ARTICLE

Concerns and Challenges Developing Mobile Augmented Reality Experiences for Museum Exhibitions

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Abstract There may be valid reasons why some technologies are readily adopted in museum exhibits, such as audio, video and touchscreen interactives, and others are not, e.g., holography and augmented reality; however, unless we collectively and deliberately experiment with, analyze and report our findings, it is likely that concerns with technologies are based on anecdotes and assumptions rather than empirical data and may be misleading and confusing. We examine concerns and the challenges commonly associated with the use of augmented reality in exhibitions and apply a case study from the Smithsonian's National Museum of Natural History to assess the veracity of these with this particular technology. Assumptions around detraction, replacement, gimmickry, and onboarding, for example, were not found to be a valid concern. Augmented reality can have high user experience rewards, yet as with any technology, there are technical and socially relevant challenges that should be considered before adopting augmented reality as a user experience.

INTRODUCTION

Museums have experimented with Augmented Reality (AR) since the early 2000s. Most commonly paired with mobile devices, the technology superimposes virtual content onto the surrounding physical environment, displaying the two as one image on a screen. The power of this technology is in merging the observational and interpretational aspects of experiencing an exhibition (Elinich 2011), consequently AR has been regarded as a tool for innovation in the hands of museum experience developers (Schavemaker 2012) to enhance the interaction between visitors, collection objects and their contextualized information (Weng et al. 2011).

AR has been adopted across museums of art, science, history, and cultural heritage sites, in different countries, independently or in partnership with research centers. For example, in museums with natural history collections and science centers, the technology has been employed for supplementing the setting with more information in an interactive fashion (Reed et al. 2014; Rothfarb 2011), reinvigorating outdated exhibitions (Mor et al. 2012), reconstructing the remote past by visualizing cultural heritage sites that have been modified or destroyed (Barry et al. 2012; Elshafie 2015), promoting social museum experiences, mostly through gamification (Ferreira 2016), and encouraging visitor participation through creative content production (Yamada and Matsubara 2013).

Yet the museum community continues to be skeptical of the efficacy of AR, and for good reasons. AR remains a relative novelty, and AR software products and support has been unstable. General design practices with a user-centered perspective (Ko et al. 2013; Kourouthanassis et al. 2015) caution against

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user cognitive overload when superimposing information into the real world, in particular when using smartphones due to small screen size. Museum settings being particularly rich with information in a non-augmented form create conditions for this concern. AR also suffers from the finger pointing that these experiences can be subject to, such as mobile devices being promoters of 'heads-down' experiences and detractors from the physical museum. Combine these factors with a glaring gap in the literature regarding best practices for implementing AR in museums and the field is left in a wait and see position rather than capitalizing on a technology with tremendous potential and making progress using AR to solve common problems with visitor experiences.

Here we review some of the concerns and challenges that have been identified in the literature regarding the adoption and implementation of AR in museum settings. These problems seem to rise across institutions of different disciplines. Through our visitor experience research and practical experience developing a mobile app featuring AR technology, we address these concerns and challenges as they presented themselves in the context of a Natural History museum, and provide insights for best practices.

CONCERNS AND CHALLENGES

Gimmickry

Gimmickry has been identified as one concern relating to the adoption of AR in museums (Matuk 2016). Being an innovative, eye-catching technology, commercial goals can drive museums to adopt AR sidestepping a deeper reflection about the real contribution to the visitor experience. This market share approach is often perceived as one that turns museums into amusement parks and other entertainment venues (Ballantyne and Uzzell 2011).

Supporting audience participation is one of the more common reasons why museums embrace AR (Schavemaker 2012). Its effect can be comparable to the adoption of radio broadcast technology in museum guides in 1952, which provided an alternative to docent guided tours, and was arguably one of the most transformative technologies for museums in the 20th century – it reflected the trend towards personal relevance and interpretations, interactivity, easy access and control of content (Tallon 2008). Above all AR is a technology, like any other technology, and it does not have an intrinsic value per se, but rather exists through the content it carries (Schavemaker et al. 2011), and the intent of the developer. To avoid what Sola called the "technology trap" back in 1997, meaning the pursuit of technology for its own sake (Šola 1997), AR needs to be a solution to the visitor experience by effectively weaving the virtual with the physical into the narrative, and ensuring that the interface becomes an integral layer, a storytelling tool (Barry et al. 2012).

Detraction or Replacement of the Museum Experience

Another commonly voiced concern regarding technology in museums, in particular mobile technology, is that visitors to an exhibition will be absorbed by the devices and disconnect from the surrounding displays. The space between engagement and distraction is narrow according to most museum professionals that strive to leverage new media without overwhelming (or underwhelming) visitors {Mann:2013tx}.

The 2012 Trendswatch Report asked: "*Does an immersive AR experience on a handheld device detract from the experience of real-world objects or environments? Will AR users become*

disconnected from their surroundings?" (Merritt 2012, 22). Different authors have shown these are valid design concerns. But is it AR that detracts? One study of a location based gaming AR experience for 8–12 years old indicated a disconnect from the surroundings, which the use of the technology aggravated (Madsen et al. 2012). Players spent most of the time looking at the screen and barely noticed the museum itself, according to the study. Another study of a mixed reality narrative took users on a tour and found that the most successful stops, from the point of view of the participants, were those where the narrative was especially meaningful to the place. The results show how important it is to keep the flow of the story continuous and to incorporate the real world into every part of the experience. This was also noted in another outdoor gaming study (McCall et al. 2010) where players' feelings of presence throughout the game, particularly decreased while navigating between locations.

