2) The virtual character could assign actions for participants to make them feel involved (e.g., *follow me*, *please help me pick the newspaper*).
3) To make participants more engaged in the story, let participants play a role in the narrative and sit next to virtual characters to talk.
4) Place participants into a dilemma at the branches of the narrative.
5) Design internal links between different narrative branches to make participants believe the branches are dependent.
6) Put more virtual or real-world furniture or decorations into the environment to make participants more immersive.
7) Virtual characters should be designed with actions and performance other than simply talking.
8) Design the story with more dramatic conflicts to build tension.

5.6. Discussion: NUI vs. GUI

The merits and disadvantage of the NUI and the GUI for HMD-based AR museums were discussed according to the quantitative and qualitative analyses performed in experiment 1. Data from experiment 1 was compared with the findings from previous studies and possible explanations were given for the phenomena. One challenge the author encountered was keeping virtual objects and virtual people consistent with the real-world objects and people in relation to the user's perception.

There are two clear advantages of NUI for the HMD-based AR museum. According to the quantitative results in experiment 1 (see Section 5.4.1), the analysis showed that the AR narrative with a NUI without the RPG experience led to more presence for the than the audience with the RPG experience. These findings are consistent with those of existing studies

(Brondi et al., 2015; Shafer, Carbonara, & Popova, 2011). The qualitative results indicated that half of all participants held a positive attitude towards NUI. One possible explanation for this could be that the tangible objects of NUI also act as shared items between the audience and the protagonist. This helps to blur the boundary between the audience and the narrative world (Gupta, Tanenbaum, & Tanenbaum, 2019). Additionally, the interview results from Section 5.5.2 revealed that NUI could give users a novel and potentially more engaging experience. Of the NUI participants, 50% reported feeling both amazed and amused, while these findings were not replicated by the GUI participants.

However, there were challenges in effectively implementing NUI. The following unexpected result emerged: audiences with previous RPG exposure experienced less presence in the NUI design than those in the GUI design. Furthermore, quantitative results further revealed that audiences with previous RPG exposure had a better experience in GUI than those without such exposure, particularly in terms of presence. Moreover, based on the qualitative results, participants with previous RPG exposure were more likely to have fixed responses and experience negative emotions when talking to virtual characters, which is an unusual design for most RPGs. Since RPGs primarily rely on GUI for interaction, though a few games do use NUI, the above findings might be explained by the fact that participants with RPG experience could inherently have a stronger preference for GUI. One research study reported a similar finding, as they found that people who had one type of interaction experience (desktop) before performing an identical task with a new interaction system (VR) performed worse than first timers without any experience (Pausch, Proffitt, & Williams, 1997). In our case, the findings may be due to inappropriate visual or audio cues linked with performing an interaction. Around one-third of participants using NUI complained about the hints linked with interaction, while 10% of GUI participants reported the same issue (see Section 5.5.2). These same users may feel confused and uncertain when using NUI.

Another challenge of NUI is the coherence of virtuality and reality in terms of perception. Conflict between virtuality and reality presents itself in two ways. The first is the mismatch of virtual sound and real-world objects. For example, the user must connect hearing the ringing of a telephone in the headset with the physical telephone in the real world. In another example, when the user shakes the gramophone's handle, they must understand that the action triggers the song playing in the headset. Spatial sound with direction is helpful for establishing the above connection. Another issue is the cognitive dissonance between the real-world voice and the virtual characters. For example, users are expected to treat the virtual characters as real when they are talking to them, instead of seeing them as a Siri-like form of artificial intelligence. Otherwise, users may feel uneasy. Section 5.5.2 pointed out that about one-third of participants using NUI encountered this issue.

5.7. **Summary**

Experiment 1 investigated RQ1, which concerns the difference between the impact of NUI and GUI (or 3DUI) on user experience in the HMD-based AR museum. The qualitative research suggested that the overall user experience of HMD-based AR museum is acceptable (over 80% of participants agreed) in terms of its sensory experience, interaction methods, and narrative experience. However, the H1 and H2 were not supported by the quantitative results. Instead, they showed that the influence of interaction mapping on presences and narrative engagement for HMD-based AR museum is moderated by prior game experience. For example, the NUI design has been proven to have better performance than the GUI design for *presence* with users without RPG experience. Meanwhile, the GUI design exhibits better performance than the NUI design in terms of *presence* and *narrative engagement* for users with RPG experience. Furthermore, in terms of narrative experience in HMD-based AR museums, the interview results identified branching narrative design and intelligent behaviour in characters, such as eye contact and seeking behaviour, as effective strategies for enhancing users' engagement. Finally, the qualitative results helped to reveal issues of sensory experience, including HoloLens hardware issues and the mismatch of virtuality and reality.

According to the above interviews and questionnaires in this experiment, I made several important improvements to the interaction design, asset development and experiment.

As described in section 4.3.3, direct manipulation is used instead of HoloLens clicker as the interaction method for prop interaction and CG character interaction; multi-layered interaction feedback is used instead of single interaction feedback, and highlighting outline shader is used instead of floating text as the visual cues for interaction. Section 4.4.3

described the improvement of the models and materials for environment assets and CG characters, as well as the motion blending algorithm for idle animation.

Moreover, the following four areas have been enhanced:

1. Narrative: More story fragments have been added to the interactive props, for example, opening a drawer to reveal a camera, toys, and more, telling the story of how Dad used to love photography before the World War and sister Hanna's favourite rattle drum.

2. Interaction: The number of interactive objects has been increased based on feedback from interviews, including the "meaningless" interaction without story pieces, such as opening drawers, moving chairs, and picking up cups.

3. Hardware: The program was migrated to the HoloLens 2nd generation in the AV version. One of the most unsatisfactory sensory experiences mentioned by many participants was the narrow FoV of HoloLens 1st generation in experiment 1, while HoloLens 2nd generation has a significantly larger FoV.

4. Interview: The interview in the following experiments included whether novelty was the main reason why participants liked or supported the immersive XR museum experience, in order to exclude the impact of the novelty of XR technology.

Chapter 6: A Comparison of Learning Effectiveness of HMD-based VR and AV in Between-Subjects Design

Experiment 2 was designed to partially answer RQ 2 and 3(see section 1.2), while also validating hypotheses 3, 4, 5, 6, and 8 (see section 3.2.5). For RQ2, it was hypothesised that an HMD-based VR museum could encourage more narrative engagement and increase learning motivation in comparison to an HMD-based AV museum. A mixed approach of quantitative and qualitative methods was used for experiment 2. The influence on narrative engagement, learning motivation, and reflection were then assessed via quantitative analysis. Structured interviews were conducted in order to dig deeper into the details of the user experience and the perceived narrative experience. Following this, the participants' answers were coded and analysed. The section then summarised the consensus, suggestions, and insights drawn from the interviews regarding acceptance of the HXRM and the HMD devices, interaction and narrative experience, and the CG character's affinity.

6.1. Experimental Protocol

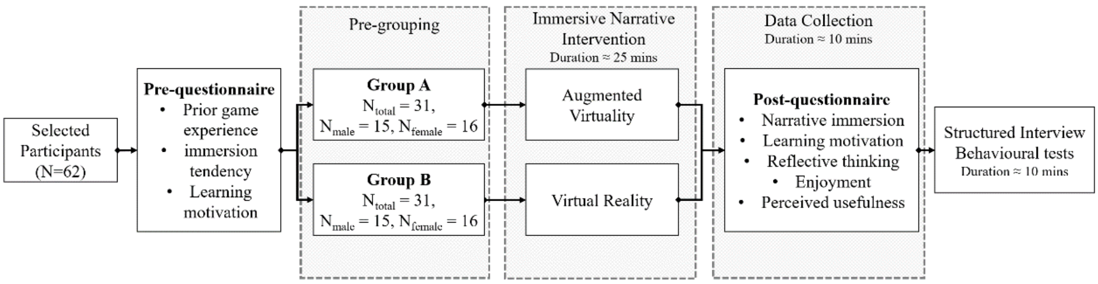


Fig. 6.1 Flow Chart of Procedures of Experiment 2

As Fig. 6.1 shows, participants were assigned to different conditions after a pre-questionnaire with the Immersion Tendency Questionnaire (ITQ), Learning Motivation Questionnaire (LMQ) measures and a quick introduction to the Holocaust. They entered the laboratory to experience the AV version or the VR version for approximately 25 minutes. Then participants were invited to another room to finish the post questionnaire, which measured the dependent variables, including learning motivation, reflection, narrative immersion, enjoyment and perceived usefulness. When the post questionnaire was completed, the participants were interviewed. Afterwards, a structured interview was conducted focusing on participants' good and bad experiences during the intervention and their comments for HMD-based immersive narrative compared with traditional narrative. Finally, all participants were thanked and asked if they were willing to scan a Quick Response (QR) code to get further information about the Holocaust and register for the further HMD-based narrative experiments with AV and VR next month voluntarily.

6.2. Participants and Design

Sixty-four participants (32 females, 32 male, Tongji University, Shanghai, China) were recruited and asked to complete a pre-questionnaire of ITQ(Witmer & Singer, 1998) and the precontemplation part of LMQ(Cole et al., 2004). The experiment uses a between-subjects design, and the participants were then split into two groups. Each group is balanced on their gender. 2 groups were then assigned to the AV group with HoloLens 2nd generation and VR group with HTC Vive Pro Eye. The age of the participants ranged from 18 to 26 years; the average age was 21.09. Due to equipment failure, two participants, one male from the AV group and one male from the VR group, withdrew from the experiment midway. Thus, 62 participants completed the experiments, and half of them joined the AV group while half joined the VR group. The participants in each group were balanced mainly in terms of gender (15 male versus 16 female).

6.3. Control Variables and Measures

Control variables that served as potential moderators were assessed before the manipulation, including different media (HMD VR or HMD AV) and gender. Immersion tendency (see Appendix A7), previous experience of 3D RPG, Familiarity of the story context and spontaneous learning interest served as covariates.

Several instruments were used to measure three dependent variables, narrative immersion, perceived usefulness and learning outcome, including learning motivation and reflection.

The *Questionnaire of Player Immersion in Computer Game Narrative* (Cronbach a = 0.87,see Appendix A5) (H. Qin, P. L. Patrick Rau, & G. Salvendy, 2009) was adopted for narrative immersion. This instrument was developed and modified from an immersion scale for video games, and it adds additional dimensions to comprehension of the story and empathy. Therefore, the instrument was not only suitable for a story-driven video game but also was able to measure user engagement and immersion in story-oriented VR or MR.

Learning motivation was measured by the Stage of Learning Motivation Inventory (SOLMI)(Cronbach a =0.87, see Appendix A9) (Cole et al., 2004). This instrument included four parts: precontemplation, contemplation, preparation and action. Precontemplation was proved as an independent negative predictor. Therefore, this part was used in the pre-questionnaire to measure the initial tendency for learning Holocaust. Contemplation and preparation parts were used to measure the learning motivation. The action part was positively associated with the learning outcome. However, it could only be assessed through a long-term learning cycle. Thus, behavioural tests, like scanning a QR code, were used to get further information about Holocaust and registration for further Holocaust learning with AR and VR.

Reflection was measured by a scale (Cronbach a =0.893, see Appendix A8)(Bartsch, 2012), which shows how a participant was provoked to think about meaningful subjects. This measure was pertinent because interactive narrative with the museum aimed to provide the public with inspiration, learning and reflection opportunities.

Enjoyment was measured using a scale (Cronbach a =0.87, see Appendix A4) developed and validated for measuring enjoyment of computer games(R. M. Ryan, Rigby, & Przybylski, 2006). As with reflection, it was used in this instance as a desirable measure from the museum's point of view to satisfy public engagement motives.

The *Scale of Perceived Usefulness* (Cronbach a =0.98, see Appendix A6) (Davis, 1989) was used to measure perceived usefulness. The wording of the questions has been adjusted to fit the context of the HMD-based XR museum and the learning objectives of moral education.

6.4. Quantitative Data Collection and Analysis

Participants rated the statements on the questionnaires with five-point Likert Scales, with 5 indicating total agreement. The final score of a scale or subscale was the total of all the ratings in the scale. A two-way Analysis of Covariance (ANCOVA) was used to analyse two dependent variables quantitatively, including the narrative immersion, empathy and learning motivation. A two-way ANOVA was used to analyse the dependent variable of reflection.

6.4.1. Narrative immersion

A 2 by 2 between-groups analysis of covariance was conducted to assess the narrative immersion of the two HMD-based media for male and female participants. The independent variables were the media type (HMD AV and HMD VR) and gender. The dependent variable was scored on the narrative immersion, administered following completion of the intervention program (AV or VR narrative experience). Scores on the immersion tendency and Familiarity with the Cultural Context of the Story (FCCS) administered prior to the commencement of the programs were used as a covariate to control for individual differences.

Preliminary checks were conducted to ensure that there was no violation of the assumptions of normality, linearity, homogeneity of variances, homogeneity of regression slopes, and reliable measurement of the covariate. Shapiro-Wilk test, Q-Q plot and Levene's test were performed to check normality and homogeneity of variance. As indicated from the result, narrative immersion and its' subscales, including curiosity, concentration, comprehension, control, and empathy, were well-modelled by a normal distribution and exhibited identical variance. Fig. 6.2 showed that the regression lines of narrative immersion based on different media groups were almost perfectly parallel. Linear regression was further carried out to validate that immersion tendency significantly predicted narrative immersion and its subscales, including concentration and empathy, narrative immersion: the model explained 12.5% of the variance and that the model was significant, $F(1,60)= 8.549$, $p=.005$; concentration: the model explained 8.3% of the variance and that the model was significant, $F(1,60)= 5.425$, $p=.023$; empathy: the model explained 10.8% of the variance and that the model was significant, $F(1,60)= 7.266$, $p=.009$. Linear regression was also to validate that FCCS significantly predicted narrative comprehension, $F(1,60)= 6.257$, $p=.015$.

Furthermore, ANCOVA was run to examine the homogeneity of regression slopes assumption. The covariate (immersion tendency) by treatment (media group) interaction was not statistically significant: F(1,58) = 0.14, p = .906, and the covariate (immersion tendency) by gender interaction was also not statistically significant : F(1,58) = 2.21, p = .143. The covariate (FCCS) by treatment (media group) interaction was not statistically significant: F(1,56) = 1.601, p = .211, and the covariate (FCCS) by gender interaction was also not statistically significant : F(1,58) = .723, p = .399. Therefore, the data met the homogeneity of regression slopes assumption required by ANCOVA.

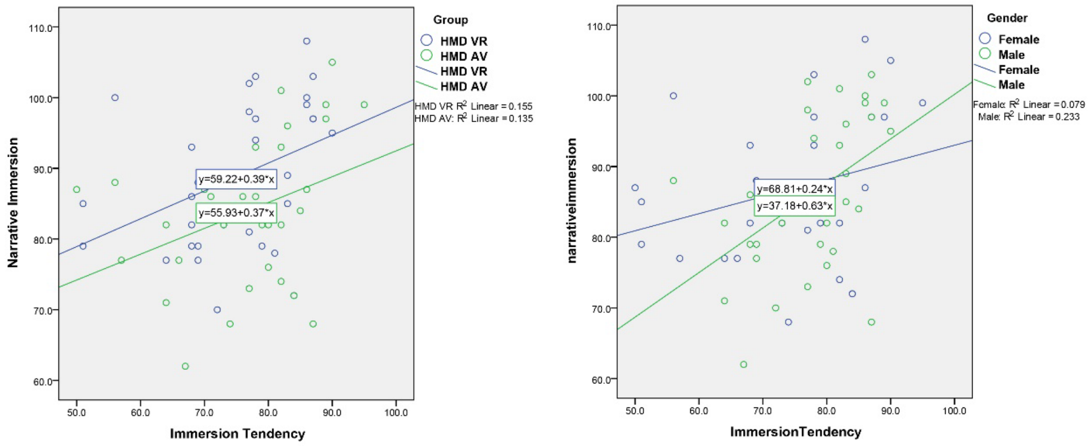


Fig. 6.2 Scatter plot of narrative immersion based on the different groups (left); scatter plot of narrative immersion based on gender (right)

After adjusting for narrative immersion scores, there was no significant interaction effect. F (1, 57) = .117, p = .733, η2 = .002, and none of the subscales from narrative immersion was statistically significant, including curiosity, concentration, comprehension, control, and empathy. The main effect of media was statistically significant F (1, 57) = 5.022, p = .029,η2 = .081. In addition, the main effect of media was also statistically significant for two subscales of narrative immersion, concentration: F (1, 57) = 5.696, p = .02, η2 = .091; empathy: F (1, 57) =5.007, p = .029, η2 = .081. The main effect of gender wasn't statistically significant F (1, 57) = .912, p = .344, η2 = .016. However, the main effect of gender was statistically significant for the concentration subscale F (1, 57) = 6.799, p = .012, η2 = .107. These results suggested that HMD AV and HMD VR led to different narrative immersion. The narrative immersion under HMD VR condition (M =89.303^{a}, SD =1.799)[38] was higher than HMD AV condition (M =83.608^{a}, SD =1.788). Such a difference was of statistical significance ($p < .05$) with a medium effect size (η2 = .081). In addition, the empathy (M =23.792^{a}, SD =.684) and concentration (M =12.653^{a}, SD =.359) under HMD VR condition were also higher than empathy (M =21.63^{a}, SD =.68) and concentration (M =11.442^{a}, SD =.357) under HMD AV condition, and these differences were of statistical significance ($p < .05$) with a medium effect size (η2 > .06). On the other hand, gender had no statistically different influence on narrative immersion, except the concentration of female (M =12.716^{a}, SD =.366) was higher than male (M =11.379^{a}, SD =.353), and difference was of statistical significance ($p < .05$) with a medium effect size (η2 =.107).

Finally, a regression analysis was used to test if the narrative immersion significantly predicted participants' perceived enjoyment in the context of HXRM. The analysis showed that the narrative immersion did not significantly predict the perceived enjoyment (B=-.2, Beta = -.13, t(61) =-.70, p= .485). In addition, analysis was used to examine if the narrative immersion significantly predicted participants' perceived usefulness. The results of the regression indicated the predictor explained 22% of the variance of the perceived usefulness (R^2 =.22, R^2Adjusted = .20, F(2,59)=8.37, p=.001). The narrative immersion level did significantly predict value of perceived usefulness (B=.21, Beta = .54, t(61) =2.98, p= .004).

In short, HMD VR made the user easier to concentrate on the story and share the protagonist's feelings than HMD AV, thereby arousing more narrative immersion. Besides, narrative immersion significantly predicted participants' perceived usefulness in the context of HXRM.

6.4.2. Learning motivation

A 2 by 2 between-groups analysis of covariance was conducted to assess the learning motivation of two HMD-based narrative media for male and female participants. The independent variables were the media type (HMD AV and HMD VR) and gender. The

[38] Adjusted mean. Covariates appearing in the model are evaluated at the following values: Immersion Tendency= 75.903.

dependent variable was scored on the learning motivation, administered following completion of the intervention program (AV or VR narrative experience). Scores on the Precontemplation Learning Motivation (PLM) administered before the commencement of the programs were used as a covariate to control for individual differences.

Preliminary checks were conducted to ensure that there was no violation of the assumptions of normality, linearity, homogeneity of variances, homogeneity of regression slopes, and reliable measurement of the covariate. Shapiro-Wilk test, Q-Q plot and Levene's test were performed to check normality and homogeneity of variance. As indicated from the result, learning motivation was well-modelled by a normal distribution and exhibited an identical variance. Linear regression was further conducted to validate that PLM significantly predicted learning motivation: the model explained 28.8% of the variance and was statistically significant, $F(1,60)= 24.285$, $p<.001$. ANCOVA was run to examine the homogeneity of regression slopes assumption. The covariate (PLM) by treatment (media group) interaction was not statistically significant: $F(1,58) = 0.244$, $p = .623$, and the covariate (PLM) by gender interaction was also not statistically significant : $F(1,58) =1.374$, $p = .246$. Therefore, the data met the homogeneity of regression slopes assumption required by ANCOVA.

After adjusting for learning motivation scores, there was marginally significant interaction effect, $F (1, 57) = 2.884$, $p = .095$, $\eta 2 = .048$. However, the main effect of media wasn't statistically significant $F (1, 57) = 1.315$, $p = .256$, $\eta 2 = .023$. In addition, the main effect of gender also wasn't statistically significant $F (1, 57) = .009$, $p = .925$, $\eta 2 < .001$. As Fig. 6.3 showed, For HMD VR, the learning motivation of female ($M =22.743^a$, $SD =.659$).[39] was higher than the male's score ($M =21.725^a$, $SD =.599$). On the other hand, for HMD AV, the learning motivation of males ($M =22.08^a$, $SD =.64$).[40] was higher than the female's score ($M =20.942^a$, $SD =.63$). In short, HMD VR was more effective for females than males, while HMD AV was more effective for males than females in evoking learning motivation.

Finally, a regression was conducted to see if learning interest predicted the narrative

[39] Adjusted mean. Covariates appearing in the model are evaluated at the following values: Immersion Tendency= 75.903.

[40] Adjusted mean. Covariates appearing in the model are evaluated at the following values: Immersion Tendency= 75.903.

immersion of the HXRM. Using the enter method it was found that learning interest explain a significant amount of the narrative immersion of HXRM (F(1, 60) = 8.15, p =.006, R^2 = .12, R^2Adjusted = .11, B = -1.27, beta = -.35).

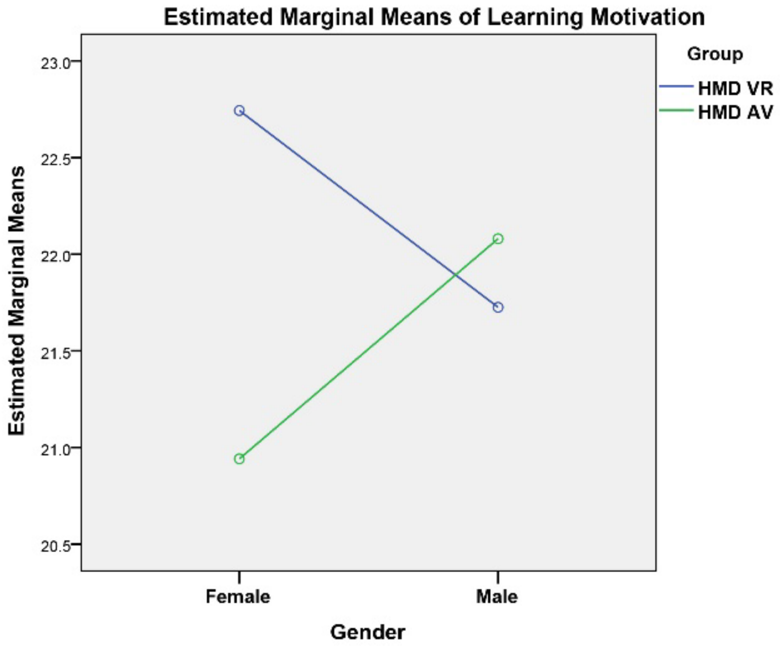


Fig. 6.3 Estimated Marginal Means of Learning Motivation

Additionally, in the behaviour test, participants were asked if they were willing to scan a Quick Response (QR) code to get further information about the Holocaust. 53 participants (85.5%) chose to voluntarily scan the QR code on-site for learning resournces about Holocaust. Although the scanning action is a low-cost learning behaviour, it can also be considered as a preparation for future learning brought by the increased learning motivation.

6.4.3. Reflection and empathy

First, a 2 × 2 ANOVA was conducted to assess the reflection of two HMD-based narrative media for male and female participants. The independent variables were the media type (HMD AV and HMD VR) and gender. The dependent variable was scored on reflection. Shapiro-Wilk test, Q-Q plot and Levene's test were performed to check normality and homogeneity of variance. As indicated from the result, reflection was well-modelled by a normal distribution and exhibited identical variance.

