Low-Cost VR Applications to Experience Real World Places Anytime, Anywhere, and with Anyone

Jan Oliver Wallgrün*[1], Arif Masrur[1], Jiayan Zhao[1], Alan Taylor[1], Eric Knapp[2], Jack (Shen-Kuen) Chang[1], Alexander Klippel[1]

[1] Department of Geography, The Pennsylvania State University
[2] USDA Forest Service, Pacific Southwest Research Station

ABSTRACT

Low-cost VR applications in our understanding are applications that run on inexpensive hardware, such as mobile solutions based on a combination of smartphone and VR viewer, and that can be created with relatively low costs, efforts, and VR expertise involved. We present our approach for creating such low-cost applications of real world places, developed with the goal of putting the content creation into the hands of the domain experts rather than of VR experts. Since the target audience of such authors often consists of groups of people, our aim, furthermore, is to go beyond typical single user experiences by incorporating a joint VR component that allows users to not only use the applications anywhere and anytime but also together with any*one* they want to share it with, resulting in new design decisions and challenges that need to be addressed. While our focus is on joint educational experiences, such as the example of an application to learn about fire ecology in the Ishi Wilderness in California used throughout this article, the approach can just as well be applied in business, entertainment, or social media oriented contexts.

Keywords: Low-cost VR, immersive technology, remote joint VR, mobile VR, content creation for VR, education.

Index Terms: H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems—Artificial, augmented, and virtual realities; K.5.2 [Information Interfaces and Presentation]: User Interfaces—Evaluation/methodology

1 INTRODUCTION

Immersive experiences (virtual reality (VR) and augmented reality, for short referred to as xR in this paper) available through low-cost hardware such as the combination of smartphones and VR viewers (e.g. the Google Cardboard or Samsung Gear VR) allow for virtually visiting and experiencing real world places anytime and anywhere in our everyday life, for instance, at home or in the classroom [1,4,9]. However, there is a second aspect of the notion of *low-cost VR* that needs to be addressed: the costs and efforts required to create immersive content to fuel the increasing deployment and proliferation of immersive applications. While the number of available immersive site experiences has been growing quickly over the last few years, there is still a significant amount of costs, manual work, and expertise required to create and edit the content needed for high-quality experiences and for the application development itself.

In our research, we are aiming at establishing workflows that allow for the creation of immersive experiences of real world places using efficient and comparatively inexpensive methods that do not require xR expertise and, hence, can be employed by laymen, e.g., the people most familiar with the content domain and the place the application is about. There are many scenarios in which these kinds of workflows and associated tools can be beneficially employed, including the following:

- Teachers or instructors creating experiences to share with their class (or the public) when visiting the actual place is too costly, inconvenient, or risky, or alternatively, to be able to revisit the place as often as desired.
- Owners or operators of indoor or outdoor facilities of any kind (hotels, museums, parks, sport facilities, etc.) who want to use VR as a medium to let people remotely experience their facilities, e.g., as a commercial product or for advertising purposes.
- Researchers, in particular from areas with a high spatial or environmental focus such as the geosciences, geography, archeology or ecology, who want to communicate insights and research results to decision makers or to the general public as part of scientific outreach activities.
- Individuals who want to share their home or other favorite places with friends around the world in the most realistic way using self-made immersive experiences as a new form of social media.

In many of these scenarios, the intended consumers of the immersive experience are, or at least could be, groups of people (students in class, circle of friends, group of decision makers). Hence, it can naturally be assumed that future authors of VR applications will often have an interest in multiple people being able to experience the VR content they produced together rather than individually. A second aspect driving the research reported in this article is, therefore, the restriction of most current VR experiences for mobile devices to be single user experiences, as currently only few applications (e.g., Google Expeditions) allow for experiencing some remote place together with a group of friends or classmates and, if so, typically only in a very restricted way. Allowing groups of people to visit a virtual place together can have many advantages, for instance, the promotion of critical joint experiences with high-levels of human-human interactivity and enhanced learning opportunities [5,6]. However, creating low-cost joint immersive experiences to be used in everyday life without restrictions on the where and when comes with its own set of technical and design challenges [2,3,7,11,16,17] and happens against the backdrop of a number of trade-offs constraining possible designs as will be discussed in later sections. Moreover, there is currently a lack of studies empirically evaluating design decisions made in this context and, as a result, also a lack of established design guidelines and best practices.