Not all AR works the same, some use the camera in the device for image or object recognition, and some use GPS signals. The studies above used GPS to geospatially trigger AR. In these examples, there was no direct connection with features in their surroundings that led users into perceptual object experiences. However, AR experiences triggered from museum images or objects are expected to activate spatio-perceptual experiences rather than detract from the physical museum given that a stronger bond with the environment is created compared to location based AR. The utilization of contextual sensory data is in fact of crucial importance for mobile AR applications (Kourouthanassis et al. 2015).

To a lesser extent, the technology is occasionally part of a larger argument that questions the intrinsic value of the museum objects and exhibitions and how that value holds when it is no longer necessary for visitors to physically go to the museum to have an experience with collections. As with any other digital experience – 2D and 3D images, videos, podcasts, interactives – AR can also provide access to museum offerings away from the brick-and-mortar institutions.

As part of the shift of the museums' priorities and attitudes towards becoming visitor-centered institutions, the traditional focus on collections has been the subject of reflection (Hein 2007). The argument of museums being the holders of the 'real objects' and therefore providing more authentic and exclusive experiences, as opposed to individuals having access to replicas or virtual 3D representations of the same objects, is multifaceted – the interpretation of the 'real object' in the museum context is complex, personal and significantly related to how the objects are presented (Latham 2015). Visitors exploring the collections in a digital context can have greater control over the experience, finding new ways to access, understand and respond to them (Hogsden and Poulter 2012), and can even express more emotions towards the digital representations than towards the real objects (Alelis et al. 2015). Some would argue there are situations where replacing the physical museum experience is particularly desirable, for example, for museums that face problems of overcrowding (Ballantyne and Uzzell 2011) or are closed for a period of time (Schavemaker et al. 2011).

Most museums have now begun or even finished digitizing their collections (IMLS 2006). The process has opened up extraordinary possibilities, from capturing accurate and reliable data that can serve both scholarly studies and exhibition and outreach uses, to revealing objects that were hidden away for lack of space or conservation concerns (Metallo and Rossi 2011). All the ways that 3D digital

representations are going to change is unknown, and as digital representation technology improves we expect it will be better integrated into the current museum experience; perhaps 1 day the 'digital object' will be as legitimate as the 'real object' (Hogsden and Poulter 2012).

Onboarding and Duration of Content

AR is not an entirely new medium, yet most people have not encountered it, and particularly in a museum setting. Thus, the relative novelty and uniqueness of AR has potential to increase visitor engagement, but the challenge of users activating the technology has to be overcome. The onboarding steps involved in unlocking AR are not familiar to most visitors – the camera turns on by itself, the mobile device has to be pointed towards a particular object, and the display has to frame the object in a certain way. Considering most museums distribute apps in a bring-your-own-device model, the entire process has to be clear and self-explanatory, especially when there is no support from a facilitator or the apps are meant to be used outside of the museum.

One study has shown the relevance of designing the initial stage of the AR experience to be wowing and instructive at the risk of visitors not going beyond the introductory screen (Madsen et al. 2012). Other authors break down the design guidelines for on-screen AR instructions to indicate the human movements involved by emphasizing the parts of the body that are in motion, for example showing a person's hand lifting the device to frame the object. Equally important for the instructions is depicting the environment where the action is taking place and providing feedback in real-time for reassurance and motivation (Rolim et al. 2015).

Once the user is onboarded, we should expect an initial stage of higher interest followed by decreasing engagement and increasing fatigue. How long an AR experience lasts and the number of AR experiences is related to visitor fatigue. As the user holds a mobile device in front of an image or object for the extent of the experience, typically with one hand, the activity is potentially taxing. Although controlling the number, spacing and duration of AR experiences can lessen fatigue, ultimately it is the user's decision which AR experience to choose based on their preferences, level of enthusiasm and stamina – as with any exhibit experience –, so there is nothing special about AR in this regard.

Indoor Exhibitions: Light, Line of Sight, Noise and Internet Access

There are additional practical production aspects to consider when delivering AR in a museum that are particular to indoor exhibitions. GPS signals, on which most outdoor AR relies on, do not penetrate buildings or differentiate elevation changes from floor to floor, making GPS generally inadequate for indoor AR. Hence, indoor museums default to visual tracking, which depends on consistent sources of ambient light for environment recognition and requires an unobstructed line of sight between the camera and the images or objects being tracked (Carmigniani and Furht 2011; Craig 2013).

The potential incompatibility between the higher light conditions necessary for proper activation of the augmented content and the lower light conservation requirements of objects on display is a known issue (Mor et al. 2012; Zoellner et al. 2009), which can be exacerbated by cameras with lower sensitivity to light. The AR museum guide at the Louvre-DNP Lab

found it necessary for the app to operate in relatively dark environments, given the dimly lit conditions of the galleries, which made triggering AR a challenge (Miyashita et al. 2008).

Visitor crowds, a constant in the 'big museums' (Ballantyne and Uzzell 2011) and in temporary blockbuster exhibitions that draw a great deal of attention in a relatively short period of time, have been observed to interfere with the physical space allotment and quality of line of sight to objects that offer augmentation. Crowds can also restrict visitors from choosing their preferred itinerary (Damala et al. 2008; Davies 2012). The high noise levels that result from large gatherings of visitors are equally a problem. AR experiences, unlike traditional audio tours that visitors enjoy by holding devices against their ears, usually couple audio with visuals, leading the user to hold the device in front of the body where sound is more readily lost to the surroundings.