The analysis showed that there was no significant interaction effect, F (1, 58) = .01, p = .92,

$\eta 2 < .001$. Moreover, neither the main effect of media type and gender was statistically significant, media type: $F (1, 58) = .031$, $p = .862$, $\eta 2 = .001$; gender: $F (1, 58) = .262$, $p = .611$, $\eta 2 < .004$. In short, either media type or gender had no impact on user's reflection in an HMD-based immersive narrative.

The empathy was one of the subscales of the *Narrative Immersion Scale*. As described in section 6.4.1 , a 2 by 2 between-groups analysis of covariance was conducted to assess the empathy of the two HMD-based media for male and female participants. The main effect of media was also statistically significant for empathy: $F (1, 57) =5.007$, $p = .029$, $\eta 2 = .081$. The main effect of gender wasn't statistically significant $F (1, 57) = .912$, $p = .344$, $\eta 2 = .016$. The empathy (M =23.792[a], SD =.684) under HMD VR condition were higher than empathy (M =21.63[a], SD =.68) under HMD AV condition, and these differences were of statistical significance ($p < .05$) with a medium effect size ($\eta 2 > .06$). These results suggested that HMD VR and led to higher empathy than HMD AV.

6.5. Qualitative Data Collection and Analysis

In this section, a descriptive analysis of the interview results is given, which is expected to help us explore the participants' acceptance of HXRM. Interview questions were as follow:

Q1: Do you feel sick or uncomfortable using the device during the experiment? If so, please describe it.

Q2: In terms of narrative experience, do you think the experience in the experiment was different from a film or P.C. video game? If so, please describe the difference.

Q3: Would you be interested in an immersive remote-site museum as a learning approach like this? What are the reasons?

Q4: Please rate the affinity of the CG characters in the XR museum's experience out of 5, and describe how you feel about it.

For the second half of Q1, Q2 and Q3, which were not yes or no questions. A two-cycle, simultaneous coding procedure was applied to analyse the results. The first cycle established an initial, in vivo coding. The second cycle used a holistic pattern coding method to summarise the content and a point of reference for discussing specific quotes (Saldaña, 2015). Two researchers coded the interview separately, and the results of the two coders were tested for consistency, and the Cronbach coefficient was 0.892.

6.5.1. Adaptation of device

In Q1, the participants were asked whether they felt sick or uncomfortable using the device. Table. 6.1 showed that 1 participant (3.3%) reported uncomfortable feelings with HoloLens 2nd, and 4 participants (13.3%) reported uncomfortable feelings with HTC Vive Pro. As far as the device's comfort is concerned, there is a low risk for users to have adverse reactions using both devices playing *The Journey*. HoloLens 2nd generation seemed to be better than HTC Vive Pro regarding the device's comfort. To be specific, Participant # 24 reported that when using HoloLens, "I felt a little dizzy, and my eyes felt distressed. I was a little struggled to focus on objects…". For HTC Vive, the symptoms included faint vertigo, headaches, and a lack of security psychologically. Some statements are presented below:

Participant # 37: "I had a short headache after the experiment. It could be due to my near-sightedness, and I had a little visual discomfort…"

Participant # 29: "I was a little dizzy then taking off the headset. I had no discomfort feelings during the experiment…"

Participant # 25: "I felt a bit uncomfortable mentally. I would feel a bit scared because I couldn't see my surroundings and then got a bit nervous. During the experiment, when I crouched down and stood up again, I lost my weight and swayed a bit…"

Table. 6.1 Number of participants with the different adaptations of the device

	Group A (AV) Number and percentage of users	Group B (VR) Number and percentage of users
I didn't feel uncomfortable	30 (96.8%)	27 (87.1 %)
I did feel uncomfortable	1 (3.2%)	4 (12.9 %)

Though some participants reported they felt the device was a little bit heavy or was not very comfortable to wear, they did not give negative feedback for this question. It indicated these device wearing issues was existent but acceptable. On the other hand, no people reported vertigo in our experiment, except very few reported slightly dizzy. Furthermore, a few people said they had 3D vertigo before, but they did not feel discomfort in this experiment. The elimination of vertigo was because the users were allowed to move freely by walking instead of teleportation.

In short, HMD VR or AV devices using our application did not let users feel unease, and a small number of users had mild discomfort with the device.

6.5.2. New experience beyond traditional media

In Q2, the participants were asked to describe the difference between the narrative experience in the experiment and those from a film or P.C. video game. Table. 6.2 showed that 4 participants (12.9%) reported worse narrative experience in HoloLens 2nd generation than traditional media like watching a movie. Their reasons were almost identical that AV brought more distraction, keeping them from concentrating on the narrative, e.g., Participant # 61: "I would see the real-world items from time to time, and the experience was kind of disconnected and broken. Thus, it might not be as good as watching a movie…". 9 participants (29.1%) reported a similar narrative experience in HoloLens 2nd generation as watching a movie or playing the desktop video game, and their reasons were also similar that the FoV of HoloLens was limited, just like a film screen, e.g., Participant # 53: "The image was still presented within a limited screen, and I think it was just like a film…". 18 participants (58.1%) thought the narrative experience in HoloLens 2nd generation was distinctly better than traditional media, e.g., Participant # 46: "It was more immersive, and the experience was a little richer. I felt like I really became a character in the game and could touch the stuff like drawers in the world. I was more engaged in this experience…".

For interactive narrative experience in HTC Vive Pro, nobody reported a worse experience than traditional media like watching a movie. Three participants (9.7%) reported a similar experience to movies or desktop video games, e.g., Participant # 27: "… the experience was similar to watching a film. I was in a third-person perspective in this story, and I was actually still in a spectator state even if Leo was talking to me face to face. I could touch and interact within the environment, but the interaction was also very limited. I would say I was slightly more immersed, but the overall experience wasn't different from watching a film…". 28 participants (90.3%) reported a better experience than traditional media, e.g., Participant # 31: "… it was quite different from watching a movie or playing video games because it felt like you were living in a small world in VR and the experience was very real. I could easily get involved…”.

In short, HTC Vive Pro seemed to be more suitable than HoloLens 2nd generation in terms of interactive narrative. Over 90% of HMD VR users and less than 60% of HMD AV users expressed the narrative experience exceeding traditional media like movies or desktop video games. Besides, over 10% of HMD AV users considered the traditional media was better than the HMD-based immersive media.

Table. 6.2 Number of participants’ comments on comparison with traditional media

	Group A (AV) Number and percentage of users	Group B (VR) Number and percentage of users
Worse than watching a film	4 (12.9%)	0 (0 %)
Similar to watching a film or playing a video game	9 (29.1%)	3 (9.7 %)
Distinctly better experience than traditional media	18(58.1%)	28(90.3%)

The descriptions stated by participants were further coded to understand the reason why users liked or disliked the experience. The top reason for participants who liked the experience was Code 1 that the experience was immersive. It was stated by 16 participants (51.6%) from AV group and 24 participants (77.4%) from VR group, e.g., Participant # 56: “… it was different from watching a movie or playing a game, the narrative experience was more intense and I could immerse myself in the story…”. Fig. 6.4 presents the results and the horizontal axis of Fig. 6.4 shows the percentage of participants, who gave the corresponding description on the vertical axis, to the total number of different media group

10 AV group participants (32.3%) and 13 VR group participants (41.9%) reported Code 2 that they had more agency to observe and explore. Some statements were listed as below:

Participant # 37: “…I could walk around in the space and be able to observe and understand the story better. I could also observe the characters’ expressions from different perspectives… I think it was better than just watching a film from screen…”

Participant # 62: “…It was quite different from a movie and a desktop video game. You could move freely around the room by yourself …”

8 AV group participants (25.8%) and 10 VR group participants (32.3%) reported Code 3 that they felt the experience was realistic so that they were there in the story. Besides, Code 9 further showed that 5 VR group participants (16.1%) even felt they forgot about the world during the experiment. It indicated that around 30% of participants felt a stronger presence in the narrative experience. Some comments were presented as below:

Participant # 23: "…The difference was still quite distinct. When I watch a film or play a desktop video game, I know it's fake because I know I'm in the real world. But this experience could detach me from reality. I could interact with the characters in the story, and I felt like I was transferred into another world…"

Participant # 20: "…I think there's a big difference. When I play games, it's often hard to have a sense of presence. I know I just operate a computer or in a phone, but this experience feels like I am actually in the scene of the story…"

Participant # 8: "…when I am playing a desktop game or watching a movie, it's easy to distinguish between reality and game. But I had a strong sense of immersion and involvement in VR when I was moving in the environment. When I took off the headset came back to reality from it, I needed to confirm that I was back to reality again…"

Moreover, 4 AV group participants (12.9%) and 7 VR group participants (22.6%) described Code 5 to have a deeper understanding of the characters in the story than traditional media. More participants in VR group reported empathy than AV group, which is consistent with the above qualitative results. Some descriptions are demonstrated below:

Participant # 52: "…I felt that I was closer to the characters, and I could view them from different perspectives. For World War II or such humanistic works, this immersive media has great advantages, the sense of immersion is powerful, and it can evoke empathy easier…"

Participant # 20: "…I feel like an observer when I am playing on a computer. But in VR, Leo was watching me and interacting with me, which made me quite involved. I think VR offers a better experience…"

Participant # 29: "…Leo should be able to know that I was in the room. His eyes were moving with me, and I felt more engaged and had a better understanding of the character's feelings…"

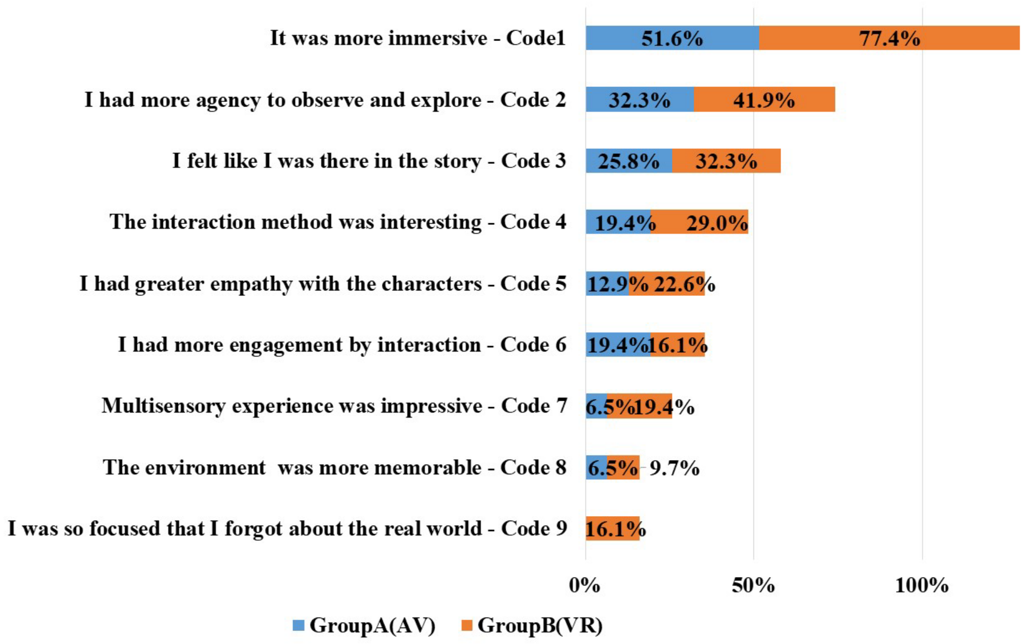


Fig. 6.4 Codes of benefits of the experience different from traditional media.

Except for impressive characters, 2 AV group participants (6.5%) and 3 VR group participants (9.7%) also reported Code 8 that the environment was more memorable in the narrative experience. Some comments are shown below:

Participant # 30: "...The biggest difference is the experience was 360 degrees, and it was wrapping me. I think the experience gave me more details, and I was able to examine the environment in depth..."

Participant # 41: "...I could also walk around and then observe freely. This (walking freedom) could help interpret the story as I could better understand the environment of the story..."

Code 4 and Code 6 revealed the contribution of interaction from the new experience. 6 AV group participants (19.4%) and 9 VR group participants (29%) commented Code 4 that the interaction method was very distinct. Meanwhile, 6 AV group participants (19.4%) and 5 VR group participants (16.1%) also stated Code 6 that they had more engagement feelings by interaction. It implied that the natural interactive experience in immersive media gives users a sense of novel and involvement, making it different from traditional media. Some remarks are listed below: (see more comments in Appendix D1)

Participant # 35: "...I interacted with virtual items directly with my hands, and it felt smarter than I expected, and the immersion feeling was better too..."

Participant # 57: "...When watching a film, I may only receive information. But it was an interactive process in AV that I could participate in and make decisions ourselves by touch and interaction. I could also have a close look at the protagonist…"

Lastly, 2 AV group participants (6.5%) and 6 VR group participants (19.4%) commented Code 7 that the multisensory experience was impressive and different from traditional media. The user's body is usually static in traditional media, and their different senses are not fully activated. Some comments are shown below:

Participant # 18: "…the senses that need to be engaged are different. VR definitely engaged more senses and led to a better experience. This kind of interactive media was better than mobile and PC games that I often got dizzy when I played 3D video games…"

Participant # 19: "…I think it amplified the senses, it was more immersive and the experience was a bit richer…"

For the 4 AV group participants who disliked the experience, considering the experience was worse than film, the reasons were similar: AV brought more distraction, keeping them from concentrating on the narrative. Some statements are presented below:

Participant # 61: "I would see the real-world items from time to time, and the experience was kind of disconnected and broken. Thus, it might not be as good as watching a movie…"

Participant # 33: "It was a poor experience as I couldn't focus on the virtual image like a typical desktop game and movies. Because AV's FoV was very limited, I would unconsciously see the floor, the electric sockets, sofa in the real world. If I am watching a movie, I could focus just on the screen in front of me, if the screen is big enough, for example, in the cinema…"

In summary, the answer to question 2 revealed that over 90% of participants considered VR a better medium for the narrative experience than traditional media like film or desktop video games. In comparison, over 50% of participants thought AV was better than traditional media. The supporters thought they had more immersion, more agency, a stronger sense of presence, and better empathy with characters in VR or AV. Besides, some supporters also thought the direct interaction method was helpful and engaged via interaction. However, about 10% AV group participants considered AV was worse than film or desktop games as there were more visual distractions when using AV, and about 30% of participants thought AV was similar to film or desktop games as the FoV was limited just like a film screen.

6.5.3. **Remote-site museum preference**

In Q3, the participants were asked whether they were interested in the remote-site museum and their reasons. Table. 6.3 showed that 25 AV group participants (80.6%) and 28 VR group participants (90.3%) were willing to use the immersive remote-site museum as a learning approach. On the other hand, 4 AV group participants (12.9 %) and 1 VR group participants (3.2 %) were not interested in the remote-site museum, and 2 AV group participants (6.5%) and 2 VR group participants (6.5%) held neutral attitude, considering remote-site museum approach needed to be determined according to the situation. In short, for both the VR and AV groups, over 80% of the majority of users were optimistic about the remote-site museum as a learning approach, and the VR group had slightly more supporters than the AV group.

Table. 6.3 Number of participants' attitudes for remote-site museum

	Group A (AV) Number and percentage of users	Group B (VR) Number and percentage of users
I am interested in an immersive remote-site museum	25 (80.6%)	28 (90.3%)
I am not interested in an immersive remote-site museum	4 (12.9 %)	1 (3.2%)
It depends	2 (6.5%)	2 (6.5%)

The reasons of the supporters were coded to understand why participants had a positive or negative attitude toward the remote-site museum. The top four reasons, mentioned significantly more frequently than other reasons (see Fig. 6.5), were: the richer learning experience (Code 1), higher accessibility (Code 2), embedded narrative experience (Code 3), and more immersive feelings (Code 4). 10 AV group participants (32.3%) and 15 VR group participants (48.4%) reported Code 1 that immersive remote-site museum could offer richer and more engaging learning experience compared with a traditional museum, giving users a more immersive experience and guide them to observe more details in a restored scenario. Some remarks are listed below (see more comments in Appendix D2):

Participant # 58: "…I was more interested in learning using this approach because the learning experience was richer rather than just a text or a video commonly seen in a traditional museum. I would be more engaged…"

Participant # 42: "…I think this approach actually attracted my attention more. If I just go to a museum, I might not read the items so less closely and carefully. However, I'd like to observe items in detail in this immersive narrative experience…"

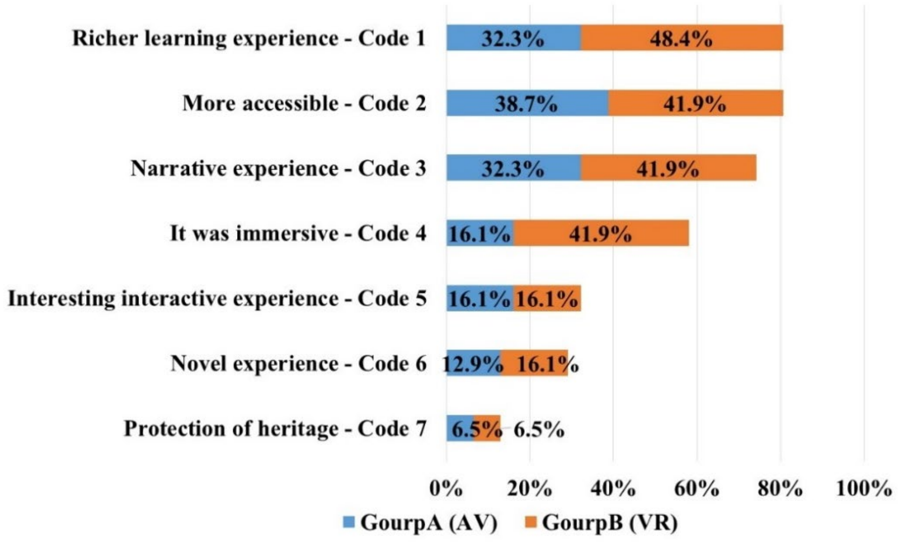


Fig. 6.5 Codes of reasons for supporting remote-site museums as a learning approach[41].

12 AV group participants (38.7%) and 13 VR group participants (41.9%) described Code 2 that the immersive remote-site museum had the clear benefit of accessibility. Some comments are shown below:

Participant # 31: "…remote-site museum is quite attractive for me. For example, if I want to go to a museum in London, I just need to set up the device here in Shanghai, load the application, and then be kind of transported to visit it in real-time. It saves time and money…"

Participant # 1: "…I think the remote-site museum is very good because firstly it saves a lot of travel costs for people. For example, I don't have to go somewhere in person, and it can offer an engaging, interactive experience rather than just looking at the heritage items through a glass…"

10 AV group participants (32.3%) and 13 VR group participants (41.9%) mentioned Code 3 that the immersive remote-site museum was attractive because it was an embedded narrative experience, which was rarely found in traditional museums. Some comments are listed below:

Participant # 11: "…It's not interesting to just exhibit items or show a piece of animation. To tell the stories behind the heritage items is the key. I felt like I was there with the headset, a witness of the story. This is definitely appealing…"

Participant # 27: "…The remote-site museum is appealing to me. The reason is the narrative experience that tells the story behind the scene. It won't work if the remote-site museum shows the artefacts through text and speaking narration, like in a traditional museum. But using this

[41] The horizontal axis shows the percentage of participants, who gave the corresponding description on the vertical axis, to the total number of different media group.

kind of immersive narrative, I think I am willing to use it…"

Participant # 35: "…I went to Suzhou some time ago, and I thought it would be amazing if I could see the virtual ancient Chinese sitting on chairs and talking there in the garden within the headset. It definitely works either on-site or remotely. This kind of immersive remote-site museum has more possibilities than a traditional museum, telling the story in a more engaging way…"

5 AV group participants (16.1 %) and 13 VR group participants (41.9%) reported Code 4 that the HMD VR or HMD AV based remote-site museum could offer users a sense of immersion and presence. In addition, more people in the VR group reported this code than AV group. Some statements are listed below:

Participant # 61 "…Because I think it has a kind of immersive feeling so that I can go and observe the details. It is more interesting than those online museums that I can only browse a website…"

Participant # 53 "…The remote-site museum experience is really impressive, I had a strong sense of immersion and presence. For example, I saw an oil painting on the wall in VR, which looked very realistic…"

5 AV group participants (16.1 %) and 5 VR group participants (16.1 %) mentioned Code 5 that the immersive remote-site museum had the advantage over traditional museums for its interactive experience. Some statements are demonstrated below:

Participant # 29 "…The main reason was that the interaction process was quite interesting…"

Participant # 46 "…The main reason was the interaction that could overcome the shortcomings of the traditional museum exhibition. VR could give me the illusion of "I have superpowers", like I could travel through time and witness history. I'm very optimistic about the remote-site museum application in VR…"

Rather than accepting the remote-site museum as a learning method, people are likely to be attracted to the novelty of the experience from the HMD device. It is deliberately confirmed whether users chose to support the remote-site museum because of the novelty. The result showed as Code 6 that 4 AV group participants (12.9 %) and 5 VR group participants (16.1 %) agreed that novelty was an important reason, e.g., Participant # 7 "…I was interested because of the novelty. As HMD AV is something I haven't played before, and its novelty would make me curious and lead me to explore…"; Participant # 51 "…Because I think it's fun, and the experience itself is very novel to me. I was quite curious about the VR stuffs, and it was the main reason that drove me to participant in this experiment…". On the other hand, others held negative opinions that novelty wasn't important or not the main reason, e.g., Participant # 9"…The experience itself had some novelty for sure. But apart from the novelty, I felt I enjoyed the storytelling and this topic even more…".

Lastly, 2 V group participants (6.5 %) and 2 VR group participants (6.5 %) mention Code 7 that the remote-site museum had the benefit of heritage protection, e.g., Participant # 39 "…Because it's more convenient and beneficial for the conservation of those artefacts. For places like the Louvre, and the British Museum, I can't really travel to there again and again to see the exhibition. But I can visit the remote-site museum over and over …"

For those who weren't interested in remote-site museums, their reasons were very similar: remote-site museums could not offer the same sense of realism as the real world, and they would like to see the real heritage artefacts. For example, Participant # 45 "…I'm not really interested in the immersive remote-site museums because I like the historical smell of the artefacts. However, in the HMD-based virtual experience, the objects did not look like heritage items from a long time ago. I still prefer to observe the heritage items on-site …".

For those who said it depended, their judgement mainly based on the theme and content of the remote-site museum, e.g., Participant # 22 "…Depending on the situation if it's something with a story that I particularly like, I'll be interested. I am fond of a history-related subjects. But if it's the kind of art gallery that just shows paintings and sculptures, I don't think it would be particularly interesting for me…".

In summary, the answer to question 3 revealed that over 85% of participants were interested in the immersive remote-site museum as a learning approach. The remote-site museum had the clear advantage of a rich learning experience, accessibility, embedded narrative, and immersion compared with traditional museums. In addition, only about 10% of participants considered the novelty of the VR/AV device as an important reason to support their decisions. On the other hand, about 7% of participants were not interested in remote-site museum experience as they preferred to observe the real heritage items on-site and thought current technology was not sufficient to make virtual artefacts realistic enough. As to the approximate 7% of participants with a neutral attitude, their main concerns were whether the museum's theme and technology were appropriate for them.

Additionally, in the behaviour test, participants were asked if they were willing to participate in the further HMD-based narrative experiments with AV and VR next month without any reward. Fortunately, 29 participants (93.5%) from HMD VR group and 23 participants from HMD AV group (74.2%) chose to volunteer for the next experiment. The volunteers' proportion of the VR group was significantly higher than the AV group, reaching over 90%. This proportion data is basically in line with the number of participants who held positive attitudes for remote-site museums described above (see Table. 6.3). Given that voluntary participation in the experiment is a relatively high-cost behaviour, the behaviour test results further supports the conclusion in the previous paragraph that the HMD-based narrative experience can engage the majority of participants and the HMD VR experience stimulates more interest than HMD AV.