In this article, we provide an overview on our low-cost VR application building methods and discuss a particular example experience, one developed for the Ishi Wilderness in California in collaboration with fire ecology experts with the goal of communicating insights and research results on this topic and area

* wallgrun@psu.edu

to the interested public. In addition to illustrating our low-cost approach, this application also serves as a prototype for the joint VR components we developed to realize a joint immersive experience. In the context of the Ishi application, these components can be used for an expert to give a group of interested people a guided tour through the environment or simply for a group of people to experience and explore the environment together. We describe the technical details and the special means and visual guidance approaches we designed for this kind of joint experience and discuss related challenges and future work that will focus on empirical evaluations and iteratively improving and extending the approach.

2 Low-Cost Content Creation

As pointed out in the introduction, the idea behind low-cost content creation for VR site experiences is that of exploring and developing approaches that will allow lay people to produce VR applications on their own and minimizing the costs and efforts involved. With lay people, we here mean people who do not have significant xR skills but rather are experts with respect to a place or domain that they are in need of creating a VR experience for. The production process comprises the creation of resources (e.g., media and 3D models) for a given site, the scene and interaction design, and the production and maintenance of builds of the final immersive experience for different platforms, in particular mobile platforms such as smartphone-based mobile VR setups that can be considered low-cost themselves. In this section, we focus on the creation of media and 3D model resources from which the scenes in the immersive experience should be built. This is typically the first step in the creation of a site experience. The two main approaches we are employing for this step in our immersive applications are 360° photography/videography and structure-from-motion photogrammetry, and we will discuss them in the following.

2.1 360° Photography and Videography

With the low prices at which 360° cameras are available these days, 360° photos and videos are truly a low-cost method for creating content for VR applications, in particular because a single 360° image can be used to create an entire VR scene for a given location. Figure 1 shows at the top a 360° image taken at a forest location in the Ishi Wilderness in California and at the bottom the process of using the image to texture the inside of a sphere that in the final experience will be centered on the camera position so that users get the impression that they are standing at the location where the 360° image was taken.

The advantages of being a highly efficient method for creating immersive content that also does not require a lot of expertise or training are offset by a number of limitations, in particular with respect to movement and options to interact with the scene content. While users in a 360° based scene are able to look around freely, they cannot move or teleport to a different location in the scene since a camera position away from the center would result in a distorted view. Each new position requires a different 360° image. Therefore, allowing for different predefined viewing positions in a local area will require a dense coverage with 360° images significantly increasing the time to create the content and space requirements of the final application. Since objects in the scene just exist as subregions in the 360° image texture, interactions with objects are typically not possible except for simple mechanisms such as triggering some action when an object is looked at. However, this requires creating and storing additional information specifying which section of the image the objects of interest occupy. Finally, for achieving a real 3D impression with 360° imagery, stereo 360° images are required with two different spheres visible only to one of the eyes and textured with the different images of a stereo pair.

