Chances and Limitations of Immersive Augmented Reality for Game-Based Learning in Museums

Ulrike Spierling[1], Jessica Bitter[1], Yu Liu[1] and Thorolf Müller[2]
[1]Hochschule RheinMain, Wiesbaden, Germany
[2]Senckenberg Gesellschaft für Naturforschung, Frankfurt, Germany

ulrike.spierling@hs-rm.de
jessicalaura.bitter@hs-rm.de
yu.liu@hs-rm.de
thorolf.mueller@senckenberg.de

Abstract: This article discusses opportunities and limitations of using immersive augmented reality (AR) with head-mounted displays for gaming and education in museums. We first report on a prototype application for HoloLens 2 that we developed and tested with 109 museum visitors in a recent project for an exhibition with large animal skeletons. The results show that the feedback from visitors was overall positive, while more steps are needed before it can be implemented in a museum routine. Based on the findings, we discuss hypotheses for the planned further development of the approaches towards game-based learning in the real environment of a natural history museum.

Keywords: Augmented reality, Head-mounted display, Location-based games, AR in cultural heritage

1. Introduction

In recent years, there has been an increasing interest in developing Augmented Reality (AR) applications for museums. While mostly these are running on handheld devices owned by visitors who bring them along to the museum, not as many applications have been developed for head-mounted displays (HMD) that allow immersive experiences for individuals. Application development for HMD-based AR so far has more taken place targeting the engineering industries such as for maintenance and construction, to be used by professionals who get trained. In museums, however, visitors as laypersons without any training would need to learn how to use these devices first (Liu et al. 2021). Moreover, application scenarios are not yet well established and development needs to start with designing use cases. Thus, with the aim of developing usable applications in this area, we entered an indeterminate field with new challenges in defining customer needs, previously unknown interaction patterns and application ideas in a team of developers, designers and curators.

In the recently completed project presentXR (2023), after developing an authoring pipeline (Rau et al. 2022), we developed a first AR prototype application for head-mounted displays (Microsoft HoloLens 2) that augmented an existing animal skeleton exhibition with digital information, and finally tested it with over 100 museum visitors. We are continuing our work in an EU-funded project LoGaCulture (2023) with the aim of applying these technology experiences and insights to locative learning games for cultural heritage in general. We therefore discuss in this paper how our initial findings from the previous experiment lead to future expectations for game-based learning in museums, particularly by focusing on immersive AR with head-mounted displays that enable increased levels of presence-based feelings. In the following, after looking at the most important related work, we first summarise our prototype to date and the main evaluation outcomes. Based on these results, we hypothesise about the potential of the technology for application to games and, in particular, to game-based learning in a museum.

2. Related Work on Immersive AR Games in Museums

The perception and expectation of museum visitors have shifted (Macdonald 2007): While visitors have so far been perceived mainly as a passive mass, museums are increasingly realising the potential of viewing visitors as active individuals or groups. A study by Sheng and Chen (2012) showed that visitors usually seek easiness and fun, cultural entertainment, personal identification, historical reminiscences, and escapism. Gamification is a recent means to address active visitors. Paliokas and Sylaiou (2016) already noticed a growth of serious games applied in different kinds of museums. They also found that the most used interaction styles based on a classification by Djaouti et al. (2011) in these games is moving around, followed by selecting and matching. Less frequently used interactions are shooting and destroying. They found that although their systematic mapping approach could not identify general learning goals for museums that are best addressed with games, there may be high acceptance rates due to other criteria than learning. The collected 'gamified' application examples could be classified into the two categories "game" or "play", with differences in whether there are strict rules and clear goals in the game type, or more freedom in the play type (Djaouti et al. 2011; Paliokas and Sylaiou 2016).