6.5.4. **CG character's affinity**

In Experiment 2, 62 participants were first asked whether they had played games involving Photorealistic 3D Characters (P3DC). Of these participants, 17 reported no experience with such games, 27 had some experience, and 18 reported having extensive experience. In the interview, the participants were asked to rate the overall presentation and affinity of the photorealistic CG characters in the experiment on a scale between 1 and 5. Analysis of the data showed that the highest ratings were given by participants with no experience of games involving P3DC ($M=3.765$, $SD=.219$), while those who reported having had extensive experience giving the second highest rankings. ($M=3.278$, $SD=.177$), followed by those with some experience ($M=2.963$, $SD=.217$). Moreover, a regression analysis was used to test if the CG characters affinity helped to predict the participants' perceived enjoyment and ability to immerse themselves in the narrative. The regression results indicated that the predictor explained 4% of the variance of the perceived enjoyment and that the model was not significant ($R2 =.04$, $R2Adjusted = .03$, $F(1,61)=7.97$, $p=.119$). Subsequent analysis showed that affinity with the CG characters did not significantly predict the participant's perceived enjoyment ($B=.33$, $Beta = .20$, $t(61) =1.58$, $p= .119$). However, the regression results indicated that the predictor could explain 28.4% of the variance of the narrative immersion and that the model was significant ($R2 =.28$, $R2Adjusted = .27$, $F(1,61)=23$, $p<.001$). The analysis shows that CG character's affinity significantly predicted the ability of the user to enjoy the narrative immersion ($B=3.23$, $Beta = .53$, $t(61) =4.8$, $p<.001$).

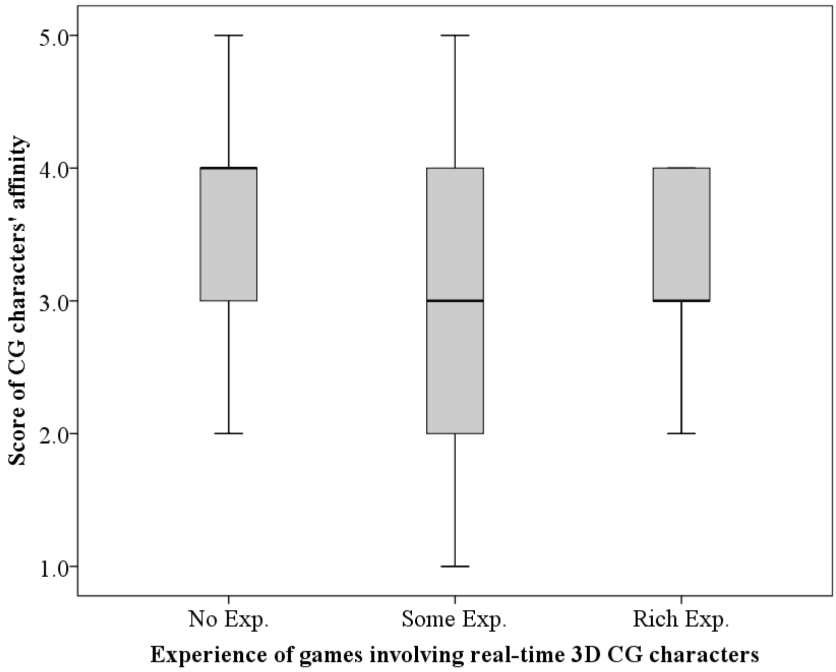


Fig. 6.6 Rating of character's affinity by participants with the different levels of gaming experiences with P3DC

As Fig. 6.6 showed, participants with extensive experience gave an upper-middle rating. The interviews further revealed that these participants usually classified the experience as a narrative game rather than an action game that relies more heavily on good graphics and animation. One participant mentioned, "… I noticed the flaws in the character design, like the body parts interspersed during the animation, and there was incorrect face culling of the model. However, I was fully immersed in the story, so it didn't affect my enjoyment…". Another said that "...It feels like the interactive narrative games I've played before, such as *Detroit: Become Human*…". In conclusion, participants that reported having had extensive experience with P3DC games had also previously seen different game types. Therefore, they tended to classify this experience as an interactive narrative game and were more tolerant of the photorealistic 3D characters' flaws. Moreover, there was a smaller standard deviation for these participants. As Fig. 6.6 showed, no one gave ratings of 5 or 1, as the majority gave a rating of 3 and 4.

Contrary to expectations, participants with some experience playing P3DC games gave the lowest scores, and these ratings varied more widely (see Fig. 6.6). Additionally, some of them used words such as "scary" and "frightening" to describe their subjective experience. According to what was described in the interviews, the following main reasons were given for the low rating: (1) there were some atypical features in the appearance or motion of the CG characters, including the expressions and lighting of the characters' faces looking strange when visitors crouched down or viewed them from different angles. Occasionally, the characters' feet would sink into the floor or characters' hands would collide with the user's body during the animation, and it was reported that the parents did not move when they were hugging. (2) They would not categorise the experience as a modern video game. For example, according to one user "...the character looked like a really bad fake model that I would see in a shopping mall...", while another expressed that "...the game was different from the games I usually play, it looked like a poorly-made game...". These interview results confirm, to some extent, the previous assumption that categorisation and perceptual mismatch work together to replicate human likeness.

For participants with no experience playing P3DC games, their ratings were significantly higher than the others, with an average score of 3.7. Some participants, who gave ratings of 5, claimed that "... the characters looked very realistic, and I could see the detailed texture of the skin and eyelashes when I came closer". According to another participant, "…I looked closely, and the character's eyes were blinking...". Based on these responses, it is clear that mid-level photorealistic 3D characters with apparent flaws in appearance and animation satisfy most audiences with no experience with P3DC.

The interviews in Experiment 3 further confirmed the previous findings. Twenty-eight participants (46.7%) said that the overall presentation of the characters had a negative impact on their experience. On the other hand, around half of the audience expressed satisfaction with the CG characters in the game. However, the participants still hoped for improvements in the CG characters' quality. Indeed, 23 people (38.3%) ranked improvement of the CG characters as their top wish. Specifically, 21 of them wanted to improve the appearance of the characters by giving them more realistic skin, eyes, hair, and so on. Another 20 participants recommended that adjustments be made to the character's animation, in particular by fixing the error of the character's colliding with the audience. Three participants suggested enhancing the facial expression of the characters, while participants proposed modifications to the sound of the characters, as Leo's voice sounded too old than his age.

From this study, the following conclusions can be drawn. For photorealistic CG characters, the dimension of human likeness consists of appearance, motion, and sound. Thus, the existing game experience can create the uncanny valley effect. Specifically, when the audience has some gaming experience using P3DC, they become more discriminating of realistic CG characters and are more likely to experience the uncanny valley effect. However, audiences who have extensive experience in gaming tend to be more tolerant of realistic CG characters, even when noticing the flaws of these characters. Both categorical perception and perceptual mismatch can possibly explain these findings.

6.6. Summary

Using quantitative analysis, RQ2 was partially investigated and the author found that users had statistically significantly more narrative immersion in HMD VR (represented by the HTC Vive Pro) than in HMD AV (represented by HoloLens 2nd generation). Statistically, HMD VR is significantly more robust in terms of generating empathy than HMD AV. However, no statistical significance was found in terms of the reflection between the HMD VR group and the HMD AV group. Furthermore, H4 was not supported by the analysis data; instead, prior gaming experience had a non-linear impact on the realistic CG character's affinity. Meanwhile, H5, which stated that CG characters' affinity can affect perceived enjoyment, was not supported. However, H8, which stated that CG characters' affinity significantly influence narrative immersion with a positive relation, was confirmed. Additionally, H6 was partially supported, as the results showed that narrative immersion significantly predicted the participants' perceived usefulness in the context of HXRM. Finally, H3, which stated that learning interest predicted a significant amount of the narrative immersion of HXRM, was also supported via quantitative data.

Moreover, in terms of learning outcome, although there was no statistically significant difference in learning motivation and reflection between HMD VR and HMD AV, there was a significant improvement in empathy for HMD VR compared with HMD AV. As discussed in Section 2.3.1 and Section 2.3.2, empathy is important for young people's education. Several studies have revealed a positive correlation between empathy and young people's personality development, moral development and learning ability (Findlay et al., 2006; Hand & Varan, 2009a; Warden & Mackinnon, 2003), making empathy an important educational goal for the Holocaust museum. Therefore, users could have a better learning outcome using HMD VR than HMD AV in the XR Holocaust museum. According to previous research that immersive 360 videos can lead to better empathy than standard non-immersive video (Fonseca & Kraus, 2016; Schutte & Stilinović, 2017), it can be further inferred that media with stronger presence like HMD VR may provide better empathy or learning outcome than those with lower presence like OST-based HMD AV.

For Q3, the interviews showed that about 90% of VR group participants and 80% of AV group participants were positive that an HMD-based remote-site XR museum could work as a practical learning approach. This was due to the museum's intentional approach that emphasized the importance of rich learning experience, accessibility, embedded narrative, and feelings of immersion, in which aspects it surpassed the traditional museum experience. Additionally, over 95% of the AV group and about 90% of the VR group participants showed good adaption capabilities for the HMD devices (HTC Vive and HoloLens 2nd generation).

Moreover, over 90% of the VR group participants also considered HMD VR to be better suited for the narrative experience than traditional media like film or desktop video games; however, only about 60% of participants agreed that HMD AV was better than traditional media. This finding is consistent with the above qualitative findings that HMD VR can lead to a better narrative experience. These interviews further revealed that participants were more immersed, possessed more agency, had a stronger sense of presence, and felt more empathy for the characters in HMD VR or HMD AV.

In conclusion, the HMD-based remote-site XR museum was widely accepted by users and had the potential to be more engaging and popular than traditional media and traditional museums. Both quantitative and qualitative analysis showed that HMD VR had the advantage of stronger immersion, concentration, and empathy than HMD AV regarding the narrative experience.

Chapter 7: A Comparison of User Experience of HMD-based VR and AV in Within-Subjects Design

Experiment 3 was designed to partially answer RQ 2 and 3(see section 1.2), and validate hypotheses 4 and 7 (see section 3.2.5). For RQ2, it was further hypothesised that that HMD-based VR museum could give users better presence and enjoyment than HMD-based AV museum. A mixed approach of the quantitative and qualitative methods was used for experiment 3. Influence on presence, enjoyment and CG character's affinity were assessed via quantitative analysis. In order to find the details that distinguished the two mediums in terms of narrative experience, structured interviews were conducted, and participants' answers were coded and analysed. Experiment 2 and 3 verified all the hypotheses for the extended TAM proposed in section 3.2 via regression analysis. Section 7.7 discusses the user experience of HXRM, summarising the revised TAM model for HXRM and the interaction experience; section 7.6 discusses the user acceptance of HXRM and the difference between HMD VR and HMD AV as the HXRM's media.

7.1. Experimental Protocol

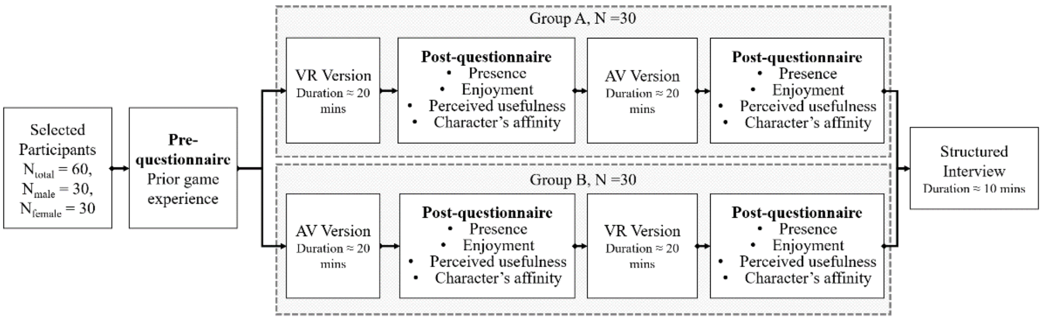


Fig. 7.1 Flow Chart of Procedures of Experiment 3

As Fig. 7.1 shows, participants were assigned into two groups after a quick introduction to the Holocaust. Participants were asked to enter the lab one by one and went through the experimental procedure individually. They were randomly assigned to use the HMD VR version first (n_A =30) or the HMD AV version first (n_B =30), which served as a means of counterbalancing to minimise possible bias from the practice effect. All participants needed to experience the VR and AV versions, respectively. After experiencing each version, participants were required to complete a post-questionnaire. At the end of the experiment, a 10 minutes structured interview was conducted focusing on participants' preference, comparison of VR and AV and their reasons.

7.2. Participants and Design

Sixty students (30 females,30 male, Shanghai, China) were recruited. The study used the within-subject design. All participants needed to experience the AV and VR versions in order. They were asked to complete a questionnaire after experiencing each version and receive an interview at the end of the experiment. The age of the participants ranged from 18 to 26 years; the mean age was 21.1.

7.3. Control Variables and Measures

Different media (HMD VR or HMD AV) was the control variable. In order to remove the interferences caused by individual differences, including immersion tendency effectively, previous experience of 3D RPG, etc., the experiment adopted a within-subjects design.

Presence was measured by the scale of Witmer and Singer's presence scale (Cronbach a =0.88, see Appendix A1). Witmer and Singer defined presence as "the subjective experience of being in one place or environment, even when one is physically situated in another" and "...presence refers to experiencing the computer-generated environment rather than the actual physical locale". Several factors were considered in this instrument, including *Control, Realism, Distraction* and *Sensory input*. These factors were helpful to evaluate the presence of experience in different versions.

Enjoyment was measured using a scale (Cronbach a =0.87, see Appendix A4) developed and validated for measuring enjoyment of computer games(R. M. Ryan et al., 2006). It was used in this instance as a desirable measure from the museum's point of view to satisfy public engagement motives.

The *Scale of Perceived Usefulness* (Cronbach a = 0.97, see Appendix A6) (Davis, 1989) was used to measure perceived usefulness. The wording of the questions has been adjusted to fit the context of the HMD-based XR museum and the learning objectives of moral education.

Five items from scales used to measure the character's affinity. The items used included: eerie, nonhuman- like, repulsive, unattractive and unlikeable (Bartneck et al., 2009; Ho & MacDorman, 2010).

7.4. Quantitative Data Collection and Analysis

Participants rated the statements on the questionnaires with seven-point Likert Scales, with 5 indicating total agreement. The final score of a scale or subscale was the total of all the ratings in the scale. A paired samples t-tests was used to analyse two dependent variables quantitatively, including the presence and its subscales and enjoyment.

7.4.1. Presence

The independent variables were the media type (HMD AV and HMD VR), and the dependent variable was scored on the presence and subscales. Shapiro-Wilk test and Q-Q plot were performed to check normality. As indicated from the result, presence and its subscales were well-modelled by a normal distribution.

As Table. 7.1 showed, the presence scale was composed of five subscales: Involvement/Control (INV/C), natural, auditory, resolution and interface quality. Paired samples t-tests revealed significant differences in overall presence (M_{HMDVR}=91.05, SD_{HMDVR}=10.135; M_{HMDAV}=81.5, SD_{HMDAV}=12.719; $t(59)$=6.154; p<.001), INV/C (M_{HMDVR}=37.55, SD_{HMDVR}=4.216; M_{HMDAV}=33.117, SD_{HMDAV}=5.758; $t(59)$=6.265; p<.001), natural (M_{HMDVR}=12.076, SD_{HMDVR}=2.041; M_{HMDAV}=10.267, SD_{HMDAV}=2.469; $t(59)$=5.318; p<.001), resolution (M_{HMDVR}=9.3, SD_{HMDVR}=1.03; M_{HMDAV}= 8.683, SD_{HMDAV}=1.255; $t(59)$=3.999; p<.001), and interface quality (M_{HMDVR}=6.9, SD_{HMDVR}=1.82; M_{HMDAV}= 5.667, SD_{HMDAV}=1.69; $t(59)$=4.319; p<.001). No significant differences were found in auditory (M_{HMDVR}=12.933, SD_{HMDVR}=2.185; M_{HMDAV}= 12.783, SD_{HMDAV}=2.124; t (59) =.514; p<.59). The result showed that HMD VR led to better presence in immersive narrative context, and participants perceived stronger involvement, better and more natural control, more consistent with reality, and lower interface distraction in the HMD VR condition than in the HMD AV condition.

Table. 7.1 Comparison of presence and its subscales

	Presence	Involvement/Control	Natural	Auditory	Resolution	Interface Quality
HMD VR	M=91.05 SD=10.135	M=37.55 SD =4.216	M=12.076 SD =2.041	M=12.933 SD =2.185	M=9.3 SD =1.03	M=6.9 SD =1.82
HMD AV	M=81.5 SD=12.719	M=33.117 SD=5.758	M=10.267 SD =2.469	M=12.783 SD =2.124	M=8.683 SD =1.255	M=5.667 SD =1.69
T-test Results	t(59) = 6.154 p < .001	t(59) = 6.265 p < .001	t(59) =5.318 p < .001	t(59) = .514 p = .59	t(59) = 3.999 p < .001	t(59) = 4.319 p < .001

A regression analysis was used to test if the presence significantly predicted participants' perceived enjoyment. The regression results indicated the predictor explained 21% of the variance of the perceived enjoyment and that the model was significant ($R2 =.21$, $R2Adjusted = .19$, $F(1,58)=15.59$, $p<.001$). The analysis shows that presence level did significantly predict value of perceived enjoyment ($B=.08$, $Beta = .45$, $t(59) =3.95$, $p<.001$). Besides, a regression analysis was used to examine if the presence significantly predicted participants' perceived usefulness. The results of the regression indicated that the presence did not significantly predict the perceived usefulness ($B=-.05$, $Beta = -.10$, $t(59) =-.54$, $p= .59$).

7.4.2. **Enjoyment**

The independent variables were the type of media (HMD AV and HMD VR), and the dependent variable was scored on enjoyment. Shapiro-Wilk test and Q-Q plot were performed to check normality. As indicated from the result, enjoyment was well-modelled by a normal distribution.

Table. 7.2 showed, paired-samples t-tests revealed significant differences in enjoyment ($M_{HMDVR}=27.55$, $SD_{HMDVR}=2.837$; $M_{HMDAV}=26.1$, $SD_{HMDAV}=3.883$; $t(59)=2.937$; $p=.005$). The result showed that participants perceived more enjoyment in the HMD VR condition than in the HMD AV condition.

Table. 7.2 Comparison of enjoyment

	Enjoyment
HMD VR	M=27.55 SD=2.837
HMD AV	M=26.1 SD=3.883
T-test Results	t(59) = 2.937 p = .005

7.4.3. CG character's affinity

Influence of Different Media Type

Sixty participants were requested to experience the VR and AR versions in random order and then then were asked to rate the five-item scale of character's affinity at the end of each version. Shapiro-Wilk test and Levene's test were performed to check normality and homogeneity of variance. As indicated from the result, the rating of the character's affinity was well-modelled by a normal distribution and exhibited an identical variance. A paired T-test was used to analyse the data. The results from the VR group ($M = 18.05$, $SD = 5.15$) and AR group ($M = 16.2$, $SD = 4.95$) indicate that the media immersion can help boost the CG character's affinity, $t(59) = 2.98$, $p = .004$. Fig. 7.2 again confirmed the conclusion in section 6.5.4 that those with some game experience of P3DC gave a relatively low score to the CG character's affinity, while both inexperienced and experienced users tended to give higher scores.

Gaming experience of P3DC did not have an interaction with media immersion in terms of influence on the CG character's affinity, as shown in Fig. 7.2, the more immersive media (HMD VR) led to a higher score of CG character's affinity than less immersive media (HMD AR) for either the users without game experience of P3DC (M_{VR}=20.03, SD_{VR}=5.01, M_{AR}=18.25, SD_{AR}=4.65), or users with some experience of P3DC (M_{VR}=16.65, SD_{VR}=5.35, M_{AR}=14.80, SD_{AR}=5.09), or experienced users with P3DC (M_{VR}=18.35, SD_{VR}=4.55, M_{AR}=16.41, SD_{AR}=4.95). The three groups of participants with different game experiences were almost identical in terms of the different ratings between the HMD VR and HMD AR scores, approximately 1.8 points.

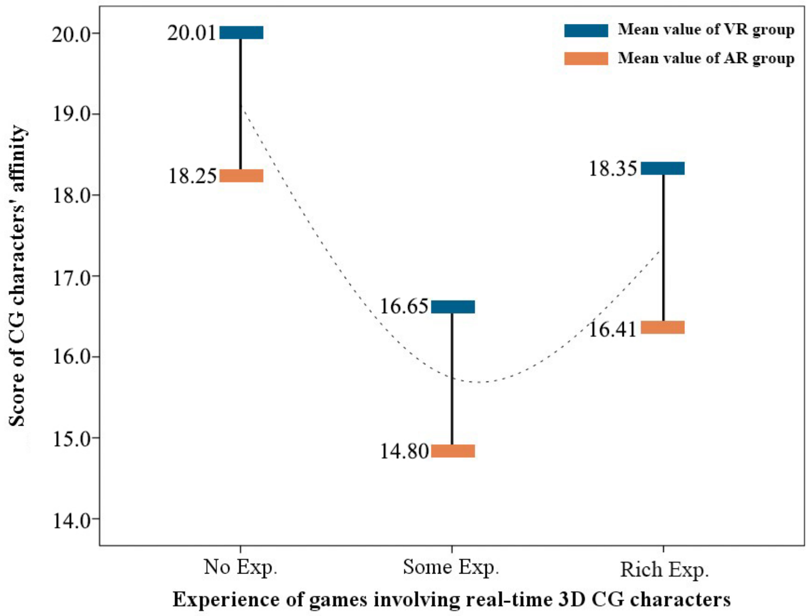


Fig. 7.2 Rating of character's affinity by participants from VR and AV groups with different gaming experiences of P3DC

In summary, for mid-level photorealistic CG characters, VR group showed better affinity than AV group. One explanation could be the inconsistent mixture between the real-world environment and the CG characters in AV, leading to the worse affinity of the CG character. In contrast, integrating the virtual environment and the CG character in VR is usually coherent. Another possible explanation is that media immersion can alleviate the uncanny valley, i.e., more immersive media can enhance the affinity of the CG character.

Influence of Character's Intelligent Behaviour

In the application of *The Extended Journey*, the protagonist Leo can seek the audience, walking towards the audience, talking to them face to face with eye contact. In order to make Leo's behaviour more natural, the eye contact with the audience was intermittent. However, in experiment 3 some audience did not notice Leo's intelligent behaviour. Specifically, 22 participants reported that they did not realise Leo had intelligent behaviour like eye contact and finding users, while the other 38 participants said they noticed Leo's intelligent interaction behaviour.

As Table. 7.3 showed, in VR, audience who noticed Character's intelligent behaviour gave a higher score (M = 18.75, SD = 4.75) than those who did not (M = 16.8, SD = 5.7). In AR, audience who noticed Character's intelligent behaviour also gave a higher rating (M = 16.65, SD = 5.25) than those who did not (M = 15.45, SD = 4.35).

Table. 7.3 Descriptive statistics of the score of character's affinity in VR and AR-based on the audience's observation of the character's intelligent behaviour

	Character's intelligent behavior was observed	**Number**	**Mean**	**SD**
Score of character's affinity in VR	No	22	16.8	5.7
	Yes	38	18.75	4.75
Score of character's affinity in AR	No	22	15.45	4.35
	Yes	38	16.65	5.25

One-way ANOVA was used to quantitatively analyse the dependent variable: the CG character's intelligent interaction behaviour. Shapiro-Wilk test and Levene's test were performed to check normality and homogeneity of variance. As indicated from the result, the rating of the character's affinity was well-modelled by a normal distribution and exhibited an identical variance. There was not a statistically significant effect of CG character's intelligent interaction on affinity of the character at the $p<.05$ level for the VR condition [$F(1,58) = 2.03$, $p = 0.16$] and the AR condition [$F(1,58) = .80$, $p = 0.38$].