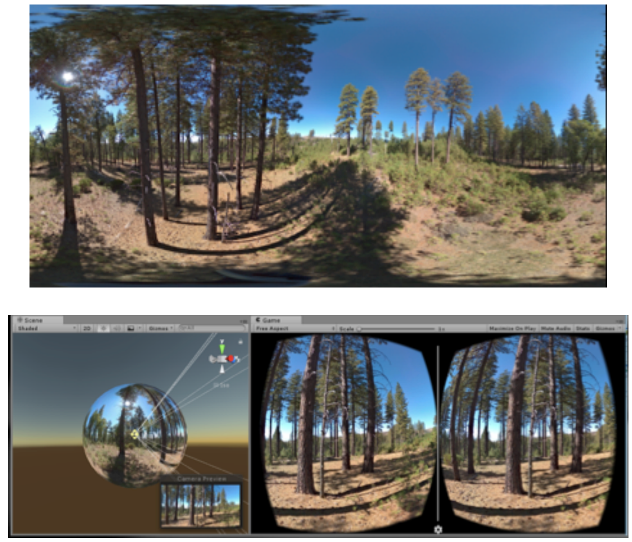

Figure 1: Example of a 360° image (top) and the process of using the image to texture the inside of a sphere surrounding the camera in Unity3D (bottom).

In our work, 360° images (and videos) are the main choice when the goal is to create experiences of locations cheaply and quickly, and when the goal mainly is to convey what a place looks like without any need for complex interactions with individual objects. Our self-developed application building framework [14] (see Section 3.2) can process sets of geo-referenced 360° images to automatically produce experiences following a certain template such as the combination of an overview map showing the image locations from where users can switch over to the individual 360° image based scenes (see Section 3.2 for an example and more details). Typically, our applications provide several views for the same location based on 360° images taken at different heights (e.g., at 1.8 meters and roughly 8 meters) to provide both ground level view and a more bird's-eye-view like perspective. We have also recently started to incorporate 360° images taken with a drone, that are becoming increasingly popular.

2.2 3D Models Created via Photogrammetry

Structure-from-motion (SfM) is a photogrammetry technique that allows for generating depth information and constructing 3D models from standard 2D photographic images [15]. SfM has been used in multiple fields, such as architecture, archaeology, or geology, but can be applied to any 3-dimensional object. By deriving 3D measurements from 2D images, SfM allows for the construction of 3D models of large areas, such as a digital elevation model (DEM) of some terrain or a 3D model of a site, but also for creating highly detailed models of small objects, such as individual artifacts, for example, wood cookies (Figure 2).

Photogrammetry software such as Agisoft's PhotoScan Pro makes the sophisticated algorithms involved available as a blackbox allowing users to employ the methods to stitch together images and produce 3D geometries without much training [15,18]. Although very precise measurement and detailed modeling require higher-end photographic equipment, the resolution of current consumer level phones or cameras is absolutely sufficient for producing quality models suitable for the kind of site experiences we are focusing on in this article.

Figure 2: Photorealistic 3D model of a wood cookie from SfM.

In our work, one way to use the produced 3D models, in particular those of smaller artifacts, is by displaying them within a 360° based scene. This allows the user to interact with or manipulate the object as well as scale and rotate it for in-detail inspection. 3D models of larger areas can be used to put together an entire VR scene without referring to 360° imagery. This has the additional advantage that it allows for unconstrained user movement within the VR scene, something that, as we mentioned, is not possible in a 360° image based scene. However, when comparing the application of SfM for 3D model generation with a 360° image based approach, even though the equipment costs are lower, the efforts are noticeably higher because of the significantly larger number of images that need to be taken, in particular when creating a 3D model of an entire area. Moreover, the costs for the photogrammetry software have to be taken into account as well and using this software requires at least a basic amount of training and experience. We still consider the SfM approach a low-cost data capturing method, in particular since the costs, efforts, and expertise required are significantly lower compared to alternatives involving scanning based 3D model acquisition methods, such as those used for modeling terrains or large physical environments, and manual 3D modeling approaches [15].

2.3 Other Content

While 360° photography/videography and 3D models from SfM are the main components for creating scenes and the ones that have the biggest impact in terms of costs, efforts, and expertise required, there are a number of other resources that we have been using frequently in our site experiences. These include audio recordings, most importantly with audio comments explaining entire scenes or individual objects but also of ambient sound recorded at particular locations to make scenes more realistic and immersive. As will be described in Section 3.2, audio comments in our site experiences are supported by a visual guidance approach to indicate what is being explained. We have developed a browser-based tool for annotating audio clips with the information needed by this visual guidance approach. Other resources include data and media that is supposed to be displayed as complementary material in a site experience such as raw scientific data, plots, photos, and texts.

