UniteXR: Joint Exploration of a Real-World Museum and its Digital Twin

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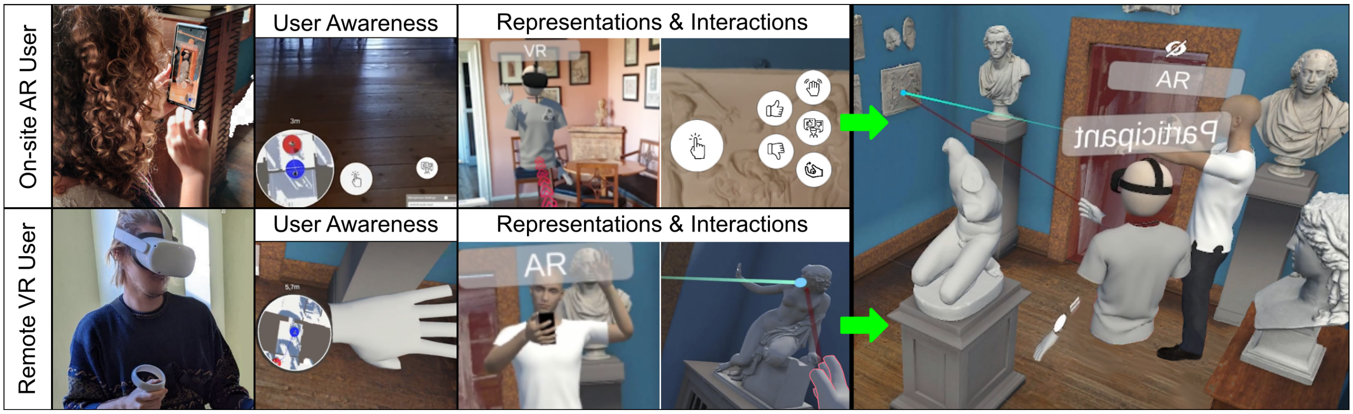

Figure 1: UniteXR allows remote VR users and on-site AR users to co-explore a physical space and its digital twin together.

ABSTRACT

The combination of smartphone Augmented Reality (AR) and Virtual Reality (VR) makes it possible for on-site and remote users to simultaneously explore a physical space and its digital twin through an asymmetric Collaborative Virtual Environment (CVE). In this paper, we investigate two spatial awareness visualizations to enable joint exploration of a space for dyads consisting of a smartphone AR user and a head-mounted display VR user. Our study revealed that both, a mini-map-based method and an egocentric compass method with a path visualization, enabled the on-site visitors to locate and follow a virtual companion reliably and quickly. Furthermore, the embodiment of the AR user by an inverse kinematics avatar allowed the use of natural gestures such as pointing and waving which was preferred over text messages by the participants of our study. In an expert review in a museum and its digital twin we observed an overall high social presence for on-site AR and remote VR visitors and found that the visualizations and the avatar embodiment successfully facilitated their communication and collaboration.

CCS CONCEPTS

• **Human-centered computing** → **Mixed / augmented reality**; **Virtual reality**; **Social navigation**; *Pointing*.

KEYWORDS

mixed reality, smartphone augmented reality, virtual reality, asymmetric exploration, digital twin, cross-device collaboration

ACM Reference Format:
Ephraim Schott, Elhassan Makled, Tony Zoeppig, Sebastian Muehlhaus, Florian Weidner, Wolfgang Broll, and Bernd Froehlich. 2023. UniteXR: Joint Exploration of a Real-World Museum and its Digital Twin. In *29th ACM Symposium on Virtual Reality Software and Technology (VRST 2023), October 09–11, 2023, Christchurch, New Zealand*. ACM, New York, NY, USA, 10 pages. https://doi.org/10.1145/3611659.3615708

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VRST 2023, October 09–11, 2023, Christchurch, New Zealand

ACM ISBN 979-8-4007-0328-7/23/10.
https://doi.org/10.1145/3611659.3615708

1 INTRODUCTION

The digitization of the real-world is happening at an ever-increasing speed and detail. Landscapes, cities, built infrastructure, cultural heritage sites and cultural artifacts among many others are being digitized. While the real world will always have a lot to offer (hopefully), many interesting and beautiful locations are never seen by most people for many reasons, e.g. accessibility, affordability, and time constraints, making it impossible for them to enjoy the exploration of these sights and attractions with their family and friends. However, the availability of digital twins allows VR users to meet real-world visitors at the same location and to explore these registered real and virtual spaces together. So far, research has only addressed the co-exploration of single-room spaces (e.g. [13, 32, 34]) and has not considered the challenges of complex spatial scenarios where VR and AR users are often further away from each other and cannot see each other by just turning around. When using smartphones, the embodiment of the AR user is often limited in expression, as the smartphone is spatially tracked, but the person themselves is usually not.