Internet access is one of the most discussed challenges of indoor museum environments considering that cellular connections in some institutions may not provide enough bandwidth or stability to download an app (Thian 2012). The situation worsens with international visitors that often refrain from using personal data plans and incurring expensive roaming fees. The alternative, which is Wi-Fi provided museum-wide or in-gallery by the institution, is not always possible, for reasons ranging from cost to having historically designated buildings which restricts renovations needed to install connectivity.

RESEARCH STUDY

Considering the concerns with AR in museum literature and challenges reported by museum professionals we spoke to, we decided to use our visitor experience research with AR and practical experience developing a mobile app featuring AR technology, in a Natural History museum, to address these concerns and challenges and provide insights for best practices.

The Setting

The Bone Hall is a permanent exhibition at the Smithsonian's National Museum of Natural History (NMNH) featuring over 300 full skeletons and skeletal parts representing all living groups of vertebrates (Figure 1). Most of the specimens in the Bone Hall predate the NMNH building, some were first on view at the Paleontology and Comparative Anatomy exhibition at the Smithsonian's United States National Museum, which opened in 1881 (Gilmore 1941). The design of the current exhibition is from the 1960s and it is intact with almost no changes since it opened.

The Bone Hall is a display of specimens mounted mostly in still poses arranged in side view without representing any particular behaviors or giving the impression of motion. Skeletons are grouped in display cases according to their taxonomic group (Order), such as carnivoran mammals and herring-like fishes. Inside the cases labels give names to specimens – nothing more – and placards describe the skeletal features shared by the group using specialized anatomical terminology, without visual examples to highlight or identify those features. Certainly, the exhibit has an overall feeling of an outdated exhibition intended for students of vertebrate anatomy, which is not congenial to the majority of visitor's science literacy. Importantly, the Bone Hall tends to be extremely crowded during periods of peak visitation – holidays, festivals and spring and summer months – as the museum hosts more than 6 million visitors annually. The Bone Hall is both linear and

Figure 1. General view of the Bone Hall. Photo credit: 2008-10806 Osteology Hall by Chip Clark, NMNH, Smithsonian Institution. [Color figure can be viewed at wileyonlinelibrary.com]

narrow, which leads to the buildup of visitors as they stop to look at the display cases. Large groups and families with strollers contribute to slowing or stopping the flow of traffic and pose significant challenges to visitors with reduced mobility. The amount of people coupled with continuous glass covered cases push the ambient sound levels considerably above 80-90 decibels.

The Mobile App

The mobile app Skin & Bones was developed to address the obstacles preventing visitors from having more meaningful, enjoyable and memorable experiences. (Marques and Costello 2018). We did not establish any specific learning goals or expected outcomes – the app was designed to resuscitate the exhibition experience by increasing the enjoyment of visitors and improving the communication of the main organizing principles of the Hall. Importantly, it would become an option to visitors interested in delving beyond what is available in the physical space, but not replace it, and preserving the possibility of exploring the historical bone collection as it was conceived by scientists from the 1870s to the 1960s.

The 13 skeletons featured in Skin & Bones tell ecological, evolutionary and anatomical stories. Ten AR experiences, 32 videos and four activities were created to narrate those stories. Production lasted 25 months and the app was deployed January 2015. Two Wi-Fi access points were installed in the exhibit space to provide cost-free internet access to visitors who download the app onto their personal devices. Visitors are made aware of Skin & Bones through posters that hang throughout the exhibition.

The AR experiences are object-based, with skeletons in the Bone Hall triggering the