3 VR Site Experience: The Example of Fire Ecology in the Ishi Wilderness

We illustrate the kinds of VR applications we are building for experiencing real world places anytime and anywhere using the example of the Ishi Wilderness mobile VR app. This application has been developed to communicate insights into the interplay between forests and wildfires and what this means for future forest management strategies to the general public. We start this section with a brief overview on the area of interest and then continue with a description of the mobile experience developed for this site.

3.1 Ishi Wilderness

The Ishi Wilderness has been a location for numerous research projects by co-author Taylor and colleagues for several years [13]. Insights into the importance of Ishi and the scientific data collected can be gained from numerous articles such as [12]. Ishi Wilderness is a 167 km^2 area located in the Lassen National Forest in the Southern Cascade foothills of northern California, United States. The wilderness contains several mixed ponderosa pine and black oaks forests that were never logged and have experienced multiple wildfires in the 20th century creating forest conditions similar to those that occurred before fire suppression.

Stand changes brought on by fire exclusion have contributed to reduced resilience to wildfire in ponderosa pine forests throughout the western US. Growing recognition of how structural attributes influence resilience has led to interest in restoring more heterogeneous conditions once common in these forests, but key information about interactions between stand and fuel development is currently lacking. Few contemporary examples of structurally restored old-growth ponderosa pine forest exist, making the Ishi Wilderness particularly interesting for investigating these interactions and demonstrating effects of wildfires and resulting management strategies.

The area we are focusing on is the Beaver Creek Pinery, a remote site in the Ishi Wilderness. Following a 1994 wildfire, plots were installed in the area to better understand forest and fuel succession over time. The area experienced five wildfires since 1900 that restored the structure to one believed similar to historical ponderosa pine forest. Geo-referenced pins in the ground mark a grid of locations that can be revisited without spatial ambiguity. Figure 3 shows a map from the web page of the Ishi Wilderness project with the location grid highlighted by the blue point markers.

Figure 3: Interactive overview map from the Ishi web site showing the grid of marked and geo-referenced locations (see https://ishiwildfire.geog.psu.edu/map.html).

We used this grid of locations to systematically cover the area with 360° images that provide the basis for our immersive experience. Figure 1 from Section 2.1 showed one of these 360° images and how it is used to texture the inside of a sphere surrounding the camera in our VR application. Instead of restricting ourselves to ground-level photography, we used a very large tripod to also take images at a height of roughly 8.2 meters. This height, while not quite the same as true aerial photography, provides the option to elevate oneself above small trees and understory and to access the environment at a larger geographic scale [8] allowing users to better relate entities and discover patterns. This is of particular importance when combined with other forms of narration such as audio (see Section 2.3). We refer to these images as pseudo-aerial.

3.2 Mobile VR Application

Figure 4 shows the exemplary mobile immersive site experience we created around the Ishi Wilderness. We integrated heterogeneous datasets (i.e., tabular data, 360° photos and videos) with 2D geospatial datasets and map visualizations and with 3D photorealistic models of real-world features, such as wood cookies, to create a geo-visual immersive experience that can be used anywhere and anytime. In the following, we provide a brief overview on the application.