In summary, although the descriptive statistics showed that the CG character's intelligent interaction could increase the character's affinity in both AR and VR conditions, it was not a statistically significant effect.

7.5. Qualitative Data Collection and Analysis

In this section, a descriptive analysis of the interview results is given, which is expected to help us deeply investigate the difference between AV and VR in HXRM, find the preference for a remote-online museum experience and the reason behind it, and serve as the basis for later discussion of design guidelines for immersive narrative. Interview questions were as follow:

Q1: Which do you like better overall, VR or AV? Why?

Q2: If you need a remote, online experience of visiting a similar museum at home, which version (VR or AV) would you prefer to use? Why?

Q3: What was your favourite moment or interaction? What was your least favourite moment or interaction?

Q4: If you have a superpower, you could change any aspect of the experience with unlimited budget and time. What would it be?

The second half of Q1and Q2, Q3, and Q4, were not yes or no questions. A two-cycle, simultaneous coding procedure was used to analyse the results. The first cycle established an initial, in vivo coding. The second cycle used a holistic pattern coding method to summarise the content and a point of reference for discussing specific quotes (Saldaña, 2015). Two researchers coded the interview separately, and the results of the two coders were tested for consistency, and the Cronbach coefficient was 0.887.

7.5.1. **Media preference**

In Q1, the participants were asked to select the one they prefer in general and describe the positive and negative experience of a VR narrative or an AV narrative. Fig. 7.3 shows the results and the horizontal axis of Fig. 7.3 shows the percentage of participants who choose the corresponding answer on the vertical axis to the total number of all participants of the relevant gender. 24 male participants (80%) and 25 female participants (83.3%) reported they preferred HMD VR, three male participants (10%) and one female participant (3.3%) reported they preferred HMD AV, and three male participants (10%) and four female participants reported that they had no preference. This result indicated that the HMD VR had a significant advantage over HMD AV for both males and females regarding immersive narrative. In addition, the male was more likely to be fond of HMD AV than the female. It was also interesting that around one in ten had no preferred option for AV or AV.

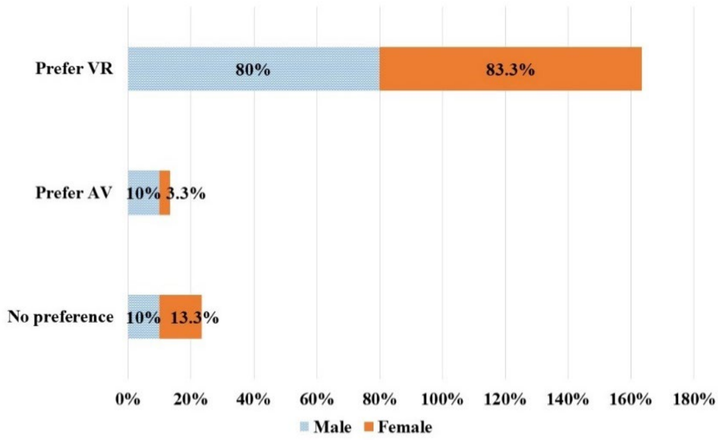


Fig. 7.3 Users' preference of media.

In order to understand the different experience participants perceived in HMD VR and HMD AV and the reason for their preference, the detailed descriptions stated by participants were further coded. In order to present the main reason why participants' media preferences visually, the code was listed in ascending order of the total percentage of participants. The blue bar indicated the percentage of participants who preferred VR who mentioned the code in their interviews, the orange bar indicated the percentage of participants who preferred AV, and the green bar indicated the percentage of participants who had no preferences (see Fig. 7.4, in which the horizontal axis shows the percentage of participants, who gave the corresponding description on the vertical axis, to the total number of all participants of the relevant category of preference).

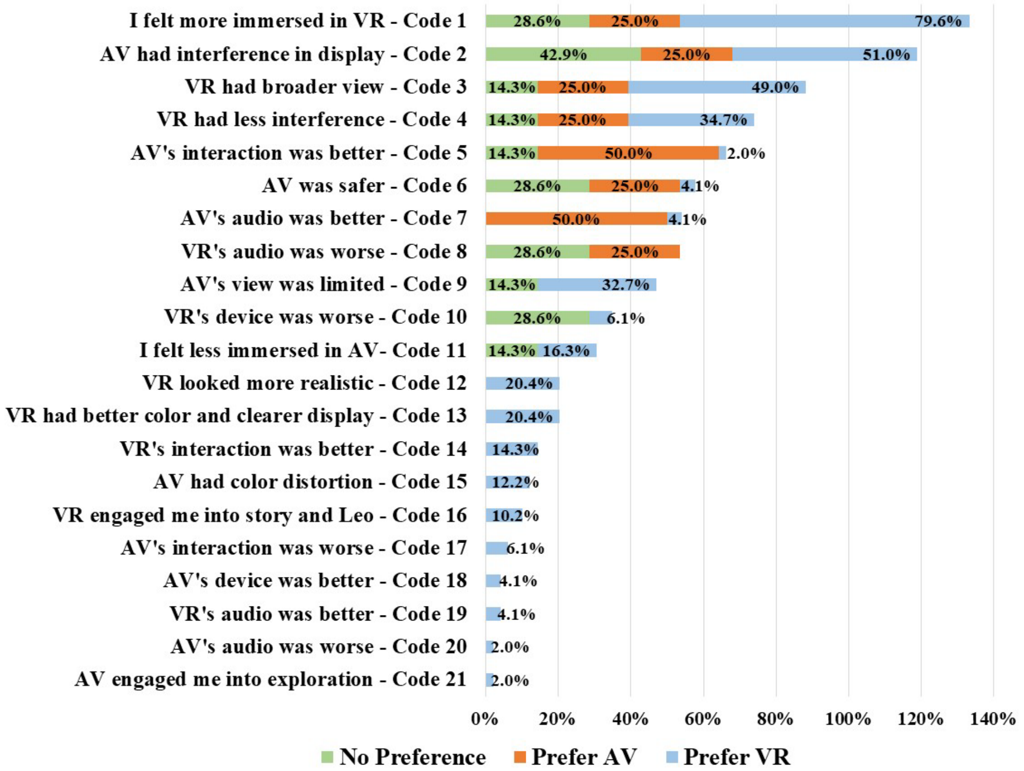


Fig. 7.4 Codes of reason for question 1 based on user's preference.

For participants who preferred VR, Code 1, Code 2, Code 3, Code 4 and Code 9 were all reported that over a third of these participants revealed the main reason why they favoured VR. Code 1 rate of 79.6% indicated that 39 participants reported more immersive feeling in VR. 25 participants (51.0%) reported Code 2, and 17 (34.7%) reported Code 4, indicating they felt more interference visually in AV while they felt less interference in VR. For Code 3 and 9, 24 (49%) and 16 (32.7%) mentioned that they had a better and broader view in VR and a limited and narrower view in AV, respectively. Some comments are presented below (see more comments in Appendix E1):

Participant # 29: "…I think the immersive display of VR was better to a certain extent because AV can't cover the whole field of view after all, but VR can…"

Participant # 55: "… VR was a little more immersive than AV. In this version of AV, you could still see some real-world items around you so that its immersion was not as strong as VR…"

Participant # 7: "… VR's overall experience was better than the AV. In AV, I didn't feel like I was fully engaged in the plot and aware that I was in the room (in Tongji University). But in VR, there were a few moments I felt that I was fully immersed in the virtual world…"

Other non-negligible visual factors that made users choose VR included Code 12, Code 13 and Code 15. For Code 12, 10 participants (20.4%) mentioned that VR's visual looked more realistic than AV's, and for Code 13, 10 (20.4%) stated that VR had better colour and clearer display. Code 15 showed that 6 (12.2%) commented that AV had colour distortion. Some statements are detailed below (see more comments in Appendix E2):

Participant # 53 "…The VR looked kind of more realistic, and its visual quality was a bit better. For the AV, possibly due to too much light in the room, I felt the visual was blurry…"

Participant # 2 "…The colour of the AV display was abnormal, very different from the VR. The overall colour looked like to have a red tint, and the colour of virtual objects was badly distorted…"

In short, most people perceived more immersion in VR to favour VR. Furthermore, the main reasons for stronger immersion in VR were VR's better visual sensory experience: 1) Real-world interference with AV caused by its limited view and semi-transparent display; 2) Natural visual experience offered by VR's broader view; 3) Colour bias with AV display.

Except for the visual aspect, two other notable factors made VR superior to AV for users. Code 14 demonstrated that 7 participants (14.3%) described that VR had a better interaction experience, and Code 16 presented that 5 participants (10.2%) reported VR's experience was more engaging in plot and characters. Though the interaction design was the same for AV and VR, AV had more accurate hand recognition than VR due to its additional depth camera sensors, and more participants reported that VR's interaction was better than AV's. There were two explanations according to the users' behaviour in the experiment and their interviews: 1) Users tended to directly manipulate virtual items in the same way as in the real world, even if they had been told that they should use specific gestures, and the detection algorithm VR used was less inaccurate but more sensitive compared with VR; 2) Because the hand interaction must be operated within the view of the headset, VR allowed the user to operate naturally over a broader range, unlike AV where the user was limited to its narrow field of view. Some comments are presented below:

Participant # 3 "…The VR version made me feel like I was playing Fallout. I felt like I was a part of the story. In the main story, I had to explore to find clues and move the plot forward. I found I was the protagonist, or I was helping the protagonist on a mission…"

Participant # 4 "…There was a bit more latency for AV than VR, and you could only perform the interaction in a very narrow range (within the FoV of HoloLens). So, it was relatively not as convenient as VR…"

VR could engage more participants in the plot, and characters was the other factor.

Because VR wrapped users' views more thoroughly and comprehensively, they could concentrate more on the plot and characters. Some comments are listed below:

Participant # 27 "…The AV's scenario made me more eager to explore it because I was unsure where the boundaries were. I wanted to try every interaction inside the room. The VR's environment was more complete visually (due to its wider FoV), and I could immediately gain a comprehensive view of the complete environment. So, I would probably focus more on the narrative itself…"

Participant # 58 "…The characters in VR made me feel more involved in the story, and the characters' eyes were able to gaze at me even if I was moving…"

For participants who preferred AV, Fig. 7.4 showed that 2 participants (50%) reported Code 5 and Code 7, which focused on audio and interaction, and only 1 participant (25%) reported Code 1, Code 2, Code 3 and Code 4, which focused on the visual aspect including FoV and display quality. It suggested that participants who preferred AV seemed to be more tolerant of visual issues like narrow FoV and semi-transparent overlay image, and they tended to be more sensitive to other aspects like acoustic and interaction qualities. Some comments are presented below:

Participant # 39 "…The sound of the AV was better matched with the picture, but the sound of the VR seemed to be a bit problematic. Sometimes there was a strange volume shifting between the left and right ear when you turned your head. Besides, the interaction in VR was not as sensitive as AV.…"

Participant # 60 "…The AV experience was a little better. Because its sound was clearer, VR's sound was a bit hazy…"

For participants who had no preference, Fig. 7.4 showed that 3 participants (42.9%) stated AV had interference in the display (Code 2), 2 (28.6%) reported they felt more immersed in VR (Code 1), and 1 (14.3%) mentioned VR had boarded view (Code 3) and less interference (Code 4). On the other hand, 2 participants (28.6%) reported AV was safer (Code 6), VR's device issues (Code 10) and VR's audio's issues (Code 8). Rather than focusing more on the visual experience, participants with no preference tended to evaluate the experience more comprehensively, including the auditory, safety of use and comfort of wearing the device. Some statements are detailed below:

Participant # 37 "…The downside of the VR was that its headset was too heavy, but it was much more immersive…The AV was slightly less immersive as the virtual items on display was semi-transparent…"

Participant # 22 "…I think AV was safer for me, but if we're talking about the experience itself, VR was definitely a bit better. It would be more immersive with VR because you can't see your surroundings. However, there were times when I heard footsteps of someone next to me, and I got worried and uneasy if someone was approaching me…"

Participant # 50 "… VR offered a better experience of the virtual environment, but the VR's interaction wasn't as smooth and responsive as AV's. However, I wasn't able to see the environment clearly in AV…"

Participant # 51 "… I thought the experience of AV and VR was similar, there wasn't big differences between them…"

In summary, the analysis for the code of question 1 inferred that most people preferred VR while a small number of people preferred AV or had no inclination. Users preferred VR because of its advantages of visual display, including a larger FoV and real-world-isolated presentation, unlike AV's translucent display, which brought many distractions, thus giving users a more immersive experience. In addition, due to these visual advantages, VR also allowed for a better interactive experience with a larger interaction range, while AV's interactions must be performed within its narrow FoV, and VR allowed users to focus more on the characters and the plot. Those who preferred AV or had no preference tended to be more inclusive of visuals and were more inclined to evaluate the experience from all aspects, like the audio, the comfort of wearing, the scenarios to be used, and the interaction feedback.

7.5.2. **Media preference for remote-site museum**

In Q2, the participants were asked to select the media they preferred for the online remote-site museum at home and describe the reasons for their preference. Fig. 7.5 showed that 15 male participants (50%) and 19 female participants (63.3%) reported that they preferred to use HMD VR at home for the remote-site museum. Meanwhile, 13 male participants (43.3%) and eight female participants (26.7%) described that they preferred to use HMD AV at home for the remote-site museum, three male participants (10%) and two female participants (6.7%) stated that their preference would depend on the situation. Compared with the user's preference of media in the last section, the number of people who preferred to use AV has risen significantly, nearly three times more. Moreover, there was a clear difference between genders that female users were more inclined to use HMD VR at home for remote-site museum experiences, whereas men were divided almost evenly regarding their preference for VR or AV.

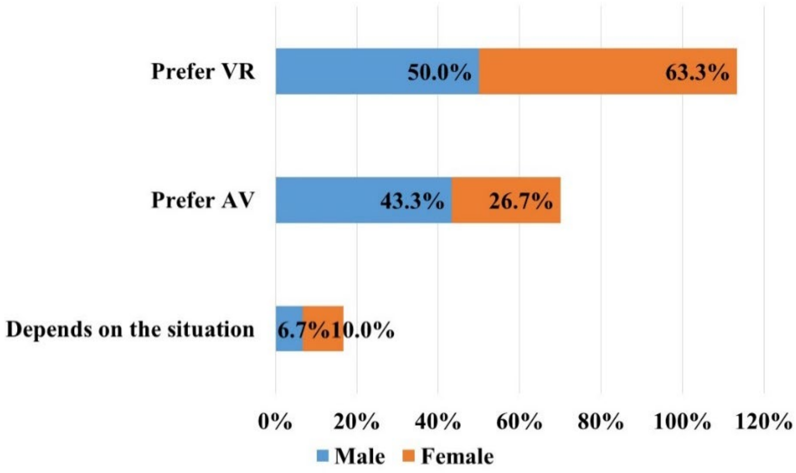


Fig. 7.5 Users' preference for the remote-site museum[42].

The reasons described by participants were future coded to understand the reason for their choices. Fig. 7.6 showed that the reason users choose HMD VR as the media for remote-site museum experience at home fell into two main points: 1) VR was more immersive (Code 1); 2) VR's overall experience was better (Code 2). 8 male participants (53.3%) and 13 female participants (68.4%) reported Code 1, and 11 male participants (73.3%) and 9 female participants (47.4%) reported Code 2. It is also aware that more females specifically mentioned the better immersion feeling of VR as their reason to support HMD VR. Some comments are listed below (see more comments in Appendix E3):

Participant # 29 "… I think the immersive display of VR was better, because AV can't cover the whole field of view, but VR can.…"

Participant # 31 "… Although VR was not very safe and it was easy to bump things in the house, the VR experience was particularly enjoyable.…"

Participant # 4 "… AV is probably a little more convenient to use, but I think I'm more looking for quality of experience.…"

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[42] The horizontal axis shows the percentage of participants who choose the corresponding answer on the vertical axis to the total number of all participants of the relevant gender

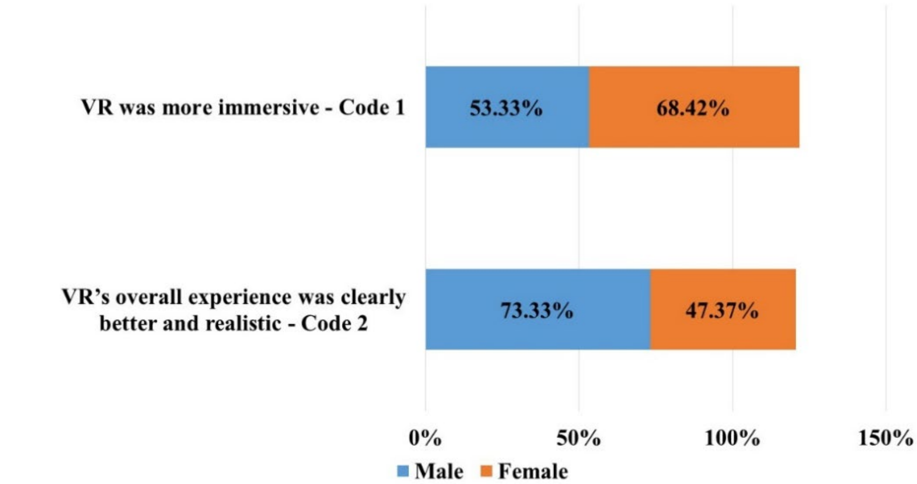

Fig. 7.6 Codes of reasons for users who choose HMD VR for the remote-site museum[43].

Fig. 7.7 showed that the reason users choose HMD AV as the media for remote-site museum experience at home fell into four main points: 1) AV was safer to use at home (Code 1); 2) AV was also able to offer an immersive feeling (Code 2); 3) The space at home was not large enough to use VR (Code 3); 4) AV's device was more comfortable and easier to wear compared with VR (Code 4).

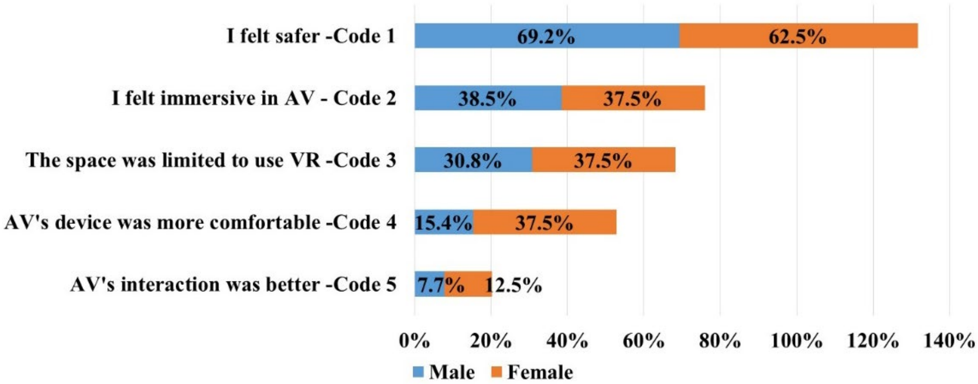

Fig. 7.7 Codes of reasons for users who choose HMD AV for the remote-site museum[44].

The code is sorted in descending order by the number of people. Code 1 was the biggest reason people chose HMD AV as their preferred media, and nine male participants (69.2%) and five female participants (62.5%) reported Code 1. It indicated that safety when using the

[43] The horizontal axis shows the percentage of participants who gave the corresponding description on the vertical axis to the total number of the relevant gender who chose HMD VR

[44] The horizontal axis shows the percentage of participants who gave the corresponding description on the vertical axis to the total number of the relevant gender who chose HMD AV.

device is essential for users regardless of gender. It is worth noting that there are two types of safety. One refers to physical safety, i.e., avoiding bumping into things, and the other refers to psychological safety, i.e., keeping from getting too immersed in the virtual world and disconnecting from the real world. Some statements are shown below (see more comments in Appendix E4):

Participant # 57 "…Because I think it's dangerous to accidentally bump into something at home if you can't see around it…"

Participant # 59 "…I'm afraid I'll get hit because there's no open space for me to walk around and there's a lot of furniture in my home that I could easily bump into…"

Participant # 27 "…The AV headset didn't wrap around the face entirely, and you can still have a sense of the real-world environment. So, AV gives you a certain sense of security…

Five male participants (38.5%) and three female participants (37.5%) reported Code 2, and the statements for Code 2 indicated that AV could also provide a fair degree of enjoyable immersion, although not as intense as VR. Some comments were presented below:

Participant # 37 "… VR made me feel dangerous because I felt like I might trip over things in the real world. In this case, AV is probably more suitable (for the remote-site museum), and I think the immersion of AV is good enough…

Participant # 59 "…Because I thought the AV's immersion was fine, … VR's immersion was better, but some loss of immersion didn't affect me too much…"

Participant # 43 "…compared to most of the games on a mobile phone or PC platform, I think the experience and immersion of AV were better than them…"

Four male participants (30.8%) and three female participants (37.5%) reported Code 3, considering the space requirements for using the equipment and the space limitation in their own homes. Some comments are presented below:

Participant # 26 "…I can't use VR at home in a completely empty room because VR needs larger and cleaner space. But I can explore the virtual environments with AV headset in my own room without interfering with my daily life…"

Participant # 36 "…If I were at home, I would prefer to use AV. There is not much space at my home, and AV has a translucent display, it is less likely to bump into things. If the space is large enough, VR experience may be better…"

Two male participants (15.4%) and three female participants (37.5%) mentioned Code 4 wearing equipment. Some comments are shown below:

Participant # 42 "…Because VR headset would cover your head completely, it was bulkier, and it felt like a burden on your head. However, AV glasses were lighter. It can be more relaxing to use it…"

Participant # 49 "…Because VR was, after all, a bit bulkier…"

Participant # 22 "…The AV's headset was much more comfortable to use, lighter, smaller and more relaxed to wear.…"

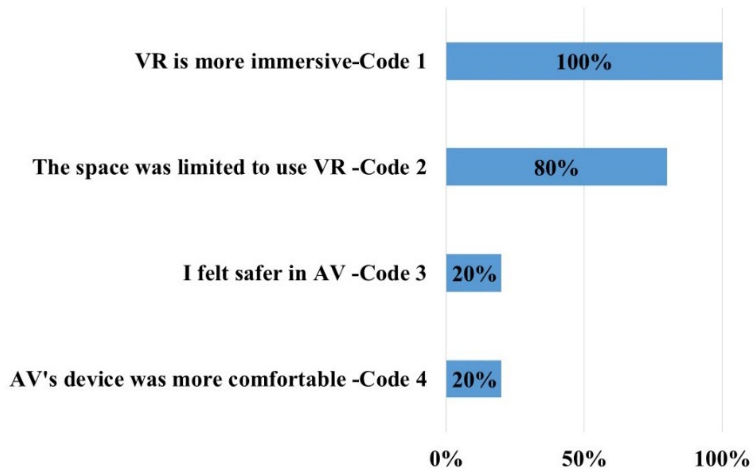

Fig. 7.8 Codes of reasons for users with no preference for the remote-site museum[45].

Fig. 7.8 showed that the reason users thought the decision should be made depended on the situation. 5 participants (100%) reported Code 1, which indicated the stronger immersion feeling was the reason they tended to use HMD VR. 4 participants (80%) reported Code 2, which indicated the limited space was the main obstacle to use HMD VR. Some statements are detailed below:

Participant # 6 "…I think it depends on the size of the available space. AV is better in a narrow space because you can still see the real-world environment. If the space is big enough, VR should be better…"

Participant # 32: "…If I have a lot of space at home, then I would use VR. If I can only have a small space, I'd like to use AV to experience the remote-site museum…"

In summary, the answer to question 2 revealed an interesting phenomenon: although the number of people who preferred AV was small in terms of the medium itself, nearly three times more people chose AV when considering the actual usage for remote-site museum experience at

[45] The horizontal axis shows the percentage of participants who gave the corresponding description on the vertical axis to the total number of participants with no preference.

home. The analysis for the code of question 2 further revealed the reason for the phenomenon. Over 40% of participants chose HMD AV or had no preference, mainly because of physical and psychological safety and the space size constraints at home. So, they tended to sacrifice some immersive experience, and one-third of them found the immersive experience of AV was also acceptable. Furthermore, the immersion and overall visual experience were the main reasons users chose HMD VR for the remote-site museum. In addition, the bulky and uncomfortable fitting of the HMD VR device was a secondary reason why users did not choose VR.