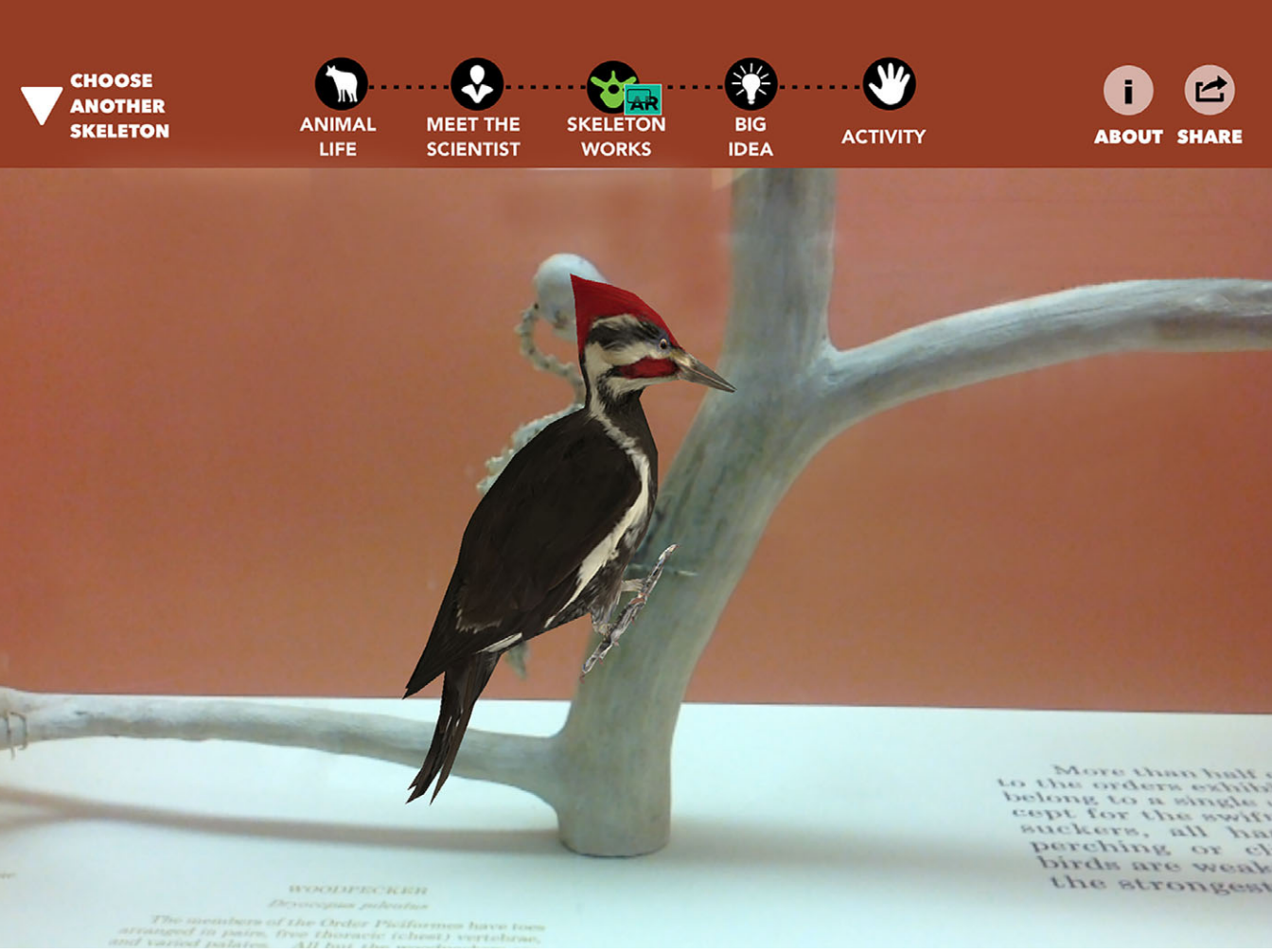

Figure 2. Skin & Bones screen capture of the AR experience triggered from the skeleton of a Pileated Woodpecker. In the augmented animation, the skeleton becomes fully fleshed and feathered; then the skull is isolated to illustrate the complex and long tongue mechanism specialized in capturing insects from behind the bark of trees. [Color figure can be viewed at wileyonlinelibrary.com]

augmented content. 3D models and 3D animations are superimposed onto the skeletons. As interpretive devices, 3D Models and 3D animations highlight the animals' unique features, particularities of the functional anatomy (Figure 2), or simply skin the bones with the corresponding fleshed exterior, linking the internal and external appearances (Figure 3). 3D tracking continuously adjusts the orientation and size of the augmented content according to any repositioning of the mobile device, and this happens in a very natural and smooth way.

The app opens with an animation alluding to the AR experiences available (Figure 4). The animation also introduces an AR icon through visual association that is repeated throughout the app screens whenever the technology is available. When the user selects a menu option with augmented content, the back camera of the mobile device turns on and a panel slides up on the display instructing the user to "*point your device to frame the* [animal]" and shows an illustration of the correct framing of the skeleton (Figure 5).

Bearing in mind visitors to NMNH are known to be mostly U.S. and international tourists commonly with tight agendas (Bitar et al. 2013; Doering and Pekarik 2010; Marino et al. 2004), all of the content pieces in Skin & Bones with a fixed duration were designed to be short (videos up to 02:42 and AR experiences up to 01:04).

Figure 3. Visitor in the Bone Hall having the Skin & Bones AR experience triggered from the skeleton of a Mandrill. A 3D model of a fully fleshed animal is superimposed onto the skeleton. As the visitor moves in relation to the specimen, the 3D model is repositioned to correct the alignment. Photo credit: Nico Porcaro. [Color figure can be viewed at wileyonlinelibrary.com]

Research Methods

During production and following deployment of the app, an in-depth research project was conducted. It was structured to answer questions such as (1) the extent to which AR in a museum exhibition modifies the visitor experience (forthcoming publication), (2) how the digital enhancement of antiquated museum exhibitions affects patterns of visitor behaviors (Marques and Costello 2018), and (3) what concerns and challenges related to the adoption of AR are present in a case study at a Natural History museum (discussed here).

Data was collected directly from visitors at the Bone Hall by randomly recruiting the subjects as they entered the exhibition, by themselves or in small groups, with ages above 12 years-old. When visitors agreed to participate in the study, they received an iPad with the research version of Skin & Bones. This version recorded all user actions with the app, which revealed every piece of content selected and the duration of viewing.