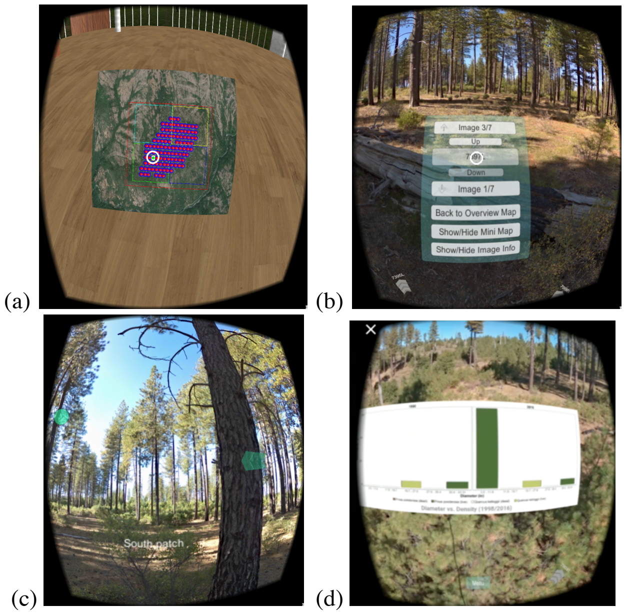

Figure 4: Ishi Wilderness mobile VR application: (a) Overview map with selectable grid locations, (b) 360° based view of grid locations (including navigation menu and navigation arrows on the ground), (c) visual guidance approach (circle marker on the left side and flashing arrow on the right), and (d) overlay of complementary materials like plots, historic photos, or 3D models of individual objects.

The experience as shown in Figure 4 has been built around the 360° images collected at the site but it also allows for the integration of additional information and resources such as maps, historic photos, and data plots. The basic experience uses two different kinds of views: First, an overview map (Figure 4(a)) showing the locations of where the 360° images, ground and pseudo-aerial, were taken. Locations are indicated by points on the map and change color when hovered over with the reticle of the gaze control. Second, upon selection by clicking a button on a simple 1-button remote control or the VR viewer, the user is instantaneously teleported into the 360° image view allowing for an embodied experience of the location (Figure 4(b)).

In the 360° view, users can open additional panels such as a zoomed-in map or an informational text display, as well as use different GUI elements (such as the navigation menu shown in Figure 4(b)) and 3D objects placed in the scene (e.g., ground arrows in Figure 4(b)) to navigate between the image locations. Navigation options include going through the locations as a tour in predefined order or moving between locations based on spatial adjacency via the arrows on the ground pointing towards neighbored locations. These interactive elements are operated via the gaze control to make sure that the application can be intuitively used on very simple (and cheap) VR platforms without additional controllers or other input devices.

When moving to a 360° image location, the corresponding audio comment (see Section 2.3) will be played with the expert explanations of the perceived scene and background information on the fire ecology related developments that lead to it. One challenge when providing audio comments for VR scenes, in particular scenes of natural environments, is that the user may have difficulties recognizing the objects or configurations of features that are currently being explained or they may even be outside of the user's current field of view [11]. Therefore, we are using a visual guidance approach showing flashing circle markers at the location currently addressed in the audio comment and additional flashing arrows pointing into the direction of the current location of interest if the user is currently looking into a different direction (Figure 4(c)). We believe that this suggestive approach is preferable over forcing the user to look into a particular direction while the audio comment is played which may also lead to disorientation and cybersickness related problems.

Our main development tool for creating and maintaining xR experiences is the Unity3D game engine. While the data capturing and 3D model generation methods described in Section 2 allow for creating content comparatively cheaply and efficiently, there is typically still a significant amount of manual editing and development work required to create and maintain the actual xR applications. As indicated in Section 2.1, we have implemented our own application building system within Unity that significantly reduces or simplifies the steps needed in our application development workflow [14]. The system consisting of a number of C# scripts for Unity and its editor environment is given a declarative specification of the application content as well as geo-referenced media and background information, and then automatically produces builds of the xR experiences for different platforms. This also allows for creating new applications by modifying template configuration files, which is typically much quicker than manual scene creation in Unity. This declarative approach is continuously being extended to increase its flexibility and expressiveness. While the domain experts in this application mainly were involved in the content creation, we ultimately want them to be able to use this application building tool themselves to perform the entire application building workflow.