7.5.3. **Favourite/Hated experience**

In Q3, the participants were asked to describe their favourite and least favourite moment or interaction. Fig. 7.9 showed the coded descriptions of participants' favourite experiences in descending order. The top 5 codes were 1) Prop interaction was interesting; 2) Highly interactive characters; 3) Good story design; 4) Good sensory experience of VR; 5) The virtual scene environment and details were impressive.

Code 1, prop interaction, was mentioned most frequently by 14 male participants (46.7 %) and eight female participants (36.7 %) as their favourite experience, ahead of the other codes (see Fig. 7.9). It indicated that good prop interaction was a critical experience of a good interactive narrative. Table. 7.4 further showed the detailed category of Code 1. 13 participants stated gramophone was their favourite, and 9 participants referred to the diary. Though the diary was the key item to trigger the main storyline and introduce the character into the environment, it was interesting that the gramophone was even more welcome than the diary. The gramophone provided multi-sensory feedback, and the gramophone played music that blended perfectly with the environment and set the historical mood well. Some comments are presented below (see more comments in Appendix E5):

Participant # 56 "…I felt that it was very interesting to be able to interact with the items as I walked through them, for example, triggering the handle to play the gramophone…"

Participant # 33 "…What I liked most was that I explored touching the gramophone, and there was a nice atmosphere when the music was playing. Although the gramophone didn't advance the story, I thought it was a pretty nice design…"

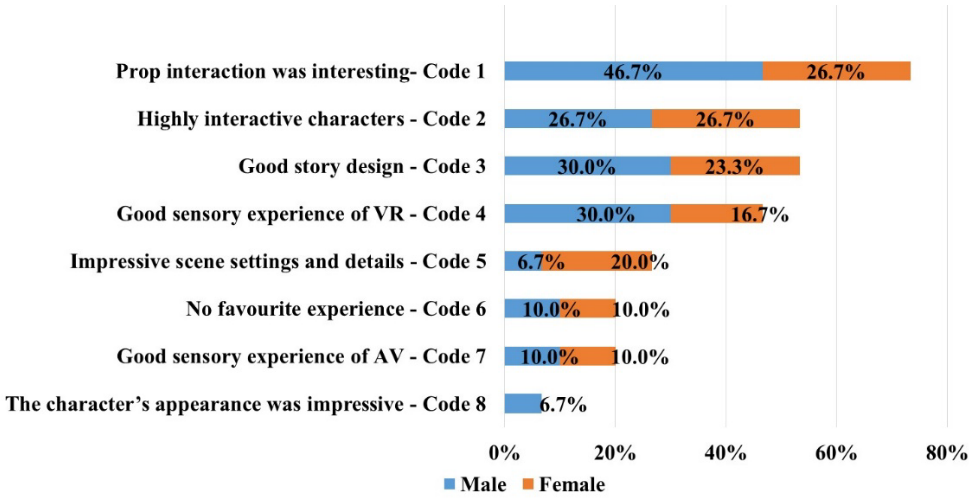

Fig. 7.9 Codes of detailed descriptions for user' s favourite experience.[46].

Table. 7.4 Detailed descriptions for good prop interaction

Category	Female	Male	Total
Gramophone was interesting	4	9	13
The interaction of diary was interesting	6	3	9
Newspaper was interesting	1	2	3
Suitcase was interesting	1	0	1
Telephone was interesting	1	0	1

Eight male participants (26.7%) and eight females (26.7%) reported they were impressed by highly interactive characters (Code 2), and nine males (30%) and seven females (23.3%) remembered the story design as their favourite experience (Code 3). It seemed eye contact and face-to-face talk was effective in immersive storytelling. Besides, exploration and branching story design were valid to make the narrative more engaging. Some comments are presented below (see more comments in Appendix E6):

Participant # 42 "…One of my favourites, I was also surprised, was that when the little boy was talking to me, he could walk into me. Then I deliberately moved around him and found that the boy could turn around to face me. This moment was amazing to me and quite funny…"

Participant # 43 "…What I liked the most would be that Leo would keep his eyes on you. He would stare at you, and when you were looking at him…"

[46] The horizontal axis shows the percentage of participants, who gave the corresponding description on the vertical axis, to the total number of their gender

Participant # 4 "…What I liked most was the moment of making a choice. I felt completely involved in the story. I could get feedback through my point of view, and I felt like I was communicating with the characters in the story…"

Nine male and five female participants commented that VR's good sensory experience was their favourite (Code 4). Some remarks are listed below:

Participant # 1 "…In VR, the moment when I put on the headset and my surroundings went dark, and then the light and image came back into my vision, I felt very astonished. It felt like I was transferred to another world for a moment. Especially, as my vision could match the movement of my body, it would give me the illusion that this virtual world was real…"

Participant # 21 "…it felt realistic I could view the characters from all angles…"

Participant # 23 "…The overall experience was novel, and as soon as I took my glasses off, I felt like I was suddenly back in the real world …"

13.3% of participants stated Code 5 that the virtual scene environment and details were impressive (see Fig. 7.9). It implied that the details in the scene could enhance the believability of the virtual environment and the user experience. Some descriptions are presented below:

Participant # 50 "…I could see details such as his mother's clothes, purse, etc. Although these things were not interactive, I found them very lively…"

Participant # 29"…What I found most impressive was the oil painting on the wall, which would just draw me to walk closer to get a better look…"

Participant # 52 "…I think the table and the tablecloth were quite well done, the coffee cups also looked nice, but the coffee seemed to be filled up too much…"

Fig. 7.9 showed that the remaining codes that were less than 10% included：10% of participants mentioned Code 6 that they did not have any favourite experience; 10% of participants said Code 7 that they liked the good sensory experience of AV; and 3.3% of participants reported Code 8 that the character's appearance was impressive. It also indicated that most users did have an impressive moment, and the above two aspects needed to be enhanced. Some statements are shown below:

Participant # 36 "…I didn't particularly enjoy a moment …"

Participant # 38 "…I particularly liked the experience in AV. When putting on the headset, I could see some virtual images overlaying on top of the real world, which made me feel great …"

Participant # 30 "…I found the character quite vivid, and I could see his skin and his eyelashes at a very close distance…"

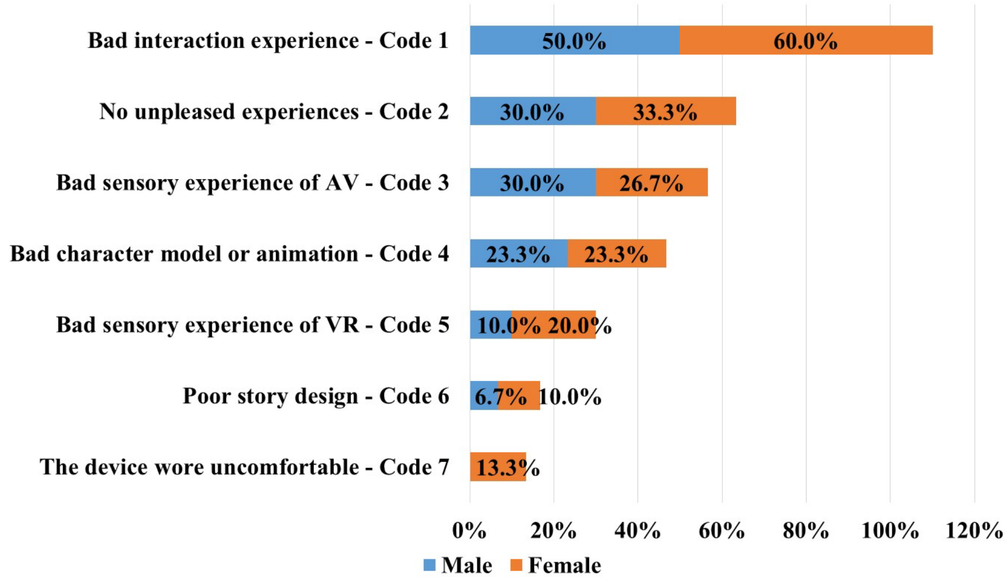

Fig. 7.10 Codes of detailed descriptions for user' s most hated experience[47].

The participants were asked to describe their least favourite moment or interaction. Fig. 7.10 showed the coded descriptions of participants' most hated in descending order. The top 5 codes were 1) Bad interaction experience; 2) No unpleased experience; 3) Bad sensory experience of AV; 4) Bad character model or animation; 5) Bad sensory of VR.

Code 1, bad interaction experience, was reported most frequently by 15 male participants (50%) and 18 female participants (60 %) as their least favourite experience, obviously ahead of the other codes (see Fig. 7.10). Table. 7.5 further showed the detailed category of Code 1. 23 participants stated they had problems triggering the interaction, while eight reported hand recognition errors. Some of the remarks are demonstrated below (see more comments in Appendix E7):

Participant # 57 "…Sometimes I needed to touch the prop several times with my hand (to activate them), and it felt like the triggering wasn't very effective…"

Participant # 8 "…There were times the device didn't recognise my hand, and I actually preferred to use the controller to operate…"

Combining with behaviour observation, it revealed that the immature hand recognition, low-mapping interaction operation and low habituation of the operation for user lead to

[47] The horizontal axis shows the percentage of participants who gave the corresponding description on the vertical axis to the total number of their gender.

unsatisfied feedback.

Table. 7.5 Detailed descriptions of bad interaction experience

Category	Female	Male	Total
I had problems triggering the interaction	14	9	23
Hand recognition error	4	4	8
Interaction design issues	1	5	6
I couldn't judge distances between the hand and virtual items	2	1	3

Nine male participants (30%) and ten female participants (33.3%) stated they did not have a hated experience (Code 2). Nine male participants (30%) and eight female participants (26.7%) mentioned bad sensory experiences as their hated experiences (Code 3). Some descriptions are shown below (see more comments in Appendix E8):

Participant # 5 "…The AV equipment made my eyes a little uncomfortable. Specifically, the view was rather small, and there was some reddish chromatic aberration…"

Participant # 33 "…With the HoloLens on, virtual content only displayed on a small frame, I could see the real world around me. I felt like I was still in the real-world environment. There was no sense of immersion…"

Seven male participants (23.3%) and seven female participants (23.3%) described the bad character model or animation as their hated experience (Code 4). Some statements are listed below (see more comments in Appendix E9):

Participant # 42 "…The most annoying thing was that the dad and mum hug each other rather stiffly in the end. Mom and dad also didn't have much action, not realistic…"

Participant # 47 "…Leo suddenly came up to me that his face looked a little creepy at such close distance. Moreover, I felt uncomfortable…"

Three male participants (10%) and six female participants (20%) reported the bad sensory experience of VR as their hated experience (Code 5). The negative sensory experiences were associated with scary, auditory or text displays. Some comments are shown below:

Participant # 22 "…In VR, there was a black screen at the very beginning, and the moment when people knocked on the door, I felt it was a bit scary…"

Participant # 48 "…As soon as I turned my head, his father suddenly appeared and frightened me…"

Participant # 19 "…The sound of the rain in the VR scenes was a little unrealistic, and it was so loud that the human voices were not clear…"

Two male participants (6.7%) and three female participants (10%) stated the unsatisfied story design as their hated experience (Code 6). The complaints were mainly about the pacing and dialogue of the story. Some remarks are listed below:

Participant # 49 "…Mum and Dad were talking over there at the beginning, the lines were written too verbose…"

Participant # 31 "…The scripting was flawed, and the characters' dialogue was too long. I could only stand there watching, and I couldn't do anything to trigger other storylines. That's annoying…"

Participant # 22 "…I thought the script lacked emotional rise and fall. It was generally a flat script. I felt the story couldn't keep people's attention all the time and then empathise with the character…"

Finally, four female participants (13.3%) said the least favourite experience was the bad ergonomics of the equipment (Code 7).

In summary, the answer to question 3 revealed that around 70% of users were impressed by the interaction of props, characters and plot, and the good sensory experience of VR only impressed by about 20% of users. It indicated the importance of interaction design of interactive narrative beyond the sensory experience. Around 70% of participants were disappointed by the interaction operation, AV's sensory experience, and characters' model and animation. Though participants liked the interaction possibility and interaction design with environments, characters and stories, over half of participants stated the bad interaction operation experience as their hated experience. The flawed interaction operation was caused by immature hand recognition, low-mapping interaction operation and low habituation of the users' operation. Narrow FoV, chromatic aberration and transparent display were the main reasons users hated the AV sensory experience. Besides, about 20% of participants reported discontent with unnatural character modelling and animation.

7.5.4. **Suggestions for improvement**

In Q4, the participants were asked what aspect they would like to change to improve the narrative experience. Fig. 7.11 shows the coded suggestions in descending order. Eleven male participants (36.7 %) and 16 female participants (53.3%) reported they wished the characters or environment to be more realistic (Code 1), including the realism of the character animation.

It indicated that about half of the participants were not satisfied with the virtual character or scene fidelity, and females were slightly more critical about authenticity. Table. 7.6 further showed that people were mainly concerned with the character's appearance. Twenty-three participants proposed that the character need to be made more realistic, more than twice the number of people who suggested the scene should be more realistic. Some comments are demonstrated below (see more comments in Appendix E10):

Participant # 4 "…The top points that I would like to improve are: firstly, the scenes could be more realistic, and secondly, the characters may also need a refinement…"

Participant # 59 "…I would like to improve the modelling of the characters. The environment and everything else were pretty well done…"

Participant # 51 "…improve the character to the point where it could look like a real person…"

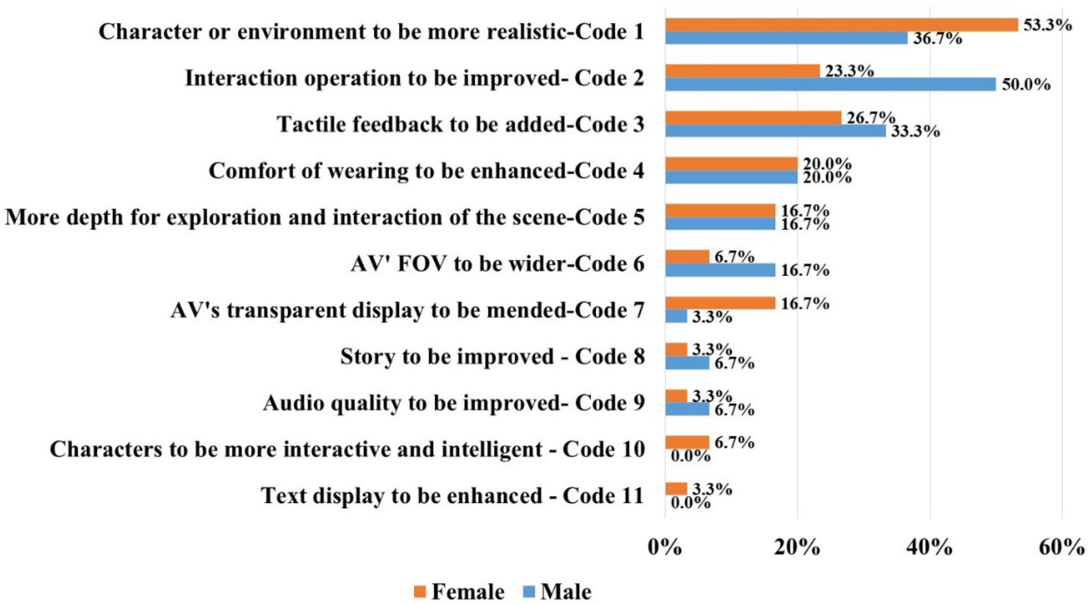

Fig. 7.11 Codes of suggestions for the remote-site museum of users[48].

Table. 7.6 Proposals for Fidelity

	Scenes need to be more real	Characters need to be more real
Number of people proposed	10	23

People who reported negative feelings of character modelling or animation or suggested

[48] The horizontal axis shows the percentage of participants who gave the corresponding description on the vertical axis to the total number of participants of the relevant gender.

that characters need improvement were further asked to what extent the unnatural characters spoil their experience. Table. 7.7 showed 7 participants (11.7%) reported mild negative impact, 15 participants (25%) reported moderate negative influence, and 6 participants (11.7%) stated severe negative impact. The above feedback revealed that the issue of characters' fidelity negatively affected about half of the participants, clearly interfered with about 35 % of participants' experience, heavily disturbed 10% of participants. Some statements are shown below (see more comments in Appendix E11):

Participant # 15 "...The fidelity issue of the characters didn't really affect my experience too much. I think different games have different requirements. I probably wouldn't pay much attention to the character models for this kind of game with a plot and profound thinking. I'd like to pay more attention to the content of their dialogue while having some reflective thinking rather than focusing on the details of the character models. I'll request high-quality graphics when I play a fun game or an action game ..."

Participant # 34 "...I thought the unrealism and unnaturalness of the characters had a big negative impact. If the realism of the characters isn't good, users cannot have a good experience..."

Table. 7.7 The extent of the negative impact

	Number of people	Percentage to the total number of participants
Slight negative impact	7	11.7%
There was an influence, but acceptable	15	25%
Seriously spoiled my experience	6	10 %

Fifteen male participants (50 %) and seven female participants (23.3%) reported Code 2 that the interaction design or operation needs to be enhanced (see Fig. 7.11). It indicated that the current interactive experience did not convince over one-third of the participants, and males were keener on interactive experience. Table. 7.8 further showed that interaction detection issue was mentioned most by 12 participants. The interaction detection included hand recognition of the user's fingers and collision detection for interactive props. Some suggestions are presented below (see more comments in Appendix E12):

Participant # 4 "...The interaction could also be improved. Though direct hand manipulation looks a bit more advanced, I think it's better to interact with a controller. Hand recognition has a delay, and direct hand manipulation is cumbersome to use. Thus, its experience is relatively poor..."

Participant # 32"...I hope that the touch function can be enhanced to be more sensitive, in the experiment, I always couldn't open or trigger the props and drawers..."

Except for interaction detection, natural interaction design was the second most mentioned by eight people (see Table. 7.8). Most users' initial reaction was to interact with virtual items using the same actions as in real life; for example, they always tried to grab handles to pull the drawers. Some suggestions are shown below:

Participant # 9 "…It was a bit unnatural and strange to click on these props to trigger the interaction, so I hope there's a more natural way to interact with them…"

Participant # 38 "…I hope there are no barriers in terms of operation. Users can know how to interact and perform the interaction straightforwardly…"

Participant # 53 "…I would like to change the interaction design. it was not natural enough. For example, the drawer was popping instead of pulling it open, I was very close to the drawer at the moment, and then I had a horrible feeling of being struck through…"

Interaction hints and the virtual hand design were also proposed to improve by 6 participants (see Table. 7.8). They mainly wanted the hints and the virtual hand design to be 'invisible' and user-friendly. Some comments are listed below (see more comments in Appendix E13):

Participant # 43 "…I felt a little strange to see interactable items highlighted. I'd like to improve it to be not so rude and dramatic, hopefully almost like the real world …"

Participant # 7 "…I would like to see better guidance design and hopefully some improvement in the interactive hints…"

Table. 7.8 Proposals for Interaction

	Number of people proposed (male)	Number of people proposed (female)	Number of people proposed (total)
Interaction detection needs to be improved	7	5	12
Interaction design needs to be more natural	6	2	8
Interaction hints need to be improved	3	0	3
The virtual hand needs to be improved	2	1	3

Ten male participants (33.3%) and eight female participants (26.7%) reported Code 3 that they appealed for tactical feedback. Nearly 30% of users made this suggestion, and it showed that people wanted the virtual experience to approach their real-life experience in every sense. The advice is listed below (see more comments in Appendix E14):

Participant # 58 "…I would like to add to the experience is the tactile sensation of the hand and the foot, for example, when I touch the desk, I could feel that there is something or a force feedback here…"

Several hardware-related improvements were raised, including the comfort of wearing (Code 4), FoV of AV headset (Code 6), display quality (Code 7). To be specific, six males (20%) and six females (20%) suggested it should be more comfortable to wear the headset; 5 males (16.7%) and two females (6.7%) proposed that the FoV of HoloLens needed to be broader; one male (3.3%) and five females (16.7%) wished that the display of HoloLens could be opaque instead of transparent. Some suggestions are presented below:

Participant # 22 "…I'd like to improve the helmet because it's heavy and uncomfortable against my face. For people like me with glasses, it's difficult to adjust the helmet to a completely comfortable position…"

Participant # 50 "…the scenes in HoloLens were not displayed clearly. I hope the display hardware of HoloLens could be improved…"

Participant # 33 "…change the field of view of HoloLens to be larger. I can see the complete character even when I am close to the character…"

The last notable Code 5 was mentioned by five males (16.7%) and five females (16.7%). It indicated that users appealed for more interesting interaction feedback or more interaction possibilities. Some suggestions are listed below:

Participant # 37 "…I think the interaction wasn't very well done. It wasn't very engaging if it was just flipping through books and pulling open drawers…"

Participant # 27 "…I saw that there were two doors in the room, and I wanted to open them to go outside and explore.…"

Participant # 31 "…I would most like to make the scene larger, where I could move freely and explore more items in the room. I also wanted to explore more rooms…"

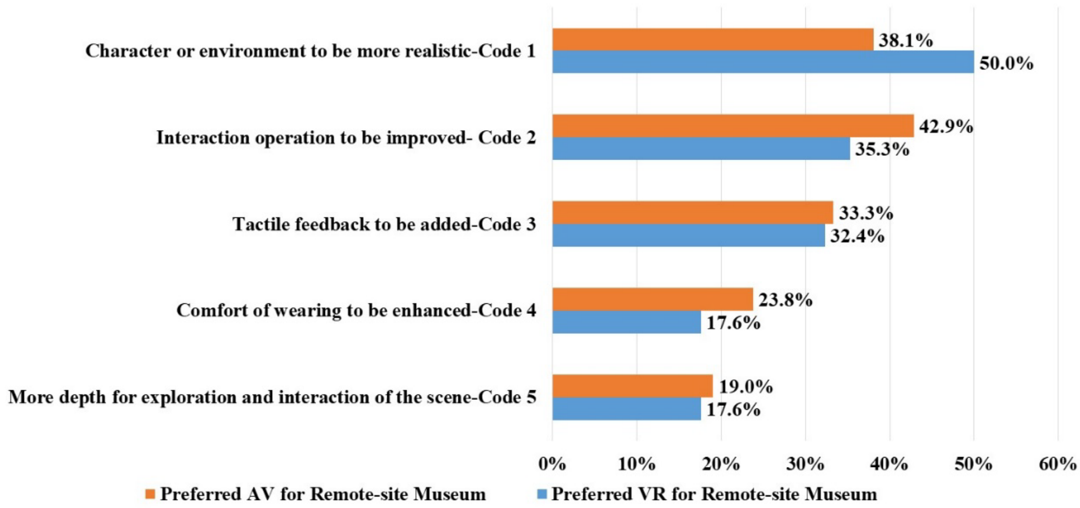

Fig. 7.12 Codes of suggestions for the remote-site museum of users.[49].

Fig. 7.12 further showed that 17 participants (50% of people preferring VR for the remote-site museum) and 8 participants (38.1% of people preferring AV for the remote-site museum) suggested more realistic characters or environments be made in the experience. On the other side, 12 participants (35.3% of people preferring VR for the remote-site museum) and 9 participants (42.9% of people preferring AV for the remote-site museum) proposed to improve the interaction experience. The above findings implied that users who preferred VR for the remote-site museum slightly tended to have a higher standard for audio-visual experience, while users who preferred AV for the remote-site museum were slightly inclined to expect a better interaction experience.