Especially location-based mobile applications are used in museums. For example, Spierling and Kampa (2017) described a system for a location-based AR storytelling experience in a Roman fort where visitors can use tablets to meet ghosts of the historical inhabitants who remember what it was like to live in this place in Roman times. It was evaluated how the app can support the sense of presence in terms of a historical aura of this place (Spierling et al. 2017). Feelings of presence and immersion appear to be important for cultural heritage projects (Pujol and Champion 2012). Marto and Gonçalves (2022) provided a systematic review of presence assessment in AR games and found a link between the sense of presence and engagement, which we consider an important goal for museum exhibitions.

Immersion is often connected to digital add-ons of an exhibition, such as Virtual Reality (VR) or AR applications (Harkvoort 2013). Bitgood (1994) highlighted that immersion is useful to achieve a sense of realism and already linked immersion to interaction, environmental feedback and multisensory stimulation, stressing the importance of adding VR or AR games or experiences to exhibitions to enhance visitor immersion. Komarac and Došen (2020) found that aesthetics support immersion more than interactive technology.

Hammady et al. (2016) have explored gamification in combination with AR. Based on their identified communication model, information about the exhibition is selected by curators or other museum staff, then coded into an AR app by developers and at the end de-coded by users. Furthermore, they found that incorporating game elements into the AR experience provides a mechanism for enriching the educational value of an exhibit. In light of these findings, the authors have created a gamified and immersive AR application specifically tailored for use in a cultural heritage museum (Hammady et al. 2020).

In recent years, AR applications for museums have grown in number and have been documented in literature reviews such as by Boboc et al. (2022). They analysed 1201 papers on the topic of AR in cultural heritage in the last ten years. However, most AR experiences are smartphone-based. Creating experiences for HMDs such as the HoloLens is still novel and not yet many examples exist, e.g. by Hammady et al. (2020). Another example demonstrated by Giariskanis et al. (2022) is an application built for the HoloLens, using hand tracking, voice commands and spatial audio to enhance the visit at a local cultural heritage site.

In summary, game-based applications for head-mounted display-based AR are still rare and in a state of research prototypes. Similar, in our work of the presentXR project, we pursued the goal of developing an AR application that shows additional information, explanations or elements that would otherwise not be observable directly on existing real exhibits in order to visualise the invisible. Our prototype was intended to be interactive, to engage active visitors and to enhance not only their immersion in digitally added content, but also their sense of presence in the physical exhibition itself (Bitter et al. 2022). This is subsequently to form the basis for serious games on museum content, which we hope will increase engagement.

3. Immersive Augmented Reality Example Application

3.1 Project aim

The aim of the development team of the applied research project presentXR (2023) was to demonstrate the creation and implementation of presentations for exhibitions using augmented reality (AR) technologies to provide a future-oriented experience for a museum. By creating a cross-reality (XR) as a fusion of real and virtual spaces, participants should have the feeling of being (co-)present in the real world with digital elements and be able to experience virtual content through the use of head-mounted displays. From the very beginning, we have geared development towards the immersive Microsoft HoloLens 2, a state-of-the-art device that enables the precise tracking required for near-fit placement of digital assets in real space, especially in relation to existing physical objects. To support the content creation, we also aimed to develop modular authoring software solutions (Rau et al. 2022) and codified design knowledge related to graphic effects, narrative structures and interaction patterns (Liu et al. 2021). For the development of the HoloLens 2 app on which the immersive experience runs, we used Unity with the Mixed Reality Toolkit (MRTK) plugins provided by Microsoft as a basis. On this platform, several exhibition-specific components were pre-configured as complex prefabs (referred to as "nuggets"), which could be used during authoring (Rau et al. 2022).

In the following, we summarise the aspects of the main demonstrator that we built to test the concepts with visitors on site at the Senckenberg Natural History Museum in Germany.