4 Joint Version of the Ishi Experience

As we argued in the introduction, the aim of enabling the creation of VR site experiences by authors that are not VR experts for education, business, or private purposes in everyday life goes together with an increased need for supporting applications that can be experienced together by groups of people, for example, those making up the target audiences addressed in the scenarios described in Section 1. This was a motivation for us to extend the Ishi Wilderness application to include a prototypical joint VR component as a step towards our goal of providing immersive applications for experiencing real word places anytime, anywhere, and together with any other (potentially remote) person or group of people. As illustrated in Figure 5, the concept is that several instances of the application potentially running on different hardware platforms (e.g., smartphone with VR viewer, tablet, head-mounted-display based devices such as the Oculus Rift or HTC Vive) can connect over the internet to form a joint session, allowing users to experience the content together and interact with each other. More specifically, our aim is to support at least the following features and capabilities we deem most important for implementing joint site experiences and supporting the different application scenarios laid out in Section 1:

1. Visualization of where users are in the joint session and what they are doing
2. Voice communication between the involved users
3. Leading other users around / following another user's lead (guided tour scenario)
4. Referring to or highlighting entities in the scene

Figure 5: Notion of a joint experience in which instances of an app running on different xR platforms are linked together.

How to best design support for these four capabilities is an open question and very much depends on the type of immersive experience and how it has been implemented. For instance, the most suitable way to visualize other users and their activities may differ between an experience in which users can freely move around in a continuous 3D space (e.g., based on an actual 3D model of the scene) and site experiences mainly based on 360° imagery in which all users in the same scene will be located at the exact same position, the center of the photo sphere. In the first case, full body avatars might at least theoretically be an option even though they may not be realizable with mobile hardware. In the second case, a more symbolic approach to indicate who else is currently at the same location and into which direction these persons are currently looking can be expected to be more adequate. Overall, the low-cost goal has a significant impact on which designs are feasible and best suited.

In our work, we are following an iterative design approach [10] that in the future will include formal user studies to evaluate the design decisions made, collect feedback to improve the design, and ultimately derive best practice guidelines for designing joint low-cost site experiences. In our current version of the joint Ishi Wilderness application we focus on points (3) and (4) from the list above. Point (1) can partially be realized by providing name lists for image locations in the overview map view and current location in the 360° scene views. In the 360° views, the cameras of all users are located in the exact same position and only differ in the viewing direction. In addition, there are no further activities possible other than looking around or interacting with the user interface. Therefore, the viewing direction remains as the only relevant piece of information to be visualized. However, we decided to rather start with focusing on the pointing capability (described a bit further below) in this prototype to address point (4). Voice communication is currently not incorporated into the application limiting its usage to scenarios in which the users that share the session are in the same real world location or to settings in which voice communication is provided outside of the app, e.g., using a separate voice communication software running in parallel on the same device.

The joint VR approach in the Ishi app is built on top of Unity's network and multiplayer component and currently uses Unity's multiplayer service for joint session management. But the plan is to replace this service with our own server in the future for scaling up the approach and providing session management specifically tailored to our requirements supporting different site applications. Instances of the app can join a named session with a single button activation. To realize guided tours (point (3) from the previous list), further GUI buttons allow to set the application into 'Lead' mode or into 'Follow' mode. Only one of the connected instances can have the lead at any given moment but that instance can drop the lead so that another instance can take over. Three status lights towards the bottom of the display can be enabled to show whether the app is currently **C**onnected, in **L**ead mode, and/or **F**ollow mode (see Figure 6).

All scene/location changes made by the leading instance (e.g., when using one of the ground arrows to teleport to another image location) will be reflected by all connected instances currently in follow mode. This simple approach is sufficient for allowing one instance to provide all other connected instances with a guided tour through the Ishi experience. While the audio comments are currently disabled in the joint experience to focus on direct communication between the connected partners, the approach can easily be modified to give the guide control over when audio comments should be played for all instances in follow mode.