In summary, the answer to question 4 revealed that over 40% of participants wanted more realistic characters in the experience. The interview also demonstrated that the artificialness of character negatively interfered with about 35 % of participants' experiences and heavily disturbed 10% of participants. About 40% of participants and 30% suggested improving the interaction action design and adding tactile feedback, respectively. These suggestions were not surprising as more than half of the participants previously disliked the interactive operation experience. It is worth noting that some users blamed the inadequate interaction action for the lack of haptic

[49] The horizontal axis shows the percentage of participants who gave the corresponding description on the vertical axis to the total number of participants of their media preference group for the remote-site museum

feedback, so they proposed to add haptic feedback rather than improving the interaction action design. In addition, users' desire for haptics increased due to the highly immersive audio-visual experience of the direct interaction by hand. About 20% of participants reported the device improvement, such as reducing weight and enhancing wearing comfort. Around 20% of participants wanted more beyond the current environment interaction design, which involved more scenarios than a single living room and more complex interaction than simply opening and triggering.

7.6. Discussion: User Acceptance of Museums in HMD-based VR and AV

The purpose of this research was to serve as a pilot study on linking an interactive narrative with a museum's artifacts to enhance the users' interest and enjoyment in an HMD-based immersive remote-site museum. The interview analysis in experiment 2 demonstrates the great potential of the immersive remote-site museum as a viable method of exhibition and learning for future projects. Over 85% of the participants were interested in the immersive remote-site museum, and they quickly adopted it as a learning approach due to the remote-site museum's clear benefits. These included a rich learning experience, accessibility, an embedded narrative, and feelings of immersion, all of which were superior to that found in traditional museum displays. As the above extended TAM indicated, narrative engagement is an important external factor for user acceptance. The interview results further confirmed that the interactive narrative design was adequate, with over a third of people in experiment 2 as found in Section 6.5.3 explicitly stating the main reason they wanted to use the remote-site museum was for the interactive experience. Some participants mentioned some additional benefits of a remote-site museum, which included preserving the heritage of the story and making it easier for visitors to revisit the exhibition.

Still, Section 6.5.3 revealed that about 7% of participants disliked these types of virtual museums. They believed that virtual items could not be as realistic and detailed as objects in real museums. However, given the recent advances in 3D scanning and real-time rendering engines such as Unreal 5, it is likely that within the next five years users will be able to experience ultra-realistic visuals of objects and characters in HMD-based remote-site museums. Furthermore, VR and AV devices are advancing rapidly. For example, over the past three years, the Oculus headset has already doubled its display resolution from 1K to 2K per eye. As for the 6% of participants who had a neutral attitude towards the remote-site museum, their decision seemed to be directly tied to the museum's theme. They were not interested if the remote-site museum merely displayed objects in a similar manner to traditional museums, but they would be willing to use the remote-site museum if it presented an interesting narrative, similar to the one in our example. In other words, they were not interested in remote-site museums that simply replicated a real museum's exhibition. This strengthens the conclusion that a virtual museum should work to compliment a real museum. This kind of complementary exhibition requires a good interactive design, a novel user experience, and the distribution of content that cannot be found in the current exhibition.

Regarding media type, the experiments provided strong evidence that HMD VR allows users to experience a higher degree of narrative immersion, presence, and enjoyment than HMD AV. The interview in Section 7.5.1 and Section 7.5.2 also confirmed these findings that showed over 80% of participants preferred the HMD VR experience over HMD AV. The main reason for this was the superior visual display of VR. However, when looking at media used specifically for a remote-site museum experience, over one-third of participants chose to use HMD-based AV. Specifically, over 40% of participants chose HMD AV, or had no preference. Due to physical and psychological safety, as well as the space size constraints at home, some of them tended to sacrifice parts of the immersive experience. One-third of them found that the immersive experience of AV was also acceptable. However, the interviews in Section 7.5.3 and Section 7.5.4 implied that female users were more concerned with immersion, the environment's details, and the authenticity of the characters, while male users were more concerned with the interaction experience.

These exciting findings suggest that other additional factors played a role in influencing people's acceptance of the technology. Furthermore, these factors mainly referred to the use of the environment, including safety concerns and spatial constraints at home. They also revealed that the HMD-based VR could not be accepted by all participants. Some users did not like the insecure feeling of wearing the VR headset. Thus, HMD-based AV, while admittedly not as visually appealing as VR, could attract users who were wary of security and space risks. Additionally, knowledge that male users are more sensitive to the interactive experience than the visual elements means that male users may be more accepting of a HMD-based AV if the interaction design of AV can be enhanced. In other words, although HMD AV like HoloLens has problems such as narrow FoV issues, colour bias and light bleeding in its display, the see-through headset has the benefit of allowing the user to stay connected with their real-world setting. They can also be less expensive in terms of space, size, and requirement for HXRM.

These findings provided a direction for the future development of VR and AV device hardware. For the HMD-based VR, the safety aspect of VR must be improved. For instance, the latest Oculus Quest 2 could switch to the external camera view to see the real world once the user was out of the assigned safety range. Furthermore, Oculus Quest 2 greatly enhanced the wearer's comfort by reducing pressure on the user's face. These improvements can reduce users' psychological feelings of insecurity. For HMD-based AV, improving the FoV is still of the utmost importance. Moreover, it is necessary to display the virtual content as opaque instead of transparent. Thus, video see-through technology could be a possible solution for transparency issues.

7.7. Discussion: User Experience of HMD-based XR museum

Based on the data from experiments 1, 2, and 3, seven hypotheses were investigated, and the final validated extended TAM model was summarised. Feedback on interactions was a major focus of the interviews, so the impact of interaction on the user experience in HXRM was given further analysis. In the HMD-based media, there were three main aspects of interaction in the interactive narrative that require attention: the agency of natural observation and exploration, the authenticity of interaction, and a stronger emotional connection with the characters. The successes and failures of the interaction design were further summarised in this study by identifying and analysing the user's favourite and least favourite experiences.

7.7.1. Extended TAM model for HMD-based XR museum

Section 3.2 presented a user experience model for HMD-based museums. This model is based on TAM theory. It extends TAM by including features of HMD-based XR museum as external factors. Section 3.2.5 goes further by proposing seven hypotheses for the proposed model. The H1 and H2 were examined in experiment 1 (see Fig. 3.10), which did not support them. H3, H4, H5, H6, and H8 were verified via experiment 2. H3 confirmed that the user's learning interest could predict narrative engagement, while H4 failed to be validated. The findings showed that prior gaming experience has a non-linear impact on the realistic CG character's affinity. Specifically, no-game-experience and extensive-game-experience users tended to have a higher affinity for the mid-level realistic CG characters than some-game-experience users in the HMD-based XR museum. This finding was also consistent with the analysis of experiment 3. H6 was partially supported in that narrative engagement only predicted the perceived usefulness. H8 was validated in that the CG character's affinity had a positive impact on narrative engagement. H7 was partially confirmed via experiment 3: the degree of presence only predicted the perceived enjoyment.

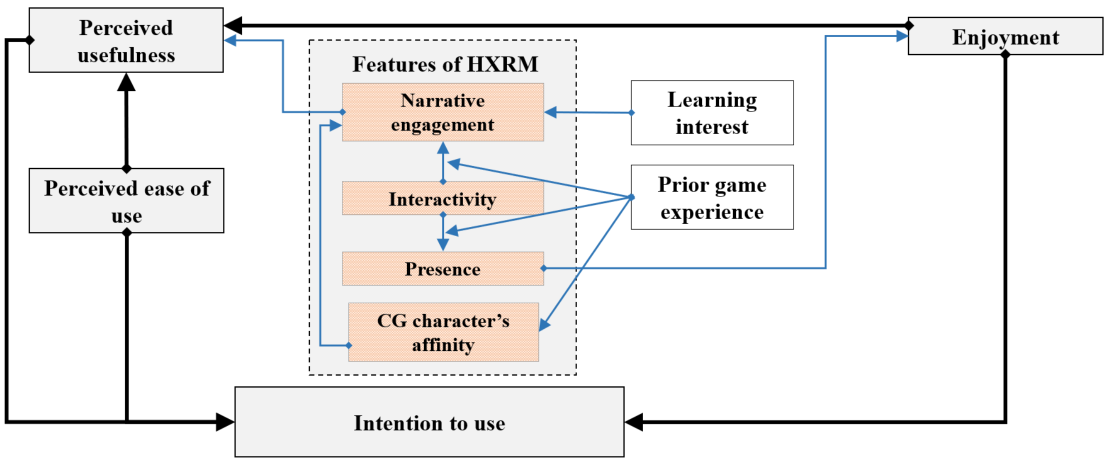

Fig. 7.13 The final validated extended TAM model (The blue line was the validated by this study, and the black line was validated by previous studies)

As Fig. 7.13 shows, the final validated TAM for HXRM consisted of four external factors, including narrative engagement, interactivity, presence, and CG character's affinity which can affect Perceived Usefulness (PU) and enjoyment. These external factors are the features of HXRM and are influenced by two user factors of learning interest and prior gaming experience.

In section 3.2.5, I proposed four features of the HMD-based XR museum as the external factors of the extended TAM, and made hypotheses that all four factors would have an impact on PU and Enjoyment (see Fig. 3.10). However, experiments and data analysis reveal that narrative engagement has a positive impact on PU, presence could predict enjoyment, and the other two factors interactivity and CG character's affinity did not influence PU and enjoyment (see Fig. 7.13). A possible explanation for the positive correlation between narrative engagement and PU may be that narrative engagement could predict empathy which is one of the key objectives of the museum's learning. One piece of evidence found in the interviews showed that more participants in the VR group, who had stronger narrative enragement than the AV group, expressed a stronger empathy for the protagonist of the story, and felt as if they were in the story and learned more from the story. A possible explanation for the positive impact of presence on enjoyment may be that presence is an important indicator of the sensory experience. The interviews in the within-group design experiment showed that the majority of participants enjoyed VR more than the AV version due to its stronger immersion sensory experience. The possible reason that interactivity did not have a positive impact on Perceived Ease of Use (PEU) as expected may be that a high-interaction-mapping design like NUI didn't mean easier to use in the XR scenario, while many participants may feel more familiar with low-interaction -mapping design like GUI. CG character's affinity also did not have a positive effect on enjoyment as hypothesized.

The validated extended TAM also revealed two user factors that were closely related to the proposed four external factors: learning interest and prior game experience (see Fig. 7.13). Learning interest is confirmed to positively influence narrative engagement. The interviews and observation also further supported this finding that participants who were interested in the topic of the Holocaust generally were more engaged in the interactive narrative. On the other side, the prior gaming experience has a non-linear impact on the realistic CG character's affinity, and CG character's affinity can affect narrative engagement positively. Specifically, no-game-experience and extensive-game-experience users tended to have a higher affinity for the mid-level realistic CG characters than some-game-experience users in the HMD-based XR museum. A possible explanation for this finding is that inexperienced participants have lower expectations, while rich-experienced participants are more tolerant of the game's visuals, so they both gave higher ratings for CG characters' affinity. CG characters play a key role in the storytelling, and low CG characters' affinity usually means that the audience feels weird or uncomfortable with the characters, which probably affects the user's engagement in the story to some extent.

Lastly, the influence of interactivity on presence and narrative engagement for HMD-based AR museums is moderated by prior game experience. In other words, users with previous gaming exposure experienced greater narrative engagement and presence in conventional interaction mapping (GUI) programs than in more natural metaphorical interaction mapping (NUI). Simply put, only users with no game experience had better narrative engagement and presence in the NUI. One possible explanation for the influence user gaming experience has on interaction mapping is further covered in section 5.6.

7.7.2. **Interaction experience in HMD-based XR museums**

In VR and AV, interaction method and quality significantly impact the experience of the user, sometimes even more than story content and sensory experience. Our analysis of the interview data in Section 7.5.3 showed that people's top three favourite experiences were all interaction-related. These included prop interaction, highly interactive characters, and interactive storytelling design. The least favourite experiences, on the other hand, were frequently reported as also being related to interaction operation methods. This demonstrates how good interaction design is essential to the user experience.

Further analysis of the interview data in Section 6.5.2 revealed that HMD-based immersive media such as VR and AV differed from traditional media methods in three aspects of interaction: the agency of natural observation and exploration, the authenticity of interaction, and a stronger emotional connection/ with characters. In our study, these three aspects of interaction were identified and praised by users. These findings signify the need to consider the changes motivated by these aforementioned aspects in head-mounted immersive media.

Thanks to agency of natural observation and exploration afforded by HMD-based immersion media, users are free to walk through a scene and observe items naturally. In order to create a more immersive and authentic experience, users need to be empowered to interact with the environment instead of just observing their surroundings. Our qualitative analysis in Section 7.5.3 also found that interacting with props was the number one favourite experience of users. The gramophone interaction ranked the first of all the prop interactions, which gave us the insight that multi-sensory interactions, the use of unconventional items, and interaction feedback that sets the historical atmosphere were all successful designs. For instance, following this principle, a good design would be an ancient virtual instrument that users can play with, such as drums or chimes, or virtual typewriters and telegraphs that players can operate. Because it is also difficult to experience the artefacts mentioned above onsite using a multi-sensory approach in a real-world museum, these interaction designs meet the above principles. The second favourite prop was the diary, which starts the story after being triggered. Unlike the other props, the stories triggered by the diary are not simply dictated by the protagonist Leo but are acted out by virtual characters within the space. In other words, the prop design offers a surreal experience that integrates the narrative seamlessly and uses rich media resources to recount the story.

Meanwhile, the least favourite experience for users was found to be the interaction operation method. Due to the realistic characteristics of HMD-based immersive media, users prefer and instinctively draw on natural behaviours and actions to operate. This generates challenges to interaction design. For example, if natural behaviour design is not used and instead artificial hand gestures or controllers are used for interaction, there will be a risk of reducing the user's immersive experience.

While basing interactions in natural behaviours creates significant challenge in technical implementation, interaction feedback is also more complicated and varied. Specifically, in terms of technical implementation, existing natural action recognition is not accurate enough. For HoloLens in particular, the recognition range is too small within its narrow FoV. As for the interaction feedback, natural actions can allow props to produce more complex animations than simple trigger animations, meaning that more realistic animations may be produced in this manner. For example, physics simulations such as rigid body and soft body simulation and collision detection may increase complexity and realism. Meanwhile, our interviews in Section 7.5.4 revealed that many participants requested force feedback when using natural behaviour for interaction.

Due to the high level of immersion, the results of our interviews showed us that users could better experience emotional communication and have a higher capacity for empathy with the virtual character through the HMD-based immersive media. In this respect, our successful designs include giving avatars the ability to move closer to and make eye contact with the active user during their conversation, both of which greatly enhanced the user experience. These results have been further confirmed by the previous data analysis of augmented reality. However, this realism also causes users to demand more from virtual characters' appearance and animation. Nearly a quarter of users reported issues with the character's model and animation, listing it as their least favourite experience (see Fig. 7.10). Additionally, improving the character's modelling and animation was the number one suggestion, with 35% of people in our interviews reporting that the artificial and unnatural-looking characters had a significantly negative impact on their experience. This finding was significantly higher in HTC Vive and HoloLens 2nd generation than the proportion of AR narratives in the HoloLens 1st generation. The number of people reporting this issue in the HoloLens 1st generation was around 10%, which indicated that the audience's expectation for the characters' authenticity significantly increased when the FoV of the device became larger. This could be because they could see the virtual environment more completely and realistically.

7.8. Summary

Using quantitative analysis to further investigated Q2, the author found that users experienced significantly more presence and enjoyment in HMD VR (represented by the HTC Vive Pro) than in HMD AV (represented by HoloLens 2nd generation). HMD VR had statistically significant stronger involvement, more natural control, and less interface distraction than HMD AV. H4 was again negated by the analysis data. Instead, prior game experience was found to have a non-linear impact on the realistic CG character's affinity. Specifically, people with either no or extensive experience tended to have higher affinity for the CG characters than people with some gaming experience. Furthermore, different forms of media and the character's intelligent behaviour were found to be influential for perceived affinity of a mid-level photo-realistic CG character. H7 was partially supported by the finding that presence significantly predicts the value of perceived enjoyment.

Qualitative results confirmed the above findings and revealed that over 80% of users chose

HMD VR as their preferred form of media. The main reason for this preference was HMD VR's advantages of visual display, including a larger FoV, a distraction-free display, and better visual quality. This differed from HMD AV's translucent display which was accompanied by many distractions. However, only around 55% of users chose HMD VR for their remote-site museum experience, while around 35% chose HMD AV. The interview results showed that the users who chose HMD AV were mainly concerned about the safety of use, space constraints, and comfort of the device, while they also believed the immersion effect was acceptable in HMD AV. Therefore, users who chose HMD VR were mainly fond of its immersive audio-visual experience. The findings indicated that the use environment and device ergonomics were potentially important factors for the acceptance of HXRM.

The qualitative results also revealed the users' favourite and least favourite experiences, as well as their top suggestions for improving the experience. These results provided a valuable reference and evidence for design guidelines of HXRM. For example, the interviews revealed that the interaction experience and the characters' fidelity were deciding factors in the success of the narrative experiences. As for interaction, the interaction design of props, characters, and the story received positive feedback, while the interactive actions that were not intuitive were unsuccessful. As for fidelity issues, the environment was verified to be appropriate, while the character's modelling and animation were ranked as unsatisfactory by about half of the participants. Therefore, users suggested the creation of more realistic characters, intuitive interaction actions, and additional feedback from the interaction. Some other hardware issues, which were not the primary problems experienced by users, included HoloLens' display weaknesses, the device's weight, and wearing comfort.

Chapter 8: Conclusion and Future Work

This chapter summarises this study, outlining the main contributions and discussing the limitations of the research, as well as future directions for the HMD-based immersive museums.

8.1. Design Guidelines for HMD-based XR Museum

One goal of this study was to identify design guidelines for HMD-based XR museums. Experiments 1 and 3 demonstrated that an interactive branching narrative was a reliable form of HMD-based XR museums, even when only simple story branches were used. Thus, branching narrative design can make the storytelling more attractive. Over 80% of participants in experiment 1 showed curiosity in finding out what would happen in other branches (see Section 5.5.3). Notably, simply allowing the audience face a dilemma when making decisions at a branch is suitable to maintaining their interest. Approximately 20% of participants were particularly impressed by the first branch since they struggled to choose whether to support Leo's mother or father. Meanwhile, in experiment 3, 16 participants (26.7%) reported that the story design was their favourite part of the experience (see Section 7.5.3). This finding is in line with previous studies(Moser & Fang, 2014, 2015). This study was the first study investigating interactive branching narrative in HMD-based AR and VR, and as such it expanded on the conclusion of previous studies to the field of XR narrative.

Moreover, this study led to an interesting finding about narrative. Based on the analysis of the interviews in experiment 1, we found that a higher percentage of participants complained about the story issues, with 14 participants (24.1%) stating that the plot was flat, and 8 participants (13.8%) complaining about the long and tedious dialogu (see Section 5.5.3). This number was significantly reduced in Experiment 3, with only three users (5%) complaining about a similar issue during the interview (see Section 7.5.4). Interestingly, the story's plot in Experiment 3 was identical to that of Experiment 1, except for the number of interactable items and the visual environment of the story. For example, the drawers in Experiment 3 could be opened and closed, and descriptive labels would slowly emerge when approaching certain items. In Experiment 1 however, only six specific props were interactable, and the AR only augmented some interactive props and several pieces of furniture in the real-world space. Meanwhile, in Experiment 3, the story environment was much richer, which meant that the user could see the virtual wallpaper, floor, and carpet. Therefore, two possible explanations were proposed for improving the narrative experience while maintaining the same plot. First, in line with Steuer's previous interaction theory (Steuer, 1992), the higher interaction range improves the user experience to the extent that the plot itself becomes richer to the user. Second, a more prosperous environment increases the cognitive information for the user to the point where it can even compensate for an insufficient amount of information in the plot itself.

Previous research stated uncanny valley varies from one individual to another (Lischetzke, Izydorczyk, Hüller, & Appel, 2017; Walters, Syrdal, Dautenhahn, Te Boekhorst, & Koay, 2008). Section 7.4.3 showed that prior CG RPG experiences have an impact on the perceived affinity of CG characters in immersive media. Specifically, users with some prior CG RPG experience are more likely to enter the declining zone of uncanny valley for mid-level photorealistic CG characters. Nowadays, more and more young people are now getting into video games including PRG. Therefore, it may be necessary to upgrade the mid-level photorealistic to high-level photorealistic CG character for an immersive XR museum. Due to the rapid development of digital human technologies like Meta-Human Creator [50] and Meta's photorealistic avatars generator by mobile phones (GROWCOOT, 2022), the cost of developing high-level photorealistic CG characters has been reduced significantly. It is feasible for small teams and studios to create better CG characters than mid-level photorealistic CG characters at present.

Moreover, section 6.5.4 revealed that the CG character's body movement, expression and voice all had a significant impact on the user's perception. Unlike the human likeness in the initial uncanny valley theory focuses on appearance only (Mori et al., 2012), it is suggested that human likeness needs to be integrated as a combination of motion, expression and voice

[50] MetaHuman Creator is a complete framework that gives any creator the power to use highly realistic human characters in a relatively easy and low-cost way. The official website is : https://www.unrealengine.com/en-US/metahuman

in a CG context. However, many CG developers are still prone to put more effort into the character's appearance, such as modelling, materials and textures. It is important to note that the developers need to invest in other aspects, especially in expressions and voice acting and ensure the balance between appearance, movement and voice.

Finally, as interaction is a built-in property of immersive media rather than a traditional flat screen, character interaction is a critical aspect of CG characters in immersive media. This study investigated the CG character's intelligent feedback to the participants, such as eye contact and finding behavior. Section 7.4.3 showed that the intelligent feedback to user interaction did not statistically improve perceived affinity, however, this study didn't conduct a rigorous with-group control experiment. Therefore, a rigorous experiment should be conducted to further validate the above findings. On the other hand, more than half of the participants described the intelligent behaviour of the protagonist Leo as an interesting and alive experience in the interview, showing the potential of making the users have better empathy for the CG character. As a result, designers need to pay more attention to the intelligent interaction design of CG characters, even though this design often indicates more programming and interdisciplinary work. In addition, it is important to understand that the CG character's interaction contains both user input and the CG character's feedback, and the user input could be multimodal, not only verbal dialogue input but also body movements and expressions. Multimodal interaction input for CG characters' interaction will be an area that deserves in-depth research and practice in both academia and industry. Based on this information, this study developed several guidelines for interactive narrative design for an XR museum:

1) Branching narrative design can feasibly make storytelling more attractive. Over 80% of participants showed curiosity in finding out what would happen in other branches. Dilemma choices, open questions, and tasks list are three branching strategies used for interactive narrative in this project, all of which were effective for improving narrative engagement.
2) Dilemma-choice design is particularly effective in an interactive narrative. Approximately 20% of participants were impressed by the first branch since they struggled with deciding whether to support Leo's mother or father.

3) Enhancing the interactivity of the virtual environment and props can increase the enjoyment of the experience and make up for the lack of drama in the plot itself.

The development of realistic CG characters is an important and time-consuming task. Most users claimed the artificiality of the CG characters had a minimally negative influence on them in Section 5.5.1, a finding that diverges from previous research (Roth et al., 2019). One possible explanation for this is found in the cognitive theory of multimedia learning proposed by Mayer. According to Mayer, people process verbal information and visual information in two separate channels, each of which have limited capacity for information processing. This causes people to allocate and adjust their cognitive resources (Mayer, 2014). Since the AR narrative applied here was dialogue-based and narrative-centred, the audience was forced to allocate more cognitive recourses towards verbal information processing. Since the AR experience of HoloLens offered a rich sensory visual mixed within a physical space, the audience was subject to a larger cognitive load than a usual movie on a flat monitor. Thus, the audience was inclined to have less sensitivity to CG characters' artificialness. Indeed, several participants asserted that they became relatively tolerant of unnatural characters as a result of the HoloLens's novel experience or because they were concentrating on the story. In terms of the realistic CG characters for the HMD-based XR museums, this study developed several guidelines:

1) The CG characters' level of intelligent interaction can increase the character's affinity in both AR and VR conditions. For example, the CG characters are visually appealing when using eye contact and interacting face to face with the audience. The virtual character should look intelligent when talking to the audience, meaning that they should be able to seek, walk towards, talk to, and gaze at the audience in real-time. Other researchers have reached similar conclusions (Marschner, Pannasch, Schulz, & Graupner, 2015).
2) Mid-level realistic CG characters are adequate for HMD-based XR museums. Therefore, designers should not spend too much effort on refining character with a limited budget. Producing a high-level realistic CG character is difficult and time-consuming, and the majority of users claimed that mid-level realistic CG characters only slightly affected their experience in an HMD-based AR narrative.