3.2 Application Design and Prototype

At the start of the AR application, visitors are first briefly instructed on how to use the head-mounted device and then familiarised with the virtual museum guide, which is a key feature of the demo application. An avatar, in our case an abstract blue butterfly, guides visitors from the entrance hall towards a chosen goal (see Fig. 1). During authoring, the avatar can be designed with different 3D shapes and animations, and either a fixed path to a specific destination can be given or, if the environment has been scanned beforehand, a variable guidance can be activated (Bitter et al. 2022). This feature can be particularly helpful for individuals who are visiting the museum for the first time or are not familiar with the layout of the exhibition. It is especially useful for longer routes, for destinations that require walking across several rooms. However, for finding destinations within sight, e.g. in the same room, placemarks are more useful as indicators, such as circles on the floor in our app. When visitors enter these circles, this can trigger certain content, such as the start of a narrative defined by authoring.

Figure 1: User following the flying avatar towards the whale exhibition

We have chosen the whale exhibition in the natural history museum as an illustrative example for the AR application. This exhibition offers the opportunity to show the diversity of marine mammals. Two skeletons of an orca and a fin whale are representatives of the suborders of toothed and baleen whales and can convey their differences to visitors. The species differ in their feeding mechanisms (hunting with echolocation vs. filtering using their baleen), and these distinctions are the focus of learning through the interactive AR application.

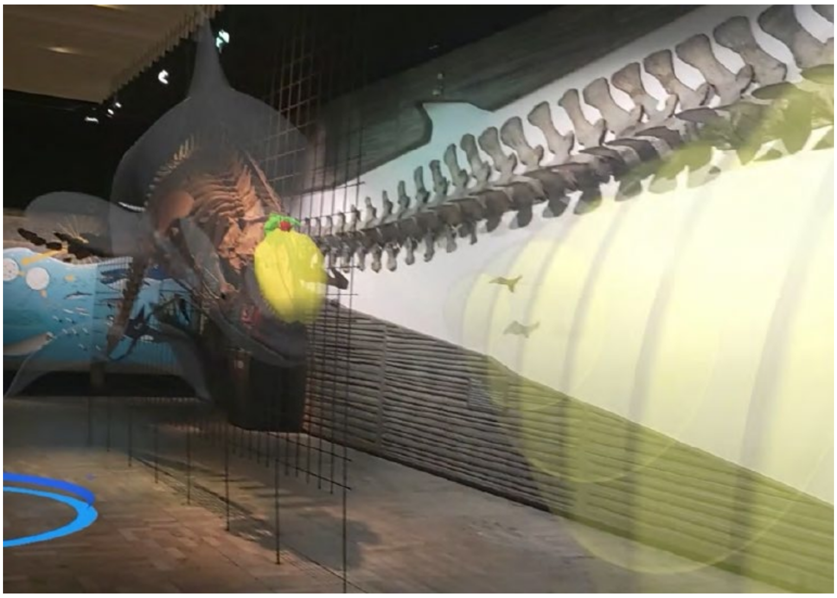

Figure 2: Visualisation of the orca's echolocation principle, viewed through the HoloLens

After arriving at the exhibit and triggering the narration, visitors hear a voice with general information about marine mammals and their characteristics, while the respective real bones or body parts discussed are synchronously highlighted by virtual graphics. Users of the HoloLens app can then select specific information about the animals' various hunting techniques via menus. To convey this, three-dimensional animations are displayed in space within and around the physical skeletons. For example, the process of echolocation used by the orca when hunting can be visualised (Fig. 2). The details of this process are presented in steps that proceed at a pace chosen by the user, while the narrative voice explains each step in short sentences and 3D models of the internal organs involved are superimposed one after the other in the orca whale's skull. In Fig. 2, the yellow melon organ can be seen in particular, which at one point begins to focus the generated waves and direct them towards a target, during which an audible clicking sound can be heard. In the next step, in which a virtual prey fish is superimposed within reach, the waves are reflected back from it to the receiver in the skull. The abstracted sound waves in both directions are animated throughout and can be viewed by the user from any direction while walking around the exhibit and listening to the clicking, all in all an immersive experience for the visitor.

From the beginning, the AR application offers visitors the possibility to interact with the virtual layer. Since one of the main interaction styles of the HoloLens operating system is the use of a hand menu that appears next to the user's palm when they raise it into the field of view, we decided to use similar interaction options. Fig. 3 shows our customised hand menu next to the left hand, with buttons to be selected with the right index finger. It can be used to access different features or chapters of the application.