With the goal of simulating, as much as possible, visitors in the Hall downloading Skin & Bones to a personal device no information about the app was provided in advance to participants. They were left to explore the exhibition on their own, while the researcher observed and tracked the visit unobtrusively. All visitor stops and stop durations were recorded, as well as behaviors related to operating the app and triggering AR. When participants returned the iPad, they were invited to fill in a self-administered, online questionnaire

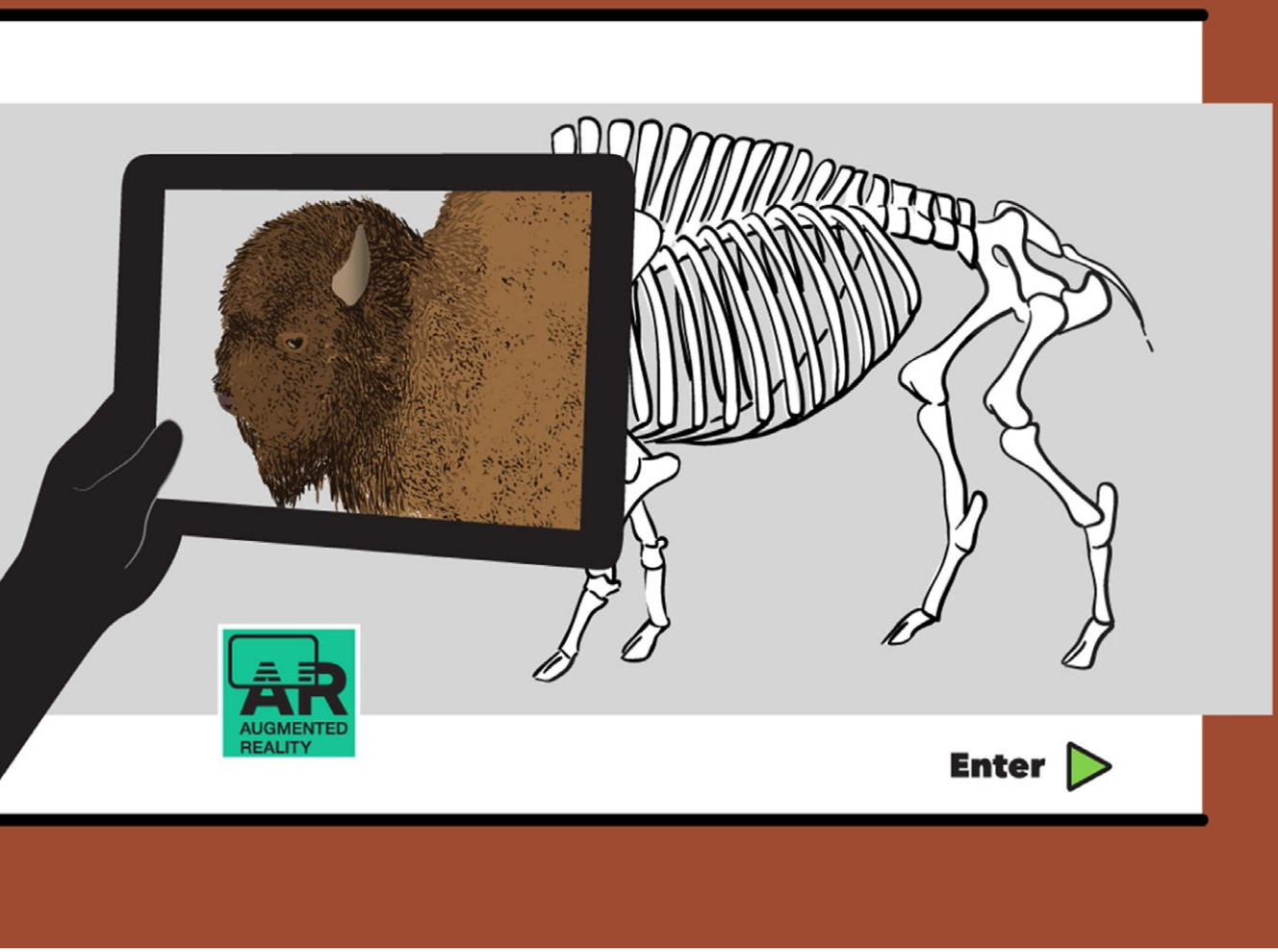

Figure 4. Skin & Bones screen capture of a frame of the opening animation. [Color figure can be viewed at wileyonlinelibrary.com]

or to sit and engage in a non-directed interview. The study included 199 participants that filled in the questionnaire and 15 that interviewed, and took place for 92 days between April 15 and August 14, 2015.

Complementing the individual data from the research version of the app, the public version of Skin & Bones is equipped with Google Mobile Analytics (GMA). GMA provides aggregated data from all users that download and open the app at least once. The setup of GMA in Skin & Bones recorded the extent to which users of the app in the Bone Hall connected to the Museum Wi-Fi and GMA data was tracked for the first year of the app (Marques et al. 2017).

RESULTS

The sociodemographic information collected on the questionnaire confirmed that the random sample of participants in the study were a representative sample of visitors to NMNH, ensuring the validity of the study. Their answers also revealed that the majority had not experienced AR or even used a mobile app in a museum setting before. Nevertheless, more than 90% declared to be comfortable with technology.