In this paper, we address these challenges by providing on-site smartphone AR and remote VR users with interactive visualizations that provide awareness of each other's locations and guidance to meet. We also present an approach that employs Inverse Kinematics (IK) to embody the smartphone AR user, so that gesturing and deictic pointing appear more natural to the VR user, increasing social presence. We implemented these methods in our system, UniteXR, which allows a museum to be explored simultaneously by an on-site AR user and a remote VR user. We conducted two user studies to evaluate and demonstrate our system. In a quantitative study we assessed the effectiveness of our awareness visualizations. In a mixed-methods study with museum experts, we gathered insights regarding the user experience and social presence at a real museum and its digital twin.

Our work was motivated by a collaboration with a local museum that was interested in building a more engaging digital presence than just a website with images and videos or an existing Matterport scan [22]. Since accessibility is always an important issue for museums, in particular historic museums, we developed the idea of being able to explore the museum jointly in VR and on-site. Our approach allows people who cannot travel to the museum to join friends and family who are visiting the museum. Our colleagues from the museum also reported that there are often groups of on-site visitors with some members that have difficulties walking through the museum. With our idea, they could enter a VR room at the museum and virtually join the rest of the group, exploring the real museum and enjoying the joint experience despite accessibility challenges. However, a full experience requires social presence, mutual awareness, and efficient verbal but also non-verbal communication. Since the museum is large and has multiple rooms, it can be challenging for users to locate each other as well as to interact with different artifacts in the museum such as pointing at a statue. Also, as museums are rather quiet and discreet places, purely verbal communication is not socially acceptable, requiring possibilities for non-verbal communication for the on-site user.

Our research aimed at addressing these challenges and resulted in the following main contributions:

- An overall design guideline for cross-platform hybrid CVE experiences for smartphone AR and VR users,
- two awareness visualization methods, which allow remote users to find and follow each other,
- indications that both methods are an efficient approach for improving a user's spatial awareness in smartphone AR,
- an accessible method for deictic pointing in hybrid CVEs,
- a XR system that efficiently and effectively supports loose and tight collaboration in a museum scenario, and
- Unity source code for bringing AR and VR users together in an aligned virtual space.

In summary, our system enables AR and VR users to jointly navigate and collaborate in a multi-room environment and its digital twin by embodying the smartphone user as an IK avatar and providing tools to find and follow each other.

2 RELATED WORK

2.1 Asymmetric Collaborative Virtual Environments

As immersive media continues to advance, researchers are exploring how different forms of interaction impact collaboration in CVEs. In particular, asymmetric CVEs, where users have access to different interactions due to heterogeneous device configurations, such as a smartphone AR device and a VR head-mounted display (HMD), are being studied. This is in contrast to "symmetric" CVEs, where multiple users use the same interaction methods [12]. Other terms used to describe asymmetric devices in collaborative settings include cross-platform, heterogeneous cross-device, and mixed reality.

Previous work in CVEs is numerous and diverse, with a focus on health, social, and entertainment applications. Research shows that CVEs improve social presence [6, 46] through user-to-user communication and interactions. Recent years have seen a surge in research utilizing smartphone AR and video streams to connect remote users [19, 29, 43]. However, there are few studies that combine smartphone AR with remote VR, and even less studies involve multiple rooms.

Grandi et al. [13] investigated and compared such an asymmetric CVE scenario (with a handheld AR device and a VR HMD) to a symmetric AR and a symmetric VR scenario in terms of task performance in a virtual object co-manipulation task. Their results show that asymmetric VR-AR collaboration performed significantly better than the AR-AR scenario and slightly worse to the symmetric VR scenario. They conclude that this was mostly due to less mutual assistance between participants in the VR-AR scenario.