In Section 3.2, we discussed the need for visually guiding users of the application to what is currently explained in the expert audio comments. The situation in the joint experience is similar in that without knowing into which direction other users are currently looking (and even then), it can be very difficult to figure out what parts of the scene they are referring to in verbal communication [11,16]. Therefore, to address point (4) of providing a means to point at things in the scene, we adapted this visual guidance approach to work with markers that users can freely place in the 360° image based scene. Figure 6 illustrates this approach: The figure on the left shows the view of the instance belonging to the tour guide in lead mode running on a Pixel 2 smartphone. On the right is a view of another connected instance running on an Oculus Go standalone headset. The guide just placed a circle marker on a couple of dead branches on the ground while referring to these in her/his explanations. The same blinking marker appears in the other instance on the right (and all other connected instances in follow mode). Furthermore, if the user of that instance is currently looking into a different direction, flashing arrows will indicate that a marker has been place and into which direction to turn to be able to see it (see Figure 4(c) again).

Figure 6: Joint session with instance on the left running in lead mode, while the instance on the right runs in follow mode. The left instance has just placed a circle marker on the ground that simultaneously appears in the instance on the right with arrows (not shown in the image) providing visual guidance.

5 CONCLUSION & OUTLOOK

The Ishi Wilderness mobile VR application presented in this article illustrates our concept for a low-cost immersive experience that can be used anywhere, anytime, and jointly with anyone around the world. Targeting mobile and other simple xR platforms addresses the aspect of being low-cost in terms of xR hardware involved. To address the second aspect, namely that of content and application creation methods being efficient with regard to costs and efforts involved as well as xR expertise required, our approach is heavily based on 360° photography and SfM 3D model generation techniques. Furthermore, our framework for automatically building and maintaining VR site experience applications from these resources in combination with declarative content specifications and templates significantly streamlines the application development workflow. The described joint VR component enables basic human-human interactions such as guiding and pointing in a virtual site experience, suitable to realize tour guide or classroom scenarios as well as to enable simply a shared experience of a place with a group of friends.

The goal of creating low-cost joint and mobile xR experiences comes with a number of significant design and technical challenges. Design decisions have to be made in the context of several trade-offs constraining the available options. First of all, there is the mentioned trade-off between costs and efforts involved in the different methods for creating content for the application (e.g., 360° imagery vs. full 3D models) and the interaction methods they afford (e.g., no free movement or interaction with objects in a purely 360° based approach). Then there is the trade-off between price, simplicity, and accessibility of the target platform and the kinds of capabilities and interactions that can be realized. Full avatar visualization of other users and free movement, for instance, require tracking capabilities that are typically not available on mobile VR solutions. Interactions such as measuring distances may be possible in a mobile VR setup but available controllers or other input devices will typically allow for implementing such interactions in a much more intuitive and easy-to-use way without a need for a smart interface design. An example of a technical challenge is the comparatively limited memory size we find on mobile devices or platforms such as the Oculus Go, which can be a problem when using a larger number of high-resolution 360° images for an app, for instance.

Given these challenges, evaluating design decisions and continuously improving capabilities and user interfaces of immersive site experiences have to be considered key objectives that need to be addressed. Ultimately, this should lead to design guidelines or best practices for future application development. Hence, one of our major goals for the near future is to run human participant studies with the Ishi Wilderness and similar site experiences. In addition to qualitative feedback, e.g., from user questionnaires, we aim at recording quantitative data related to spatial behavior, memorization and knowledge acquisition, and other performance parameters to gain a better understanding of how different visualization, interaction and navigation options as well as general application and interface designs affect these parameters.

In addition to this evaluation work, there are different additions we are planning to make to our site experiences including (a) in-app voice communication, (b) more advanced visualization and information display for activities of other users in the joint experience, and (c) more sophisticated support for the tour mode in which one user is guiding others through the experience. As we already mentioned, we are also continuously extending the Unity based automatic application building framework to increase its flexibility. We are, furthermore, evaluating different options for providing a visual and intuitive interface (e.g., web based) to this tool and its content description format removing the need to interact with the Unity editor, and for conducting first tests in which people without xR skills create their own VR site experiences supported by this framework.

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