In the interviews participants commented positively and enthusiastically on how Skin and Bones enhanced their museum experience. They did not refer to the app as a distraction

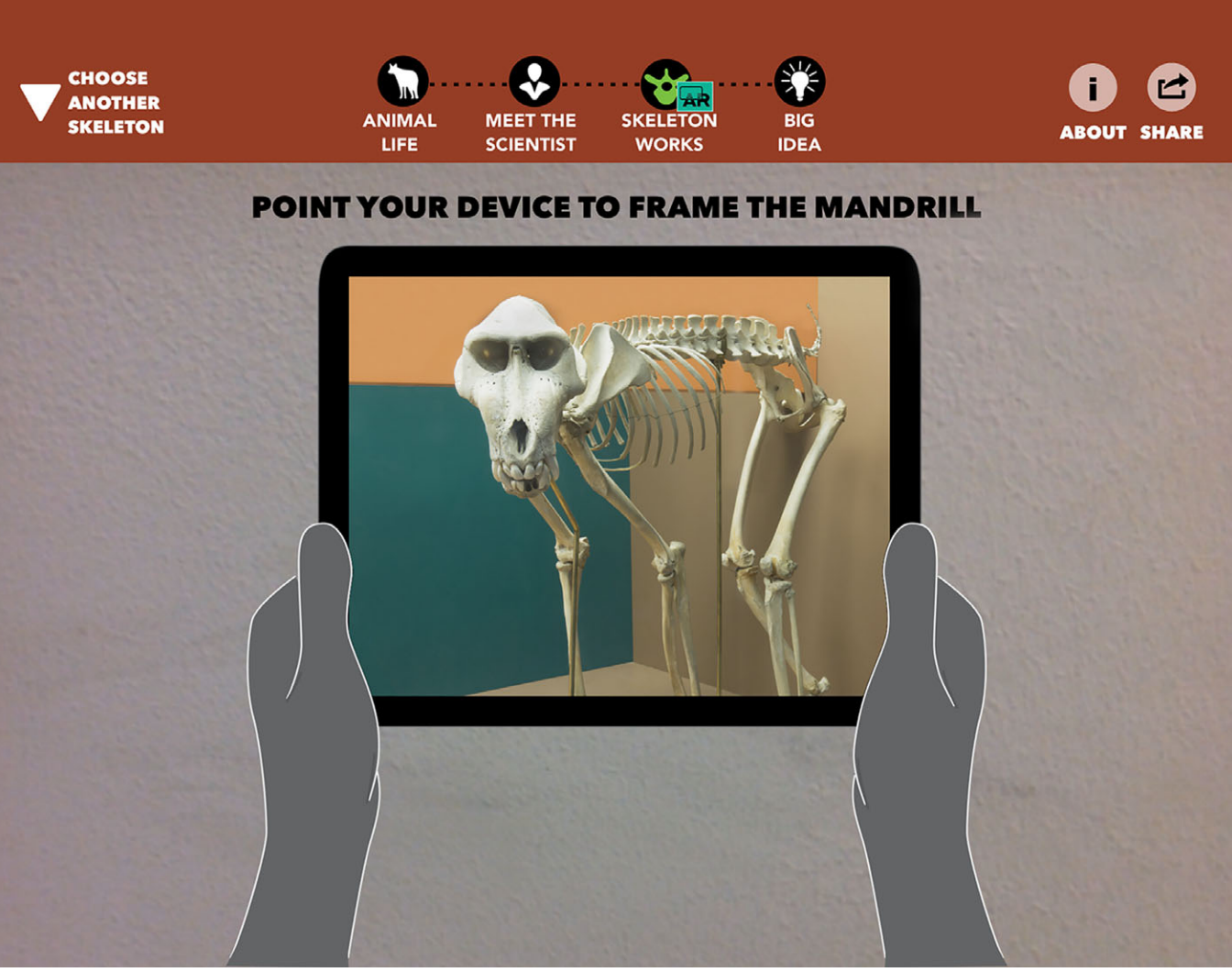

Figure 5. Skin & Bones screen capture of the instructions to activate the AR experience for the Mandrill. [Color figure can be viewed at wileyonlinelibrary.com]

from the exhibition or considered it to be a self-sufficient tool they could use instead of visiting the Museum. Skin & Bones was seen as a tool that gave visitors an opportunity for self-interested direction at their own pace.

> "So that was really cool. And I like that it's self-paced so that if you didn't want to do everything you could just stop. . . you could pick and choose what you could listen to."

> "The good thing with it is that all people have different interests, so if someone wants to know more about that fish, someone wants to know more about birds, then you can choose what you want to see more about."

For some participants, it was an extension of the museum, allowing them to dive deeper and get more information.

> "It gave us a lot more information. It was nice to kind of sit here, look through it, and see the skeleton and you could go back and look at the information."

> "It was better than just watching the skeletons. Because I don't know much."

The overall failure rate in triggering AR experiences was 6.9%. Participants who were unsuccessful either pointed the device at the wrong skeleton or were too close to the display

case, a condition commonly caused by the dense flow of visitors forcing them right up against the cases. Those who did step back far enough occasionally saw their experience interrupted when other visitors crossed between the device and the case. The objects with the highest success in facilitating access to AR were larger specimens that stood out in their cases, yet were not so big to force users to step back too far.

The on-screen instructions for activating AR seemed to be readily understood, even if some participants took several attempts to get the correct framing. When users faced the correct skeleton, and framed their cameras according to instructions, the augmented content never failed to activate. Light in the exhibit remained uniform and was never a confounding issue. There were no windows to the outside that could introduce variation in lighting.

Participants ranged from not seeing any content (just browsing the app like a table of contents and not playing videos, activities or engaging with AR), to seeing as much as 31 pieces. Most consumed content for one to 5 minutes, but several longer than 21 minutes, with an average of 08:10. This is not the amount of time they spent in the exhibit, which was always greater. Interviews revealed that some participants felt using the app threatened their goal of seeing as much of NMNH as possible in the time they had, and especially because some thought they were supposed to watch all the content in the app.

> "In this big museum, if you should spend more than 5 minutes on each display, you take 2 days to get through all of it."