3) The interview also showed that the characters' animation quality is as important as their modeling, texture, and material. In HMD AR, the users tend to stay closer to the CG character and their focuses are mainly on their heads and expressions due to the narrow FoV of HMD AR. In HMD VR, which has a larger FoV, the users are more likely to notice the issues in the character's body movements. Therefore, depending on the target platform, the development needs to choose to focus on either facial expression or body movement.

4) Designers may consider taking note of whether target users have 3D RPG experience or not. Users with some 3D RPG experience are inclined to be more fastidious about the authenticity of CG characters, the response speed of interactions, and diversity of interaction feedback. Users without RPG experience need more guidance or visual/audio cues for interaction than those with RPG experience.

In terms of the user interface and interaction, this study also developed several valuable suggestions based on data from the in-depth interviews. Conclusions based on Section 5.2.1, 5.2.2, 5.2.3 were analysed to propose the guidelines below:

1) Gaze and commit with a clicker is a reliable interaction method for graphical interface in HMD-based AR. When compared with direct hand manipulation or hand gestures, this method is easy to learn. The participants using this method in the experiment did not report any problems or give negative feedback. However, they also did not demonstrate surprise or praise the feature.

2) Tangible interface design for HMD-based AR can achieve positive feedback, and some audiences may report new and interesting feelings. However, tangible interface design also requires more visual or audio cues and hints for interaction; otherwise, the audience may feel confused. For example, it is better to highlight the gramophone crank with a rotating icon floating above, rather than simply a floating text bubble with the phrase "Please turn on the gramophone".

3) A natural language interface for talking to a virtual character in HMD-based AR should be employed. Otherwise, the audience may feel embarrassed speaking loudly in a space like a museum. Additionally, it may feel strange to speak to a virtual hologram character as though they were a real person.

4) Slow interaction response should be avoided. Virtual characters must respond quickly to the audience's actions or words the way a real person would in order to maintain a sense of realism. Numerous participants noticed that virtual characters would delay one-second before their response. This finding confirmed Steuer's research on interactivity influencing presence (Steuer, 1992). Steuer highlighted that response speed and range, which refers to the number of possibilities to alter or interact with, were key interactivity variables. In this study, we found that the slow response of a virtual character could have a potentially harmful impact, as it could break the suspension of disbelief.
5) Visual or audio cue design can be conducive to alleviating negative feelings of narrow FoV. The on-screen arrow or spatial sound can help redirect the audience's attention when they lose their target on the small screen.
6) Interaction feedback should be diverse and include elements such as animation, audio, and character's actions. For instance, when a virtual newspaper is triggered, it can unfold while being accompanied by an offscreen introduction. The protagonist then walks over and stops in front of the newspaper, describing its influence on his life.

Finally, as HoloLens and HTC Vive pro were the representatives of HMD-based devices in this study, they have the core features of an immersive HMD headset: integrated display of virtual items and real-world objects in the headset, spatial understanding based on the 3D scanning, and interaction recognition technologies like speech and hand gesture recognition. As a wearable design, HMD-based XR represents the future of immersive technology. Therefore, the findings in this study can also apply to all XR museums and XR narratives using other HMD devices.

8.2. Summary of Thesis

Museums are an important part of modern society, playing an essential role in cultural development and knowledge dissemination, education, and the promotion of science. With the rapid development of immersive media technologies, conventional museum exhibits or introductory videos and animations no longer fully meet the requirements of accessibility and attractiveness in modern museums. Additionally, the outbreak of COVID-19 and the subsequent lockdowns have resulted in restrictions on access to museums.

Museums provide unique active learning opportunities through artifacts, environments, and scene reconstruction. HMD-based immersive for both on-site and remote-site museums have emerged as a new possibility for sharing knowledge, and several products designed for VR online museums have already been released in the Quest Store. This study focuses on application of the latest HMD-based VR and AR technologies in museums. The thesis first presents a critical review of related literature on VR, AR, interactive narrative, and museum education in general. Its intention is to provide an overview of the previous work on the subject and identify knowledge gaps. The main body of research consists of both technological development and experimental studies. Specifically, this thesis is focused on the objectives outlined below:

Technological development

Objective 1. To design and develop an interactive narrative virtual museum system with an alternative storyline branching sub-system and interactive props/items sub-system;

Objective 2. To construct assets of virtual collections/items and CG characters that are compatible with VR and AR system development;

Objective 3. To implement different application versions for a popular HMD platform that allows users the choice of both onsite or remote interaction.

Experimental studies

Objective 4. To propose the user experience model and to evaluate the external factors for TAM in the context of HMD-based immersive museums;

Objective 5. To compare and contrast the user experience, learning outcome and user acceptance differences between HMD VR and HMD AV as the media for immersive remote-site museums;

Objective 6. To investigate the design guidelines for HMD-based immersive on-site and remote-site museums.

Objective 7. To investigate the user's perceived affinity for realistic CG characters.

The design science research method was adopted for the purposes of this research. This research method is suitable for the subjects of computing and information technology, and it includes three cycles. At its core is the design cycle, in which theoretical models are iterated, refined, and driven by design practice. Scientific experiments are used to validate the conclusion. Design and development are a critical part of this research method. The experts from NHCM, who are committed to furthering Holocaust education, helped with the script development. The museum had previously expressed interest in using new media technologies for education due to its remote location and had already developed several successful projects, including an IOS App *The Virtual Journey*, as well as *The Forever Project,* which utilises the testimonies of virtual Holocaust survivors (Ma, Coward, & Walker, 2017). In the permanent exhibition *The Journey*, the narrative is based on the experiences of a fictional German Jewish boy growing up in 1930s Berlin. It follows his journey to the UK as a child refugee on the Kindertransport. The museum had already developed HMD-based VR and AR apps for the on-site and the remote-site museum experience of NHCM. The design and development of the applications fits with the design cycle of the research, and the prototyped applications were used for the experiment to assess the proposed models and theory.

Narrative is widely used in modern museums. With the help of new media technologies such as VR and AR, a non-linear narrative with the option for audience manipulation may produce a better user experience and greater learning outcomes. In chapters 2 and 4, a literature review on interactive narrative in immersive media was conducted. Based on Chatman's framework (Austin & Chatman, 1980)and Koenitz and Chen's model (Koenitz & Chen, 2012), a narrative strategy has been explored for the NHCM's VR and AR applications. The strategy used branched structure (also known as conditional-path structure) as the interactive narrative structure and the second-person perspective as the narrative PoV. The NHCM experts and I planned to communicate the historical events and introduce important objects to the audience via the fictional Jewish boy Leo's story. Leo's experience is typical example of what a child would have undergone in pre-WWII Germany.

To ensure historical accuracy, the script and dialogues from the parallel project *The Virtual Journey* IOS app were rewritten in collaboration with a historian at the NHCM. The dialogues and plots were directly drawn from the personal experiences of Holocaust survivors. The interactive narrative consists of two parts, the kernel, referring to the main story, and the satellites, referring to the story fragments. These can be discovered and explored by the user. In the experience, after finding the key item, Leo's diary, the main story is activated. The story begins with a family debate between Leo's parents about whether they should migrate to another country or defend their right to stay in Germany. Through the debate, the audience learns about the hardships that Jewish people in Germany faced before World War II. Afterwards, they are prompted to pick a side in the debate between Leo's parents. Different decisions send the story onto different paths. Afterwards, Leo gives a monologue about suffering numerous injustices at school in which he questions whether or not people are truly equal. Then, the doorbell suddenly rings, and the Hitler Youth breaks in and threatens Leo's family. Through asking his father questions, Leo then learns more about the Hitler Youth and the wave of Jewish unemployment. Thus, the three branches in the story are: (1) choosing which side to support in Leo's parents' argument; (2) Leo's reflections on whether everyone is equal or not; and (3) the decision to ask about either the Hitler Youth or Jewish unemployment.

The other part of the experience was story fragment discovery and exploration. In the exhibit, several items were available for exploration in the room, including a telephone, radio, suitcase, newspaper, Iron Cross, and gramophone. Through interactions with these items, audiences can stumble upon more story fragments. For example, Leo's grandfather was awarded the Iron Cross for his bravery in a battle fought for Germany, the *Der Sturmer* newspapers include examples of derogatory stereotypes of Jewish people, and the gramophone is accompanied with an anecdote about Leo's father having an interest in listening to classical music. Through these fragments of daily life discoverable within the items in the room, visitors can gain a deeper understanding of the situation Jewish people faced in pre-war Germany.

Chapter 2 provides an overview of the software and hardware for immersive media, including VR, AR, and the Microsoft HoloLens and HTC Vive, which were selected as the hardware platforms for the AR, AV, and VR versions of this study. The chosen devices had the best overall performance at the time. With this technology, two types of products were developed. One was an AR experience with HoloLens 1st generation that could be used in the museum, with which the photorealistic virtual CG character could be presented in real space through a hologram, strengthening the audience's impression and understanding of the exhibits and stories. The other products were virtual remote-site museum apps for HoloLens 2nd generation with real-world props (AV version), while the HTC Vive (VR version) program allowed visitors to remotely visit and interact with NHCM's exhibitions from their own homes.

In terms of the theoretical model, I proposed the framework of the uncanny valley for realistic CG characters and a user experience model for visiting museums in immersive media. As real-time realistic CG characters are difficult and expensive to develop, it is important to understand how users perceive realistic CG characters. Understanding the uncanny valley theory is of the utmost importance in this field. For the realistic CG characters, I clarified the ambiguous definition of human likeness in Mori's original model, specifying that human likeness consists of three factors: appearance, motion, and sound. Furthermore, I expanded the original model by introducing two factors: media immersion and the character's level of interactivity, which modulate the uncanny valley effect.

On the other hand, analysing the user experience of the interaction process is important to understand user satisfaction, user acceptance, and learning outcomes. In this vein, I proposed a user experience model for the HMD-based eXtended Reality Museum (HXRM) based on Norman's emotional design (Norman, 2008), Patrick Jordan's pleasure theory (Jordan, 2002), and Nascimento et al.'s user experience model (Nascimento, Limeira, Pinho, & Santa Rosa, 2014). The model consists of expectation, emotional and cognitive perception, and overall evaluation. At the core of this model is an extended TAM based on emotional design and Jordan's pleasure theory. In addition, the three characteristics of HXRM (narrative, presence, and interactivity) as identified in previous research were used as external variables for TAM. *Narrative* refers to storytelling as a means of communicating information, providing users structured information in an immersive and engaging way, all while encouraging their curiosity, concentration, and empathy. *Presence* is a subjective experience as a sense of being there. According to Steuer's framework, *interactivity* consists of speed, range, and mapping. In this model, the impact of Perceived Usefulness (PU), Perceived Ease of Use (PEU), and Perceived Enjoyment (PE) on intention to use, as well as their influence on each other, have all been investigated and well-established in previous studies in the context of VR. Therefore, the focus of my study is about the proposed external variables (narrative, presence, and interactivity) and the other variables in the expectation stage of user experience (prior gaming experience and learning interest). The purpose was to find the influence of these proposed variables on PU, PEU, and PE. The hypotheses proposed are based on my model of user experience:

H1: Prior gaming experience affects the user's presence and narrative engagement, meaning that the experienced user has lower presence and narrative engagement than inexperienced users.

H2: Interactivity affects narrative engagement and presence. The more natural the mapping, the higher the narrative engagement and presence. Specifically, the NUI version for the HMD-based immersive museum could yield more presence and narrative engagement than the GUI (or 3DUI) version.

H3: Learning interest affects narrative engagement with a positive relationship.

H4: Prior gaming experience affects the CG characters' affinity. The more experienced the user, the lower the CG characters' affinity.

H5: CG characters' affinity can affect the enjoyment with a positive relationship.

H6: Narrative engagement can affect the perceived usefulness and enjoyment with a positive relationship.

H7: Presence affects perceived usefulness and enjoyment with a positive relationship, meaning that higher presence results in higher perceived usefulness and perceived enjoyment.

H8: CG character's affinity can affect the narrative immersion with a positive relationship.

In order to test these hypotheses, four applications of Leo's story for NHCM's *The Journey* exhibition were developed in the project produced by this study entitled *The Extended Journey*, which is based on an interactive narrative approach. Firstly, a comprehensive summary of the interaction strategy and the user interface is presented in Chapter 4. For the on-site museum experience, I developed an application titled *The AR Journey*. The *AR Journey* uses different user interfaces with different interaction mapping including: a 3DUI based on the user's gaze and external device manipulation, alongside a NUI based on the tangible object and natural dialogue. A VR app entitled *The Virtual Journey* for the immersive remote-site museum was also developed. There is also an HMD VR version and an HMD AV version of *The Virtual Journey*. 3DUI and direct manipulation through the user's gaze were used as the interaction methods in *The Virtual Journey*. The software platforms include Unity3D, Holotoolkit, and MRTK (for the AR/AV version), and the SteamVR kit (for the VR version).

After software development was completed, three controlled experiments were conducted to examine the hypotheses. In the experiment 1, 58 participants were recruited and surveyed about their prior gaming experience and then divided into two groups. These two groups experienced *The AR Journey* in 3DUI and NUI, respectively. Following this, they were instructed to complete questionnaires which asked about their experiences with presence, narrative engagement, and interaction. They were also asked to complete a short interview. The main aim of this experiment was to verify H1 and H3, which promote the belief that the prior gaming experience and interactivity influences the presence and narrative. For experiment 2, we recruited 64 participants, surveyed their learning interests prior to the experiments, then divided them into two groups. The two groups were then asked to experience the HMD VR and HMD AV versions of *The Virtual Journey*, respectively. Following this, they were asked to complete questionnaires on the topics of narrative immersion, reflection, perceived usefulness, presence, and enjoyment scales. The primary purpose of this experiment was to examine the impact of narrative immersion and presence on perceived usefulness and enjoyment. In the third experiment, 60 people were recruited to experience the HMD VR and HMD AV versions of *The Virtual Journey* in turn. After each experience, they were asked to fill out questionnaires on presence and enjoyment. They were also interviewed about the user experience of both versions and the use intention of the immersive remote-site museum.

Finally, I conducted a quantitative analysis of the data from the three experiments, including paired t-tests, ANCOVA, and multivariate linear regression. Qualitative analysis of the interview data was conducted through vivo coding. According to the results of this analysis, the previously mentioned hypotheses, the proposed user experience model for immersive museums, and the uncanny valley framework for realistic CG characters were validated and revised. The findings and the revised models are presented in the next section.

8.3. Contributions and Implications

The major contributions at conceptual level include:

C1. A conceptual framework based on the uncanny valley theory which dictates realistic and interactive CG characters;

C2. A user experience model for HMD-based immersive museums derived from Norman's emotional design, Patrick Jordan's pleasure theory, Nascimento et al.'s user experience model, and TAM to propose a model of the user experience in an HMD-based immersive museum.

At the empirical level, three robust sets of experimental studies have been conducted and have provided the following contributions:

E1. A validation of factors influencing the user's perceived ease of use, usefulness, and enjoyment in the HMD-based immersive museums. The findings include:

1) Interaction mapping can have an impact on a user experience with presence and narrative engagement, but a user's prior gaming exposure moderates this effect. Specifically, for users with prior gaming experience, a 3DUI design, which is a lower mapping interaction method, produced better presences and narrative engagement. For users without prior game experience, a NUI design, which is a higher interaction mapping method, produced better experiences with presence.
2) Using a multiple linear regression model, it was found that learning interest had a positive effect on narrative immersion, meaning that users with higher levels of prior learning interest were more likely to experience a greater degree of narrative immersion.
3) A user's level of presence significantly predicts their perceived enjoyment in the context of HXRM.
4) A user's level of narrative immersion significantly predicts the value of perceived usefulness in the context of HXRM.

E2. An investigation of user acceptance of HXRM showed that university student more easily accepted HXRM and revealed the potential factors influencing said acceptance, such as their use of the environment and the ergonomics. Meanwhile, it was demonstrated that HMD-based VR offers a significantly higher narrative immersion, presence, empathy and enjoyment than

HMD-based HMD AV. The findings include:

1) Using the between-subjects experiment validated that HMD VR offers a significantly higher level of narrative immersion than HMD AV.
2) Using the between-subjects experiment validated that HMD VR offers a significantly higher level of empathy than HMD AV, which is one of the key learning goals.
3) In the within-subjects experiment, HMD VR offered significantly higher levels of presence and enjoyment than HMD AV. The within-subjects design can exclude the influence of individual differences and the subsequent conclusion is reliable.
4) In the experiment, 58 out of 60 participants interviewed (96.7%) expressed their interest in this type of remote-site museum. Fifty-four participants (90%) chose to voluntarily scan the QR code which linked to a website with more information on the Holocaust, and 52 participants (86.7%) chose to voluntarily participate in “the next experiment” to experience the “new version of the immersive remote-site museum” free of charge. We considered the above behaviours to be effective intention, demonstrating the high rate of user acceptance of the immersive remote-site museum.
5) Though over 80% of users chose the HMD VR as their preferred form of media in the experiment, around 55% chose HMD VR for a remote-site museum experience, while around 35% chose HMD AV. The interviews revealed that the users who chose HMD AV were mainly concerned about the safety factors, space constraints, and physical comfort level. These concerns can all be considered factors of *perceived ease of use* in the HXRM context. These could include foe example the use environment and ergonomics of the hardware. The main reason that HMD VR was chosen as the preferred media was its high immersion and low interference.

E3. The results of an analysis of human likeness, media immersion, the perceived intelligence of the character’s interactions, and their affinity among the users were all applicable to the uncanny valley theory. It shows that stronger media immersion and more intelligent behaviour from the characters can increase their affinity. Meanwhile, prior gaming experience can respecify the effects of uncanny valley. The detailed findings are as follows.

1) Prior gaming experience can respecify the effects of the uncanny valley. More specifically, when the audience has some gaming experience in R3DC, they become

more discriminating of the realistic CG characters and are more likely to experience the effects of the uncanny valley. However, users who possess rich gaming experience tend to be more tolerant of the realistic CG characters, even when noticing their flaws. This finding is instructive for application development and can help to define the target audience.

2) For mid-level realistic CG characters, media immersion can alleviate the effects of the uncanny valley, meaning that more immersive media can enhance the affinity of the CG character.

3) Descriptive statistics showed that the intelligence of the CG character's interactions, with such behaviours as looking for the audience and making eye contact, can result in an increase in affinity for the character in both the AR and VR conditions. Although this is not statistically significant, the finding suggests that increasing the intelligence of the CG character's interactions helps to increase the character's affinity in the context of immersive media.

At the methodological level, this thesis has made the following contributions:

M1. The development and implementation of two systems for the HMD-based extended reality museums. This includes the alternative storyline branching sub-system and the interactive props/items sub-system that can be extended for other virtual museums and exhibitions:

- System 1: Room-scale HMD-based AR museum system that can be deployed on-site
- System 2: HMD-based remote-site VR museum system

M2. The design guidelines for HXEM development were created based on the users' feedback collected during the design cycle and the interviews during the experiments. The detailed design guidelines are summarised in section 8.1. A brief description of the different elements is as follows:

1) Branching narrative design can feasibly make the storytelling more attractive. Choices based on dilemmas, open questions, and tasks list are three branching strategies which were found to be effective for improving narrative engagement.

2) Dilemma-choice design is particularly effective for an interactive narrative.

3) Enhancing the interactivity of the virtual environment and props can increase the enjoyment of the experience and make up for the lack of drama in the plot itself.
4) Having the CG characters engage in intelligent interaction could increase the character's affinity in both AR and VR conditions.
5) Mid-level realistic CG characters are adequate for HMD-based XR museums.
6) The character's animation quality is as important as its model, texture, and material. Depending on the target platform, the development of the characters must be focused on both their expressions and body animations.
7) Designers must pay attention to whether the target users have 3D RPG experience or not. Users with some 3D RPG experience are inclined to be pickier about the authenticity of photorealistic CG characters, the response speed of the interaction, and the diversity of their interaction feedback.
8) Gaze and commit with a clicker is a reliable interaction method for a graphical interface in a HMD-based AR museum.
9) Tangible interface design for HMD-based AR can achieve positive feedback, and some audiences may experience new and interesting feelings. However, tangible interface design also requires more visual or audio cues and hints to guide interaction; otherwise, the audience may feel confused.
10) A natural language interface for talking to a virtual character in HMD-based AR should be employed. Otherwise, the audience may feel too embarrassed to speak publicly in the museum space or may feel strange about speaking to a virtual hologram character as a real person.
11) Slow interaction response should be avoided. The slow response of the virtual character could be harmful in HXRM as it can break the extension of disbelief and disrupt the narrative experience.
12) Visual or audio cue design can be conducive to alleviating the negative feelings caused by a narrow FoV. The on-screen arrow or spatial sound can help guide the audience's attention when they lose their target on the small screen.
13) Interaction feedback should be diverse and include characteristics such as animation, audio, and character's actions.

Several helpful development tips, including character animation merging and refinement, expression animation, real-time shading, stabilisation of the hologram in HoloLens, optimisation for FPS, and more detailed suggestions can be found in section above.

8.4. Future Work and Limitations

Due to the relatively small number of participants in the experiment, Structural Equation Modelling (SEM) was not used to validate the proposed user experience model. Instead, multiple linear regression and ANOVA were adopted. However, these cannot fully account for the interactions between the factors. Therefore, a more rigorous experiment which includes over 200 participants, which can be analysed via SEM is suggested.

The second limitation of the study is the participant demographics. All the participants in this study were university students aged 19 to 29. However, the target users of the immersive narrative in museums are younger generations. Subsequent studies should be conducted on younger audiences in primary or secondary education. On the other hand, the developed world's population is also rapidly ageing. It therefore makes sense to focus on user experience and acceptance from an older audience.

Thirdly, as the NUI in the project was not able to be fully implemented, a Wizard-Of-Oz approach was employed instead, which could have potentially polarised the results. Since the number of participants only satisfies the minimum requirements, this may introduce the risk of relevant effects going undetected. This presents the risk that the study's findings do not depict the actual effects. Given prior RPG experience, which may include different relevant pockets of participants, subsequent research should include more participants to validate the findings of this study.

Hardware issues (e.g., the heaviness of the equipment, narrow FoV, and uncomfortable ergonomics design) presented another limitation for this study. Since both VR and AR technologies have been rapidly evolving over the past few years, some consideration should be paid to whether the hardware has also improved dramatically. For instance, HoloLens 1st generation was used in experiment 1, but HoloLens 2nd generation was released after the experiment ended. HoloLens 2nd generation has double the size of FoV and is lighter weight than HoloLens 1st generation. For this reason, results would likely to differ if the HoloLens 2nd generation was used in the original study. The HTC Vive Pro Eye was used in the experiments 2 and 3 but following their completion, the Oculus Quest2 was released. Quest 2 is a new VR device that has arguably overcome some of the hardware issues of the HTC Vive Pro. Quest 2 is lighter weight, more comfortable to wear, and includes more safety features. For example, the device's display will automatically switch to the camera view when the user steps out of the safety range, thus allowing a person to see the external environment immediately without removing their headset.