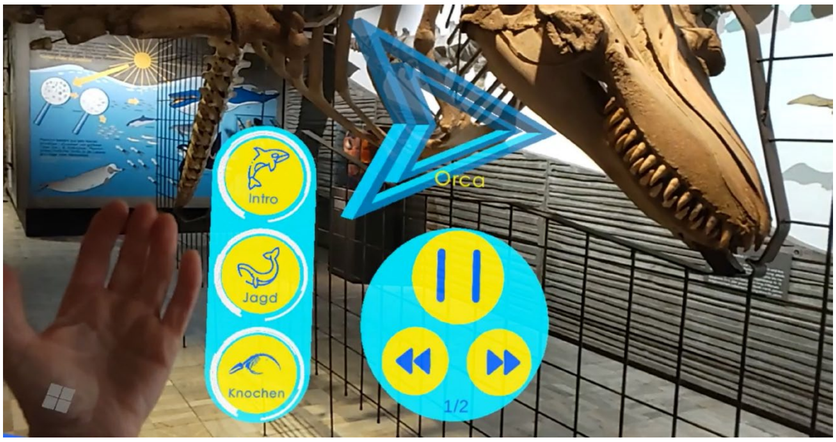

Figure 3: Hand menu of the HoloLens 2 application

In another chapter of the app, the user can control the display of labels on the bones that appear when approached from a certain distance. In this way, simple information about details of the skeletons can also be displayed. Additional text explanations for each bone group explain how the anatomy of both whales is analogous to that of a human.

Overall, the AR application offers an immersive and interactive learning experience. It responds directly to visitors' movements and choices. Therefore, our expectation was that it would increase users' engagement in exploring the real exhibition and motivate them to learn by visualising and comparing elements. We also hoped that the spatial experience of walking around among the 3D animations would provide a sense of immersion that would be enjoyable and intriguing, enriching the museum visit beyond learning facts.

3.3 Evaluation

A combination of quantitative and qualitative methods was used to evaluate our prototype. During individually supervised tours, user reactions were observed and recorded, and post-tour oral interviews and standardised questionnaires provided data on user opinions. For the observation of the viewing directions and user-selected content, the HoloLens viewport of the subjects was replicated on a portable monitor carried by a researcher who accompanied each participant on their tour through the museum (Liu et al. 2023). The evaluation itself was organised by a team of 8 people on 6 evaluation days on site at the museum. The test users were partly acquired in advance and could book a specific time slot, partly they were approached ad-hoc in the museum. For liability reasons, we have only addressed adults and excluded children under the age of 18. Participation was based on voluntariness and a certain level of pre-interest, which meant that self-selection bias could not be avoided. We expected that with regard to the HoloLens experience, mainly first-time users would participate.

Eventually, 109 test users could be recruited, of whom 48% were female, 50% were male, and 2% were undetermined. The results of the survey showed that respondents were overwhelmingly positive, but the observation also revealed that there are still difficulties and disruptive factors that can pose challenges to museums and their visitors in making full use of the technology. In the following, we discuss those selected evaluation results that we consider important for a future use of this technology for game-based learning in museums, focusing on the general acceptance, the usability and the experiences of engagement.

Appreciation. Based on a 5-point Likert scale, we obtained 94% of the votes for the two highest scores (50% very good, 43% good), with no one giving the lowest rating. Further, 87% of participants confirmed that they would be willing to pay an additional fee for the experience if it were offered by the museum. Freely expressed opinions in the additional interviews mentioned the overall presentation of the information as positive, and 19 out of 109 respondents highlighted the particular added value of the experience for the museum. Many comments concerned the orientation function with the butterfly, which was rated very positively 48 times and mentioned positively 37 times but with suggestions for improvement.