As asymmetric setups provide different windows into a virtual world, users might not be aware of another user's attention or actions. Therefore, Piumsomboon et al. [34] suggest the use of different visual awareness cues to enhance user performance, usability and collaboration in asymmetric collaborative setups. In their work they evaluated different visualizations (Field of View (FOV) frustum, eye-gaze ray, and head-gaze ray) and their impact on the communication between a HTC Vive [17] VR user and a Microsoft HoloLens [26] AR user. Although the employed awareness cues improved collaboration in an object placement and identification task, the study setup was limited to only one room. We consider the proposed cues unsuitable for a museum scenario due to the fact that they distract from museum content and do not support finding and joining others across multiple rooms. Furthermore, we opted for handheld AR over AR glasses due to their lower cost and greater accessibility.

2.2 Social Presence in CVEs

Social presence refers to the sense of being present with another person in a technology-mediated communication environment. Short et al. [39] first introduced the term and identified two main components: intimacy and immediacy. Intimacy refers to the connection between users, while immediacy represents the emotional bonding between users, also known as psychological distance. Gunawardena et al. [14] argue that these components can be influenced by verbal and nonverbal cues such as facial expressions, gestures, or appearance. The form of the medium used in communication also affects social presence, with richer mediums leading to a better sense of social presence [9, 39, 44].

Biocca et al. [5] identify three main structures that impact social presence: co-presence, psychological involvement, and behavioral engagement. Co-presence relates to the degree to which users believe they are not alone and their level of awareness of each other. In VR, tracked HMDs and controllers provide verbal and nonverbal cues of the user, creating a sense of togetherness between multiple users within a CVE [46].

The limited FOV of AR devices poses a challenge to user-to-user interaction. Olin et al. [32] conducted a study on heterogeneous cross-device collaboration (HMD VR and mobile touchscreen device) to understand how it affects social roles and user interaction. They found that despite the less immersive medium of the handheld device (their smartphone did not operate in AR mode, unlike ours), the handheld user reported an acceptable level of social presence. Further, Miller et al. [27] investigated the social presence outside the FOV of AR devices, revealing that avatars outside the periphery led to lower social presence scores. This highlights the significance of user-to-user awareness in low-FOV device conditions, including asymmetric CVEs.

Various visualization methods have been explored to improve user-to-user awareness. In general, previous works describe awareness as knowledge that a person acquires by interacting with their environment [10]. Furthermore, multiple concepts for awareness have been explored such as situational awareness and workspace awareness [15, 40]. Gutwin et al. [15] present a descriptive framework for workspace awareness that focuses on three essential aspects: users (who), actions (what), and location (where), all of which are crucial for facilitating effective collaboration.

Osmers et al. [33] proposed different approaches for locating objects in a multi-room AR setup, including a map, X-ray visualization, and compass needle, which were tested with Microsoft HoloLens 1 [26]. They conclude that participants preferred the map and that the proposed visualizations enabled users to locate and identify other users within their environments, covering two of the three aspects of workspace awareness - who and where. To support the third aspect (what), we focus on visualizing and communicating user interactions with other users in a CVE.

2.3 User Interactions in CVEs

Previous work on interactions in Virtual Environments (VEs) often focuses on virtual object manipulation through grabbing and releasing virtual objects [6, 7, 13, 47]. This is mostly due to the design metaphor of virtual hands used by HMD VR. Other forms of interactions or communications are made possible via hand tracking in VR, allowing them to further express themselves and communicate with other users, for example by waving or nodding in agreement.

Deictic pointing is the most basic form of user-to-object or user-to-user interaction and has been a recent focus in VR and CVE research [23, 37]. Piumsomboon et al. [34] successfully allowed HoloLens 1 users to point at virtual objects and share this information with collaborating users in VR. For handheld AR users, Grandi et al. [12] enabled object manipulation through smartphone interactions, including touchscreen-based and movement-based designs. The system was evaluated in a single user and collaborative task, with participants quickly and easily understanding and using the different interaction methods.

Several interaction methods, including gestures like pointing, have been explored for smartphone users [2, 41]. Typically, the phone's camera is used to directly film the user's hand or indirectly assess the user's posture through a mirror. Multiple research approaches propose tracking methods that determine the pose of an AR avatar by inferring the pose of the user via tracking the position and orientation of the phone and using IK [3, 30]. Although using IK for AR avatars does not yet provide rich expressiveness and interaction for the AR user, previous work [20] has proven it to be an acceptable approach for social smartphone AR CVEs.