In the aftermath of COVID-19, online museums have begun to play an increasingly important role and, in recent years, HMD hardware devices have been undergoing rapid development. Software, including VR and AR-relevant SDKs and game engines, have also shown significant progress. My research demonstrates the potential of HXRM as an alternative for young people who may not be able to visit a real museum. This study shows that there is a high user acceptance of HXRM among university students. As VR devices have become cheaper and more popular in recent years, the demand for HXRM will likely continue to increase in the future. However, HXRM is not simply a digital replication of a real museum. Indeed, more than half of the users listed the interactive narrative as one of their reasons for using HXRM in the future in their interviews. Therefore, the user experience, user interface, and design strategies of HXRM should be further developed and investigated. In summary, this study presents an initial attempt to analyse the user experience and design guidelines for HMD-based immersive museums. Further explorations in this field will increase our understanding even more, while the development of further guidelines will be increasingly fruitful in the future as the technology in the field continues to advance.

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Appendices

Appendix A Questionnaires

A1 Questionnaire for Presence

1) How responsive was the environment to actions that you initiated (or performed)?
2) How natural did your interactions with the environment?
3) How completely were all of your senses engaged?
4) How much did the visual aspects of the environment involve you?
5) How much did the auditory aspects of the environment involve you?
6) How natural was the mechanism which controlled movement through the environment?
7) How compelling was your sense of objects moving through space?
8) How inconsistent or disconnected was the information coming from your various senses?
9) How much did your experiences in the virtual environment seem consistent with your real-world experiences?
10) How completely were you able to actively survey or search the environment using vision?
11) How well could you identify sounds?
12) How well could you localize sounds?
13) How compelling was your sense of moving around inside the virtual environment?
14) How closely were you able to examine objects?

15) How well could you examine objects from multiple viewpoints?

16) How involved were you in the virtual environment experience?

17) How distracting was the control mechanism? (-)

18) How much delay did you experience between your actions and expected outcomes? (-)

19) How quickly did you adjust to the virtual environment experience?

20) How much did the visual display quality interfere or distract you from performing assigned tasks or required activities? (-)

21) How well could you concentrate on the assigned tasks or required activities rather than on the mechanisms used to perform those tasks or activities?

22) Were you involved in the experimental task to the extent that you lost track of time?

5 Likert scale : Strongly Agree, Agree, Neither agree or disagree, Disagree, Strongly disagree

Note：(-) indicates reverse coded.

A2 Narrative Engagement Scale

Narrative understanding

1) *NR4*:* At points, I had a hard time making sense of what was going on in the program. (-)
2) *CP4:* My understanding of the characters is unclear. (-)
3) *EC2:* I had a hard time recognizing the thread of the story. (-)

Attentional focus

4) *DS1:* I found my mind wandering while the program was on. (-)
5) DS2: While the program was on I found myself thinking about other things.(-)
6) DS3: I had a hard time keeping my mind on the program. (-)

Narrative presence

7) NP4: During the program, my body was in the room, but my mind was inside the world created by the story.
8) NP3: The program created a new world, and then that world suddenly disappeared when the program ended.
9) NP1: At times during the program, the story world was closer to me than the real world.

Emotional engagement

10) EP5: The story affected me emotionally.
11) EP3: During the program, when a main character succeeded, I felt happy, and when they suffered in some way, I felt sad.
12) SM1: I felt sorry for some of the characters in the program.

5 Likert scale : Strongly Agree, Agree, Neither agree or disagree, Disagree, Strongly disagree

Note：(-) indicates reverse coded.

A3 Questionnaire for Emotional Engagement

- **Connectedness**

1) I had a connection to the people shown in the hologram film.
2) I understood how the people in the hologram film were feeling.
3) I was able to put myself 'in the shoes' of those depicted in the hologram film.
4) I was able to relate to those depicted in the hologram film.
5) I cared about what happened to those shown in the hologram film.

- **Reflection**

1) I was inspired to think about meaningful issues.
2) I was inspired to gain new insights.
3) I thought about meaningful events in the world.
4) I thought about myself in relation to others.
5) I found the task thought-provoking.

5 Likert scale : Strongly Agree, Agree, Neither agree or disagree, Disagree, Strongly disagree

A4 Enjoyment Questionnaire

1) I enjoyed doing this activity very much.
2) This activity was fun to do.
3) I thought this was a boring activity. (-)
4) This activity did not attract my attention at all. (-)
5) I would describe this activity as very interesting.
6) I thought this activity was quite enjoyable.

5 Likert scale : Strongly Agree, Agree, Neither agree or disagree, Disagree, Strongly disagree

Note：(-) indicates reverse coded.

A5 A Questionnaire of Narrative Immersion in Computer Game Narrative

Curiosity

1) The story quickly grabs my attention at the beginning.
2) Many events in the story are novel.
3) I want to know the rest of the storyline in the course of playing.
4) The avatar in the game is attractive.

Concentration

5) I concentrated on the story for a long time.
6) I become less aware of the real world and unhappy things around me when I concentrate on the progress of the game story.
7) When I enter into the game story world, time flies quickly.

Comprehension

8) I can make sense of the relationship between events.
9) I can comprehend the game story clearly.
10) I can make sense of the relationship between the characters in the game story.
11) The obstacles or tasks do not influence my comprehension of the game story.

Control

12) I am interested in the style of the interaction interface.
13) I felt like that Leo was aware of my presence in the room and Leo was communicating with me.
14) I can control the game interface.
15) I explored actively what I want to in the game story.

16) Parts of the story are formed by me in the course of playing the game.

Empathy

17) Sometimes I think I really am the avatar in the game.

18) My emotion often varies with the story's progress.

19) After finishing the game, it takes a long time for me to return to the real word psychologically and emotionally.

20) I was able to put myself 'in the shoes' of those depicted in the hologram film.

21) I cared about what happened to those shown in the game.

22) I will discuss my experiences in the game story with other players.

5 Likert scale : Strongly Agree, Agree, Neither agree or disagree, Disagree, Strongly disagree

A6 Scale of Perceived Usefulness

1) Using HXRM improves my learning of Holocaust.
2) Using HXRM saves me time.
3) Using HXRM allows me to accomplish more work than would otherwise be possible.
4) Using HXRM reduces the time I spend on unproductive activities
5) Using HXRM enhances my effectiveness on the job.

5 Likert scale : Strongly Agree, Agree, Neither agree or disagree, Disagree, Strongly disagree

A7 Immersive Tendency Questionnaire

6) Do you ever get extremely involved in projects that are assigned to you by your supervisor or your tutor, to the exclusion of other tasks?
7) How easily can you switch your attention from the task in which you are currently involved to a new task?
8) How frequently do you get emotionally involved (angry, sad, or happy) in the news stories that you read or hear?
9) Do you easily become deeply involved in movies or TV dramas?
10) Do you ever become so involved in a television program or book that people have problems getting your attention?
11) How mentally alert do you feel at the present time?
12) Do you ever become so involved in a movie that you are not aware of things happening around you?
13) How frequently do you find yourself closely identifying with the characters in a story line?
14) Do you ever become so involved in a video game that it is as if you are inside the game rather than moving a joystick and watching the screen?
15) How good are you at blocking out external distractions when you are involved in something?
16) When watching sports, do you ever become so involved in the game that you react as if you were one of the players?

17) Do you ever become so involved in a daydream that you are not aware of things happening around you?
18) Do you ever have dreams that are so real that you feel disoriented when you awake?
19) When playing sports, do you become so involved in the game that you lose track of time?
20) Are you easily distracted when working on a task?
21) How well do you concentrate on enjoyable activities?
22) How often do you play arcade or video games? (OFTEN should be taken to mean every day or every two days, on average.)
23) How well do you concentrate on disagreeable tasks?
24) Have you ever gotten excited during a chase or fight scene on TV or in the movies?
25) Have you ever gotten scared by something happening on a TV show or in a movie?
26) Have you ever remained apprehensive or fearful long after watching a scary movie?
27) How frequently do you watch TV soap operas or documentaries?
28) Do you ever become so involved in doing something that you lose track of time?

5 Likert scale : Strongly Agree, Agree, Neither agree or disagree, Disagree, Strongly disagree

A8 Reflection Scale

1) I was inspired to think about meaningful issues.

2) I was inspired to gain new insights.

3) I thought about meaningful events in the world.

4) I thought about myself in relation to others.

5) I found the task thought-provoking.

5 Likert scale : Strongly Agree, Agree, Neither agree or disagree, Disagree, Strongly disagree

A9 Learning Motivation Questionnaire

Precontemplation

1) Learning the Holocaust material is pretty much a waste of time. (-)
2) I think I need to spend time learning the information presented in the experience.
3) I would rather coast through this class than spend a lot of time learning the Holocaust. (-)
4) All of this talk about Holocaust is boring. (-)

Contemplation and preparation

1) It would be beneficial for me to learn the material about the Holocaust.
2) I got some good information from this experience.
3) This experience can help me learn the Holocaust.
4) I am sure how learning this material will benefit me.
5) It might be worthwhile to learn more of the Holocaust.
6) I am preparing to spend more time learning about the Holocaust.
7) It is time to start spending more time on learning about the Holocaust.

5 Likert scale : Strongly Agree, Agree, Neither agree or disagree, Disagree, Strongly disagree

Note：(-) indicates reverse coded.

Appendix B Interview Questions

B1 Semi-Structure Interview Questions for Experiment1

Q1: Was the overall sensory experience acceptable during this activity?

Q2: How do you like and dislike the sensory experience? Please describe in detail.

Q3: Do you think the interaction methods were fine and easy to use?

Q4: How do you like and dislike the interaction experience? Please give details.

Q5: Did the interactive story make you curious?

Q6: Please describe the narrative experience you felt good and bad.

Q7: Did the AR narrative experience engage you? Will you recommend it to your friends?

Q8: Do you have any other suggestions about improving the interactive AR narrative?

B2 Semi-Structure Interview Questions for Experiment2

Q1: Do you feel sick or uncomfortable using the device during the experiment? If so, please describe it.

Q2: In terms of narrative experience, do you think the experience in the experiment was different from a film or P.C. video game? If so, please describe the difference.

Q3: Would you be interested in an immersive remote-site museum as a learning approach like this? What are the reasons?

Q4: Please rate the affinity of the CG characters in the XR museum's experience out of 5, and describe how you feel about it.

B3 Semi-Structure Interview Questions for Experiment3

Q1: Which do you like better overall, VR or AV? Why?

Q2: If you need a remote, online experience of visiting a similar museum at home, which version (VR or AV) would you prefer to use? Why?

Q3: What was your favourite moment or interaction? What was your least favourite moment or interaction?

Q4: If you have a superpower, you could change any aspect of the experience with unlimited budget and time. What would it be?

Appendix C Verbatim Responses in Experiment 1

C1 Selected participants’ responses for negative sensory experiences

Participant # 22: “…the virtual objects and characters were too bright, which also did not match the light in the physical room…”

Participant # 18: “…the model of the character was not satisfied, however, the stiff expression distracted me most…”

Participant # 19: “…Leo’s expression was unnatural. I found his eyes did not blink when he talked to me…”

Participant # 20: “…characters’ movement was stiff, still far from realistic…”

Participant # 40: “…some props (e.g., diary, radio) were arranged studiously on the floor…”

Participant # 51: “…the number of the props and furniture was too little. It did not look like a living room…”

Appendix D Verbatim Responses in Experiment 2

D1 Selected participants' responses for how HMD-based immersive experience differs from traditional media

Participant # 41: "…like playing games and watching movies, no matter what, they are all flat on the screen, unlike 3D hologram that I could view them from all angles and interact with them directly with my hands. The interaction experience was sweet…"

Participant # 3: "…the interaction was very different, rather than using a keyboard for indirect control. It gave me a stronger sense of involvement…"

Participant # 55: "…I felt a little more involved in the interaction process and exploring. It was an active experience rather than a passive process of information input like film…"

D2 Selected participants' reasons why they were interested in an immersive remote-site museum experience

Participant # 4: "…This experience had both heritage items and storytelling, similar to the National Treasures TV program, so it was quite appealing to me. I think this approach was actually more effective for educational purposes than just observing a cold relic in a typical museum…"

Participant # 43: "…I was immersed in interacting with the objects. Normally, even if I went to a museum, I wouldn't be able to interact with the heritage items, like opening a drawer to see the interior. But in this approach, I can have deeper understanding through interaction and have fun while learning…"

Participant # 11: "…I think the immersive remote-site museum is very attractive because I think the interactive learning experience is very engaging. To be specific, it's not like a typical museum that just exhibits the heritage items with an introduction text or videos. I could click to interact within the virtual environment, and characters could come to talk to me. This approach actually integrated all the items and elements into the story, and I was able to understand and remember better the meaning of the items in this context…"

Appendix E Verbatim Responses in Experiment 3

E1 Selected participants' descriptions for the difference between HMD-based VR and AV in terms of field of view

Participant # 4: "…You won't have any external elements that may interfere with you in VR. Whereas with the AV, you could still see some of the external real-world objects, like the sofa, the desk, the ornaments or whatever, and it harmed your understanding of the stories…"

Participant # 52: "… VR was more immersive. The lab assistant came up next to me at the end of the film, however, I didn't notice it at all…"

Participant # 43: "…The overall experience of VR was more comfortable, and the field of view was very wide. In AV, I couldn't see the suitcase at first glance, however, I could catch the suitcase in VR easily when I was walking over to the desk. I think I preferred VR for a short period of experience. Though VR's headset was a bit heavier, the weight was still acceptable, and it gave us a stronger sense of immersion…"

Participant # 46: "…I preferred VR mainly because of its (wider) field of view. There were some differences between the two devices: the VR wrapped my face completely so that it seemed that I could have more immersive feelings…"

Participant # 11: "…I think the VR experience was a bit more immersive. Because the AV could only cover the front part of your vision, you could see the real-world scene outside the headset's display. Besides, its display was semi-transparent. You could still dimly see some real-world items in the back of the semi-transparent virtual image…"

Participant # 1: "… VR allowed me to be more immersed in the virtual world and less influenced by the real world. But it was easy to be influenced by the real world in AV. Moreover, AV's view was only a limited small frame, which was different from VR's 360 degrees view…"

E2 Selected participants' descriptions for the difference between HMD-based VR and AV in terms of visual quality

Participant # 59 "… VR was probably a little better in terms of realism because it was completely immersive and you could not see anything else when you wore the headset…"

Participant # 23 "…the VR's visual was sharper, but the AV seemed to be not very clear, and the characters looked a bit blurry…"

Participant # 12 "…The VR's colours were better. the AV's colours were reddish…"

E3 Selected participants' responses for their preference using HMD-based VR or AV

Participant # 23 "… Because I want to have the feeling that I do enter into the museum. I don't want to see the outside world through the glasses still.…"

Participant # 33 "… I would definitely choose VR for the remote-site museum experience. VR seems to have all the advantages over AV, and without the weakness of AV…"

Participant # 12 "… You may stumble when using VR at home, but I would still choose VR anyway. I wanted a more realistic sensory experience.…"

Participant # 15 "… I still want to use VR to experience the remote museum, as the immersion and engagement feeling of VR is better…"

Participant # 58 "… though the VR helmet was a little heavier, but its overall experience than was obviously better than AV…"

Participant # 24 "… I'd like to choose VR, maybe I'm more of a visual guy.…"

E4 Selected participants' reasons for choosing HMD-based AV

Participant # 10 "…It's probably better to use AV, as I'm afraid VR can be too addictive to get out of the virtual experience…"

Participant # 28 "…I think I am more likely to use AV at home because I can still see the real-world objects with AV headset. AV may not be as immersive as VR, but I can distinguish well between reality and virtual. I would feel a little unease and unsafe with VR…"

Participant # 34 "…If I were at home, I would choose AV instead. Though VR did give me a great experience, I was kind of in a daze when I took the device off. If I am detached from reality for a long time, I'm probably not able to bring myself back into reality. Therefore, I'm a little bit worried that if I immerse myself in this VR for a long time, I could just get trapped in the virtual situation and disconnect from real life…

Participant # 27 "…I was obviously more cautious in my steps in VR, because I didn't know what I was going to step on or if I ran into something with a VR headset. But I can explore in a more relaxed way in AV…

E5 Selected participants' descriptions for their favourite interactive

props

Participant # 25 "…I liked the design of the gramophone. It made me feel like I was transported back in history. Because the gramophone itself didn't belong to our modern society, and the music of the gramophone blended with the environment of the last century, which made me feel very realistic and immersed in the atmosphere. I felt it was very engaged compared to the other interactions, and it was in line with the story…"

Participant # 60 "…I liked the diary open up, and Leo came out telling the story, and the phonograph … when I clicked on it, the handle started to turn, and the audience would be able to find out some of the stories about his mother and his father…"

Participant # 20 "…the moment the diary was open. In the beginning, I thought I just needed to search for something in the drawer, and I didn't expect a character performing in front of me, with dialogue and plot…"

E6 Selected participants' descriptions for their favourite moment of the CG characters or the stories

Participant # 59 "…The little boy could run towards me and talk to me. His voice could let me know that he was right behind me. I felt I could have close contact with him. I was very immersed that sometimes I wanted to give him a hug and a few words of consolation…"

Participant # 23 "…For this story, it was a bit like one of those little puzzle games I've played. I can go exploring, and although there was no decryption part, the exploration itself was quite interesting…"

Participant # 35 "…make the first choice in response to Leo's parents' different opinions, and I was able to influence the plot. The third choice was to learn about different events, I actually wanted to know about both events. But the third choice wasn't as good as the first choice, that I was able to influence the direction of the plot and I felt a bit more engaged…"

Participant # 17 "…I thought it was quite cool when Leo came up to me. I could look around the character and environment, and it was quite amazing when they sat there discussing…"

Participant # 44 "…What I liked most was that the little boy asked me to make a decision. I felt quite involved…"

E7 Selected participants' descriptions for their least favourite interaction experience

Participant # 55 "…When I tried to click on the diary, I hit it several times without triggering it…"

Participant # 30 "…In both experiments, I always had problems with triggering the interactions, and in VR, the shape of the virtual hand sometimes messed up. It seemed like a recognition error…"

Participant # 24 "…the interaction seemed to be a bit problematic or delayed, when I performed the trigger actions, like pushing or pulling a drawer, they often didn't respond. I've tried several actions. One was to grab the handle and pull or push, the other was to touch it directly, but it always didn't work…"

Participant # 6 "…I couldn't pull the large cabinet open for a while so that it may be an issue with hand detection…"

Participant # 16 "…I couldn't open the drawer after trying for ten seconds. My initial thought was that I had to hold the handle to open the drawer, but the right way to open it was to click the handle as a button, and the drawer would pop out. This interaction design was quite inconsistent with my perception, or at least not very comfortable for me…"

E8 Selected participants' descriptions for their least favourite sensory experience

Participant # 21 "…For AV, the field of view was small, and sometimes the display was a bit unclear and dim. I wore the glasses and HoloLens at the same time if I adjusted the position of glasses, and then the image became much clear…"

Participant # 29 "…Maybe I was not wearing HoloLens properly, the colours displayed were lighter, and I could see the real-world objects through the HoloLens. It had a somewhat negative impact on my experience. With the correct viewing angle, I could see the wall as orange, but if the angle was tilted a bit, the wall looked yellowish…"

E9 Selected participants' descriptions for their least favourite experience from the CG characters

Participant # 24 "…The character looked not very good. It had a bit of the uncanny valley effect. When you look at his face, it was like looking at a badly made figure model in a shopping mall, and it was a bit scary…"

Participant # 12 "…I would look around the model, and I would feel uncomfortable in a few moments where the model was intersected. For example, his dad's shirt and trousers were hollow. Dad could insert his hand in mom's shoulder. Leo's feet sometimes went under the floor. But the above issues were OK for me, and I could still get into the story…"

E10 Selected participants' suggestions for improving the CG characters

Participant # 11 "…I think that the modelling and texturing need to be made with a little more accuracy; otherwise, it would be rather different from the real thing. It would be good to make the models in the room a bit more detailed so that people can see the details…"

Participant # 52 "…I think the models need to be made more precisely. Otherwise, it would be rather different from the real thing. It would be good to make the models in the room a bit more elaborated so that people can see the details…"

Participant # 30 "…The most important thing that I would like to improve is the gestures of the characters during their movement and the walking animation, especially the movement of their legs and feet…"

Participant # 17 "…to make the character modelling look better. The environment like the wall, the floor and the furniture were OK, but the character animation made me feel artificial and sometimes the character model intersected with each other…"

Participant # 41 "…I think if the modelling were done more elaborately, it would be more immersive. The characters were rough and made it feel artificial, whereas the furniture and environment were made more realistically, and it can give people a bit more realistic feeling…"

Participant # 26 "…I hope the scenes to be as realistic as real-world itself, i.e., ultra-realistic and possibly with some tactile feedback…"

E11 Selected participants' descriptions of the negative impact from the unsatisfied CG characters

Participant # 4 "…of course, I'd like to see the better graphics, but I thought the characters were still OK as far as this story was concerned. The characters' expressions and animation were not as natural as commercial games, and there was still room for improvement. But I can accept the current characters…"

Participant # 37 "…I wished the modelling could be more realistic and fix intersection animation issues. As for the models, the current results were acceptable…"

Participant # 33 "…If I wanted to immerse myself, I would convince myself that they were believable characters. The character model issue wouldn't bother me if I engaged in the plot. But I was always aware that they were virtual…"

Participant # 44 "…the experience was spoiled (by the unnatural characters). I felt rather odd to find the little boy's legs shaking…"

Participant # 34 "…the experience was spoiled (by the unnatural characters). I felt rather odd to find the little boy's legs shaking…"

E12 Selected participants' suggestions for improving the interaction design

Participant # 1 "…There was a problem in terms of hand operation. I have to put my hand far enough away from my head for the device to recognise the hand for interaction…"

Participant # 3 "…The first thing I want to improve is interaction. My hand could only interact in the central area of my field of view, and it distracted me quite a lot. The interaction process was also not smooth, and I could feel a delay in the response of my hand movements.…"

E13 Selected participants' suggestions for interaction hints or the virtual hand design

Participant # 25 "…I saw my hands as simulated and abstract hands, which made me feel quite strange. I wish I could be blended in the environment, but the hand pushed me away from the environment…"

Participant # 42 "…The way of interaction needs to be improved. Interaction hints can make the interaction easier and smoother, but I think it would be better to 'hide' these hints, including the virtual hand, text or highlight for a more direct and realistic experience…"

E14 Selected participants' suggestions for multimodal interaction

Participant # 45 "…I want to add the sense of touch. I could see my hands and the virtual objects, but my hand had no force feedback. Therefore, sometimes I can't tell if I am touching the object…"

Participant # 9 "…Haptic feedback would be ideal, but it may be difficult to achieve. The physical object could match virtual environments, e.g., I saw a chair in the virtual environment and I also could actually sit down (on the chair) at that position…"

Participant # 11 "…You can add some other experiences other than visual and auditory, such as tactile feedback, thermal environment simulation and perception. For example, it would be colder there if it's a rainy night, and it would be warmer if there is a fireplace in the room…"

Appendix F Web Links for Demonstration Video, Extrudable Files and Source Code

- Demonstration YouTube link:

  https://youtu.be/ctuv_YLV8_Q

- HoloLens executable files of *The AR Journey* download link:

  https://drive.google.com/drive/folders/1Fc6QGMqVKwbLB9uwRyFJIcpQAw1h6t9L?usp=sharing

- HoloLens executable files of *The Virtual Journey* download link:

  https://drive.google.com/drive/folders/1JXBVj5_UQqhohcaT6jvcBdLEES-A_MYT?usp=sharing

- HTC Vive executable files of *The Virtual Journey* download link:

  https://drive.google.com/drive/folders/1ime-aqfE1sraqpLioOcZq9-xdg1kCLGB?usp=sharing

- Source Code download link:

  https://drive.google.com/drive/folders/1gHgQbq32zI7Ony_jcTO6Vpjdq7km90Ef?usp=sharing