> "Surely we didn't do all of the videos either, because we're pressed for time and we don't want to spend a whole lot of time in one exhibition, and some of the videos are like three and half minutes long."

> "Some of the ones we saw, we stopped after, I don't know, a minute or two. We're tourists so we have to proceed."

The requirement of holding the iPad for the entire duration of the animated AR experiences was mentioned only by one participant.

> "I think I would like it better if you didn't have to hold it up the whole time, if you could just snap a picture and then it comes to life from there."

The extreme sound levels in the Bone Hall, felt during the summer when the study was conducted, interfered to a great degree with the visitors' experiences. Participants having difficulty hearing Skin & Bones audio were observed holding the device to their ears and increasing the volume. Their comments illustrated the problem and hinted at the social implications:

> "Started watching the first one for about a minute, then I couldn't really hear it. It's kind of annoying to watch the subtitles, then try to watch the video, your eyes going up and down."
> "I'm not the type of person who can watch foreign movies."

> "The sound is a problem if you don't have earphones."

> "I couldn't hear the videos. If you were to integrate some sort of noise canceling headphones that go over the ears, I think then you'd be on to something."

> "I don't know if two people can really use it, because if you have headphones it's mainly one."

Analysis of GMA data revealed the large extent to which visitors in the Bone Hall did not connect to the Museum's Wi-Fi to download and use Skin & Bones. In fact, 38.2% of all AR experiences seen at the exhibition were viewed on mobile devices through a data plan. Another aspect of internet connectivity is that the crowds at the Bone Hall interfered with the speed of the connection. Even when not in use, visitors' personal phones and tablets can be set to automatically scan for Wi-Fi which can slow performance. And as more people occupy the space, they absorb the radio waves transmitted by the Wi-Fi system creating additional performance degradation.

DISCUSSION

Gimmickry

Developing Skin & Bones with AR as one of the main features was a deliberate choice, a mechanism to enhance the visitor experience. The objective was to repair an exhibition that was not meeting visitors' expectations. The technology made it possible for the historic collection and outdated exhibition to coexist with a media driven, engaging experience that revealed the core messages of the exhibit, which had been concealed for over 40 years. Using AR was never about seeking market share or attracting younger audiences. It was a carefully selected tool with the potential of revitalizing and fostering a positive visitor experience. Data on visitor experiences with Skin & Bones refutes the idea that AR is unavoidably a gimmick in a museum setting and it illustrates how AR can intensify object experiences (Marques and Costello 2018).

It is the 'fitness' of the media that matters. Intent and design are critically important to the performance of an AR event on visitor experience outcomes. When an AR event can be justified as integral to effectively communicating a feeling or theme, outcomes are more likely to be positive. When these boxes are checked, gimmickry is not an issue.

Detraction or Replacement of the Museum Experience

Study participants referred to the experience using Skin & Bones, both the augmented and non-augmented content, as an extension of the exhibition, never as a distraction or replacement. Importantly, many participants valued the self-pace and controllable nature of the experience. Other studies have shown how much visitors appreciate having control over the visit (Alonso and Hayward 2013; Swift 2013), as they have the opportunity to personalize their experiences by selecting the kind and amount of information they consume according to their preferences. Also, study participants set Skin & Bones apart from traditional audio tours, which can have negative emotions associated with them, such as monotony (Jarrier and Bourgeon-Renault 2012). The results of this research project confirm previous findings and support what has been regarded as the true strengths of mobile technology in museum settings – participation, customization and individualization (Jarrier and Bourgeon-Renault 2012; Stogner 2009).

The 'heads-down' experience commonly associated with mobile devices and their potential to distract and disengage from the surroundings (Hsi 2003; Woodruff et al. 2001), and the spatial disconnect witnessed with geo-located AR experiences (Madsen et al. 2012; Wither et al. 2010), were not reflected in the case study. Skin & Bones direct reliance on the exhibition specimens to trigger the augmented content strongly interconnected the real and virtual environments, which did not go unnoticed by the participants – e.g. "*You could see how it actually*

moves based upon its skeleton." This reinforces the idea that mobile AR technology is unique in fostering visitors' exploration of the surroundings, if image or object based AR is employed. The object and its interpretation became one from the point of view of the visitor, coexisting on the display and depending on one another.

This blurs the argument of museums being the holders of the 'real objects' and gives a new meaning to the process of exploring a collection digitally. Museums are collages of techniques for people to have meaningful, inspiring, personal experiences and this has been the case from the beginning – through dioramas Natural History museums were early adopters of virtual reality. Applying a spacio-perceptual coating of AR is nothing more, and our creations should have the effect of focusing visitors and raising their awareness of the surroundings.

Onboarding and Duration of Content

Even though the user experience concerns identified in the literature were largely unsupported by this case study, several of the production and known implementation challenges of mobile AR in museum environments were real issues and some were pronounced.

The process of onboarding AR experiences in Skin & Bones, for the most part, was not problematic. A 6.9% failure rate to trigger the augmented content was lower than expected considering that participants received no verbal instructions on how to operate the technology and the great majority had never encountered AR before. The visual instructions to point and frame the device proved to be clear. The few failures were related to triggering specimens themselves. The factors shown to affect a successful AR event were the scale of the object in relation to the surrounding objects, the position of the object in the display case, and the distance between the user and the object. The interferences that resulted from visitor crowds are to be expected in any exhibition with medium or high visitation and can only be prevented with careful selection of the objects featured within an existing exhibition, or with proper planning if it is an exhibition being designed.