Areas of improvements. The prototype also had some issues raised by users, which we do not classify as general problems but as opportunities for improvement for a revised version. Examples were some holograms that were too transparent, some labels that were not optimally positioned and should be clearer, or improving the quality of the voice output, which was a prototype electronic voice at the time of the evaluation. The most common criticism of the butterfly was that the speed was not satisfactory, mostly too slow, and the height of its flight. Although the butterfly already reacts to the users' speed and can for example wait for them, it should be even more adaptable. The feedback showed that all speed aspects, including voice, are very crucial for credibility and acceptance. Also, the narrative chapter control menus could be improved to give users better feedback on chapter progress and expected narrative duration.

Usability. Apart from selective need for improvement in usability, we were particularly concerned about how users were able to operate the app via the given hand menu (Fig. 3). The questionnaires showed that only one third of all users admitted difficulties with the hand menu. However, the observation logs show that a significantly higher number of users sometimes forgot how to access the menu during the experience or needed additional help to understand it properly. 37.5% of all subjects over the age of 50 experienced general difficulties with operation, while only 21.5% of those under the age of 50 had problems. Regardless of age, subjects with previous experience in augmented reality were less likely to have problems operating the app. Of 84 participants with no AR experience, 25% had problems, while this was only the case for 16% of participants with experience. These results are not surprising, but even though our entire subject group was self-selected, the results give us hope that there will be a target group for future immersive apps. However, opportunities for assistance in the museum would be essential.

Different preferences. In the interviews, different opinions were also expressed on some aspects, which gives us the impression that there are groups with different preferences. Some users mentioned that the app did not provide enough information, while others explicitly mentioned that the experience was inspiring especially in the parts where the animated visualisation could be explored without additional explanations. A few subjects expressed that the butterfly guide was superfluous, while a large group of users found it attractive. Some said that they would have liked more opportunities for active interaction, while others said that it was too much interaction for them and they would have preferred to just follow the narration. We think these are interesting aspects to explore in future evaluations, as we did not directly ask for such preferences.

Immersion and presence. Our questionnaire also did not directly address feelings of presence, however, through observation and remarks in interviews we received insights. Some interviewees mentioned that they had to reorient themselves after putting down the HMD, it felt like resurfacing from the sea they were in before. We found that when users followed the avatar, they seemed to focus more on this digital content animation rather than being able to connect it to the perception of the physical environment. On the other hand, our observations showed that users were often not intrinsically motivated to move around the exhibits and change their viewing position during the AR presentation, e.g. for echolocation, although this could have led to a stronger sense of spatial presence when perceiving the 3D holograms. Most users remained fixed in one place and did not move. We acknowledge that the situation of being observed may have had an influence on this, and we plan further research to explore how information load and presence are related.

3.4 Discussion

Based on our evaluation results and our experience in designing and building the prototype in collaboration between our university and the museum, we reflect on what our findings mean for the opportunities and limitations of using immersive (HMD-based) AR for game-based learning in museums of the future.

3.4.1 Chances

Our user evaluation supports the positive expectation that immersive AR with head-mounted displays will generate visitor interest in museums. New visitors could be attracted by the opportunity to participate in such an experience and, according to our findings, would be willing to pay an additional fee. Without being embedded in a game, the existing physical museum content enriched with interactive virtual assets created an interactive learning experience for visitors. Test users stated that the virtual overlay helped them gather information that would not have been as impressive without the AR layer. For example, the immersive explanation of echolocation as a 3D visualisation directly in the real physical skeleton gave them an impression they will not forget. The inclusion of animation can also greatly enhance the realistic impression of size and presence for visitors. For example, visitors were able to better appreciate the true size of the giant fin whale skeleton after the movement of a superimposed virtual model started in our app. Playful elements such as the butterfly guide were appreciated by most users, although some considered them non-mandatory and thus superfluous.

Even users who were using the HoloLens for the first time were able to operate the system after a short introduction, despite the possibly confusing unfamiliar way of interacting with the hand menu. If head-mounted displays also become established for consumer applications in the future, a larger user group will not have any problems in principle.