3 SYSTEM DESIGN

We wanted to design our UniteXR system for a seamless collaborative experience for remote VR and on-site AR users. To ensure similar interaction possibilities for both users in such an asymmetric setup, the following three particular challenges emerged:

1. Bringing both users together in the same room and ensuring a coherent perception of the room and the peer's avatar, so that the users have the impression that they are indeed co-located.
2. The possibility to locate each other when being in different rooms. Here especially the different capabilities of the users such as the fast movement of the VR user have to be taken into account.
3. Support for user-to-user interaction and user-to-world interaction in verbal and nonverbal ways.

The next sections will elaborate UniteXR's design and development decisions with respect to these three challenges. To allow other researchers to build upon our work, we provide a Unity package that enables AR and VR devices to meet in an aligned digital twin at https://github.com/VWDG-TU-Ilmenau/com.vwds.twinalign.

3.1 Challenge 1: Bringing AR and VR Together

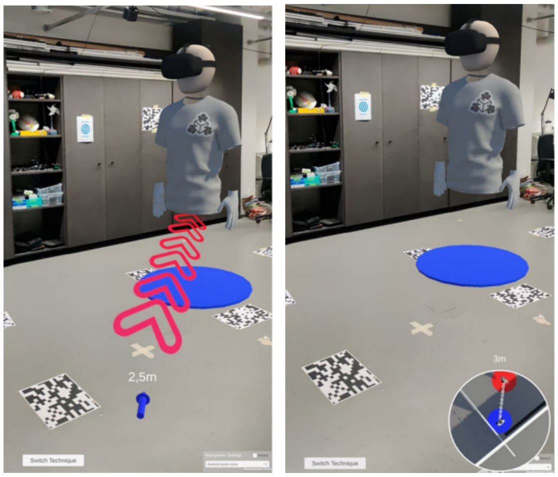
Bringing multiple users together in a CVE follows multiplayer game development logic by syncing avatars' position and orientation across all users' devices. In multi-user VR experiences, syncing is simple because both users share the same local coordinate system origin. In our case, with smartphone AR users, this becomes more challenging. Most AR applications, including UniteXR, use Google's ARCore [11] for Android devices and ARKit [4] for iOS devices. The coordinate system's origin of both frameworks is decided upon application launch as the initial position of the phone; therefore, the origin is different in each session of UniteXR. To resolve this, we integrated Microsoft's Spatial Anchors [25]. Spatial anchors are world-locked frames of reference that allow applications to create and recall coordinate systems at real world locations without the need for traditional markers. We use this technique to define common coordinate systems in the real museum and its digital twin. Prior to running UniteXR, we use AR markers to set the spatial anchors at relevant positions and assign virtual coordinate systems to them. The defined anchors are then stored in the cloud and can be retrieved by UniteXR. As UniteXR runs, it scans the real world for the spatial anchors' features and realigns with the VR coordinate system accordingly allowing for the continuous accurate synchronization of users' positions in the virtual and real world.

While UniteXR is running, tracking could be lost for a short period of time, creating an offset between the virtual and real world. Therefore, multiple spatial anchors were placed around the museum so that UniteXR can re-calibrate if necessary to ensure that the virtual and real world correctly align again.

3.2 Challenge 2: Awareness Visualizations

Similar to previous works [33, 35], we designed and implemented multiple visualization methods for user-to-user awareness. Our requirements for a robust visualization of spatial awareness are that it includes a visual representation, informs about relative position, distance, and path to other users, continuously updates the user's position, is understandable to new users, as well as being accessible to individuals with color blindness. We analyzed various awareness visualization methods including a bar-compass, mini-map, compass-needle, and navigation path. We found that most of the visualization methods do not fulfill all our requirements individually. Thus, we combined different awareness visualizations, hereby focusing on two perspectives that are as different as possible; an egocentric perspective, and an exocentric perspective. For the egocentric perspective, we combined a compass needle and a navigation path. For the exocentric perspective, we combined the mini-map with the navigation path.

3.2.1 Needle-Path Visualization. As displayed in Figure 2a, the compass needle (blue arrow at the bottom of the screen) provides information about another user's relative position and direct distance. Therefore, an arrow is rendered that points to the VR user's head. The distance is provided by a text field above the arrow as well as the length of the arrow. In addition to the compass needle and the text field, a navigation path visualizes the path to the VR user as well as the path length, using a color coding. Here we use blue to indicate long distances and red for short distances. Those colors where chosen, to also allow users with different forms of color blindness to interpret the visualization. The decision to use the compass needle was due to the limitation of the bar compass and other compass methods in providing precise information about the relative position regardless of the smartphone's orientation without being subject to axis mismatch.