If human computer interactions were not complicated enough, AR on a mobile device in an exhibition involves human-computer, computer-exhibit interactions. We concluded that simplistic interactions are important to onboarding users quickly and without frustrations. Simplistic and instructive visual simulations of the human-computer and computer-exhibit interactions help to get users across the onboarding threshold and on their way to enjoying brief experiences.

Indoor Exhibitions: Light, Line of Sight, Noise and Internet Access

The Bone Hall is a reasonably well-lit space and did not present particular challenges with light impairing the activation of AR. Controlled lighting of a sufficient level is helpful if not critical and bones are more light-tolerant than some other collection objects.

The amount of the total content – both augmented and non-augmented – on the other hand did raise concerns among some visitors as they confronted an overwhelming thought that they were supposed to use all of the available content. Typically, visitors to NMNH move at a fast-pace. Other institutions with fast-moving visitors should expect similar results, whereas other classes of institutions offering more contemplative experiences may see visitors responding with more patience and attentiveness.

For the user, the greatest challenge noted in the case study was listening to audio, which seems ironic in the context of the history of audio

tours. The problem was repeatedly voiced by participants, extensively observed, and it proved to be multidimensional. Visitors predictably become frustrated and less satisfied with their experience if they were not able to listen to the audio, or share the experience socially. The indispensable use of a headset or earbuds individualizes the experience and isolates the visitor, which participants were sensitive to. Audio in museum exhibitions is possibly the ultimate trial, especially in large, loud and overcrowded institutions. More reliance on visuals and on written text are options but not without consequences to the visually impaired or disabled, and to those who do not appreciate or are not used to captioned text. Skin & Bones is as much an audio experience as it is a visual one. At a time when museums show an interest in furthering experiments with audio in the galleries and its advocates consider creating soundscapes (Bubaris 2014), new technical solutions of sound delivery are needed. Better crowd management helps.

The substantial number of visitors that used their own data plan to download and operate Skin & Bones when there was free internet access available indicates that they were either not aware of the courtesy Wi-Fi, despite the posters spread throughout the gallery, or they encountered a problem establishing the connection. Internet access is among a number of technical hurdles that will not disappear from the list of concerns of museum professionals any time soon. As of mid-2017, within the European Union, mobile roaming charges no longer apply. This is a promising first step on one continent to alleviate the situation, at least for institutions that for one reason or another are not able to provide internet access. Human facilitation, through docents and volunteers on the museum floor, is still the best guarantee of resolving connectivity issues, especially visitor awareness and assistance with connecting and onboarding processes, and they can be a valuable resource in troubleshooting mobile app operations.

Computer-exhibit interactions vary as conditions do, and nothing replaces testing AR triggers and alignments, and Wi-Fi connection, over and over again at times when crowds peak, and if lighting conditions vary, then at the lowest light levels. These variables are particular to each museum and there is no general rule other than to be aware of the factors that can prove challenging and trying to avoid or ameliorate them.

CONCLUSIONS

The design of the user experience in Skin & Bones as a case study mitigates and eliminates many of the concerns we find in the literature on AR and mobile technology. Far from being a perfect tool, it is nonetheless one that even now, after three and one half years and 35,000 downloads, is still recognized as part of the movement in museums towards visitor engagement with new media (Pardes 2018). As long as the new versions of the iOS operating system continue to support Skin & Bones, the app will be available for onsite and offsite users. After that it is likely to be retired, having served its purpose at NMNH and as a research case study for museum professionals.

Setting aside the concerns and manageable challenges one must confront when producing AR experiences, what does the future hold for the adoption of AR in science and natural history museums? Google's AR Core and Apple's AR kit and other Software Development Kits (SDKs) have made it easier and less expensive to integrate AR into mobile experiences. Production barriers are lowered in ways similar to video production. And yet AR has not had the growth and impact in museums that several predicted it would (e.g.,

Merritt 2012; The New Media Consortium 2005). AR bubbles up here and there rather than being a pervasive technology, which seems odd given it is such a good fit at natural history museums. Technology is no longer the principle impediment. It is the limitations of our own skills designing and producing experiences with AR technology, and successfully distributing them to the visitors. More risk-taking and experimentation is what museums need to embrace while carefully recording and reporting their production hurdles and visitor experiences so that a library of trials is built over time that contributes to reducing the concerns and challenges we all face in the process of creating meaningful experiences.

ACKNOWLEDGMENTS

The authors would like to thank the other members of the Skin & Bones development team: Jim DiLoreto, Mason Glaves, Brittany Hance, Don Hurlbert (deceased), Phat Nguyen, Wei Qian, Frances Pitlick, David Price, Sophia Roberts, Reid Rumelt, David Schulman, and Dane Webster. Thanks are also due to Blake Stenning, Catherine Denial, Guarina Lopez-Davis, Michael McCormick, Nico Porcaro, Paul Sturtevant, Ryuichiro Hashimoto, and Sasha Montero for their assistance with data collection. We are grateful for the valuable contribution to the research by Prof. Dr. José Azevedo (University of Porto), Andrew Pekarik and James Schreiber. The production of *Skin & Bones* and research were supported by the Booz Allen Hamilton Corporation, the co-funding of the European project POPH/FSE and a grant from the Foundation for Science and Technology (SFRH/BD/51840/2012), under the UT Austin|Portugal, CoLab. END

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