3.4.2 Limitations

However, some users already found an immersive HMD-based AR experience without gamification elements overwhelming. Learning new forms of interaction, experiencing something new for the first time, observing physical and virtual information simultaneously and paying attention to where people are stepping in the environment requires a high cognitive load. In recruiting our test users, we assumed self-selection and therefore may only have recruited people interested in technology, so we cannot yet directly assume that such an experience is transferable to a wider audience.

Technical difficulties in handling our app could be due to user error, but also to glitches due to immature technology or bugs, so that in our test intermediate help was required, which may interrupt the experience. In the future, it is expected that such an experience will require the constant presence of qualified staff. The special hardware may be a barrier to access for some visitors, as well as medical reasons that prevent the use of an HMD. However, no one reported simulator sickness in our evaluation.

Furthermore, the app currently isolates people, as groups cannot experience it together, only one individual at a time. A first step was to export the image of the head-mounted display to let others see what the main interactor is experiencing, but developing real multi-user experiences is part of future work. Also, the entire conception and implementation of the immersive augmented reality experience, including the design of interaction patterns and content options, was still part of applied research reserved for technology-savvy individuals, and we could not yet rely on established design principles.

4. Conclusion and Outlook to Gamification

We reported on selected evaluation results of our immersive HMD-based AR museum application and discussed the chances and limitations for the development of educational games that we inferred from the feedback. In order to proceed with our research in the framework of the EU-funded project "Locative Games for Cultural Heritage" (LoGaCulture 2023), we conclude with hypotheses based on these considerations. One work package aims to explore how engagement with cultural heritage can be enhanced by increasing the sense of immersion and presence through AR-based locative games in museums. To approach this, the different levels of experience addressed by these terms for games need to be explored (Marto and Gonçalves 2022). In a museum or heritage site, the sense of presence of the virtual content in parallel with the real physical environment is crucial.

Given the overwhelmingly positive evaluation by our test subjects, it seems reasonable to assume that applications like the one described above will flourish. Whether their further development will lead to games that can be implemented in museums depends, on the one hand, on how the identified limitations can be overcome. On the other hand, we need to set goals and priorities for the experiences we want to achieve and evaluate them after the development of the next prototype. Obviously, the costs of development and implementation are high for the museum in terms of organisation and staff, and the question is what prospects justify this effort.

We have identified the development of multi-user experiences that allow visitors to be co-present in shared AR scenes as an important sub-area of our future 'research by design' to address the fact that many visitors are not alone when they visit a museum. To tie in directly with our existing scenario, we design cooperative tasks, such as attaching labels together or answering quiz questions about the homology of whales and humans, 3D puzzles where visitors can put individual bones together, or interacting with echo waves about feeding whales virtual prey together. We will continue to develop scenarios and technical solutions in parallel.

In addition, we speculate that integrating competitive games into an immersive AR application could reduce the users' sense of presence with the physical exhibition or location they are visiting. In our example of the butterfly guide, we found that visitors may rush through an exhibition to reach a particular destination rather than taking the time to enjoy or explore the physical environment as well. Also whenever there were usability issues, such as difficulties with the hand menu, this distracted from the content and affected the flow of the experience.

Following the analysis of Paliokas and Sylaiou (2016) with their distinction between categories of 'game'-oriented applications and 'play'-oriented ones, we favour the play category. This would mean that players do not have to focus on strict game rules and objectives, but are offered small and playful interactions within the AR application that invite them to take their time and perceive the exhibits at their own pace. Users must be prompted to move and change their point of view in order to fully perceive the spatial presence of the virtual objects together with the real environment that the exhibit represents. Feedback from the system during cooperative play could encourage trial and error so that users explore the content. We think that further development of our application in this direction could lead to greater (co-)presence with the exhibits and other visitors. We plan to incorporate several such play ideas into our future prototype and test their impact on immersion, presence and ultimately learning and remembering to find out which level of gamification works best for immersive AR.

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