(a) Needle-path points to VR user **(b) Mini-map showing VR user**

Figure 2: Awareness visualization methods as displayed for the smartphone AR user.

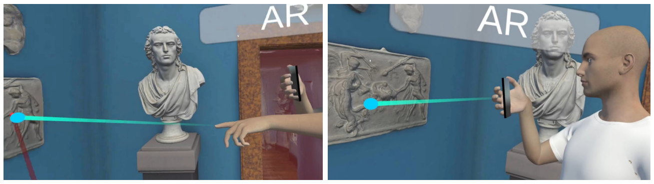
3.2.2 Mini-map Visualization. We chose a mini-map since it provides an exocentric view. The mini-map shows the AR user as a blue circle in its center from a top-down perspective, with the north-direction corresponding to the user's line of sight. The other user is highlighted by a red circle. The map's zoom level is dynamically adapted to keep the other user in sight, with a minimum radius of 3 meters to always provide an overview of the AR user's social proxemic zone [16] and a maximum radius of 20 meters. The current radius is displayed above the map. If the VR user is farther away, we display an indicator in the form of an arrow at the edge of the mini-map, showing the direction. To highlight the path between the two users, the map also displays a navigation path. The path shows the shortest path between the users as seen in Figure 2b.

3.3 Challenge 3: AR Avatar Interaction

Smartphone AR users have an interaction disadvantage due to the FOV of the smartphone's camera limiting their view of the virtual world. In social scenarios like museums, their interactions with the CVE are typically also limited to their smartphone's touchscreen, as tracked gestures in front of their phone's camera might be awkward or offensive towards other visitors. In comparison, VR users usually have a tracked HMD and two controllers that not only allow them to interact with and see the VE, but also to express themselves to other users (e.g., via hand gestures, head tracking, and potentially even eye- and face tracking). The AR user does not have this freedom of expression as they are only being tracked through their smartphones. We use ARIKA (AR IK Avatar) [20] to position the AR user's avatar in space. ARIKA uses the tracked pose of the phone from ARCore [11] as a target for the avatar's right hand to compute the IK. We derive the direction and velocity of the phone to animate the avatar by blending between different animations. To support gesturing by the AR user we further extended ARIKA with animations from Mixamo.com [28] which can be easily controlled through buttons. Figure 3 shows two of the gestures, an AR user can use during a collaborative experience to communicate with the VR user. Here, we implemented animations for waving, gesturing ok, and pointing with a ray emerging from the smartphone or from a simulated finger. Note that the finger-based raycasting is an animation and does not require hand tracking.

Since the situations in which the AR user gets to see their own avatar are limited, we employ the AR avatar mainly to reinforce the VR user's sense of social presence. Research in avatar representations in VR suggests the possibility of avatars becoming uncanny as the avatars become more human-like or realistic in representation or behaviour [38]. For that, we enable the VR user to switch between a gesture based communication or text-based communication as seen in Figure 3.

(a) Waving



(b) Pointing

Figure 3: Visualizations of a gesturing AR user as perceived by a VR user. (a) shows animated and text-based *Wave* gesture (b) shows two methods of pointing.

4 CONTROLLED USER STUDY

The overarching goal of this work is to enable AR and VR users to collaborate seamlessly and equally in asymmetric CVEs. Since the AR user is the more constrained one due to the smaller field of view, we focused on investigating the performance of the awareness visualizations in the AR context. The described visualizations of this work act as an indoor navigation system. To our knowledge, AR indoor navigation systems have not been evaluated for moving and teleporting targets, like a virtual peer. Our egocentric (needle-path) and exocentric (mini-map) approaches differ in their presentation of spatial cues and the size of screen space required. Both factors might affect the AR user's ability to quickly find and follow a virtual peer. Therefore, we conducted a controlled single user study to compare our awareness visualizations in three distinct tasks. We were interested in the initial time that it takes a user to find a virtual peer and the ease of following a constantly moving or a jumping peer between two rooms.

Figure 4: Image of the study room with the markers placed to act as feature points to improve ARCore's tracking.

Figure 5: Particle trail that follows the jumping user to new location.

4.1 Experimental Setup

We divided an approximately 12m x 6m room into two squared spaces that were separated by a curtain (Figure 4). A 1.5m wide opening in the curtain on one side of the wall functioned as a passage between the rooms. This simulates a two-room setup as one would find it in, for example, a museum. Our mobile ARCore-based application contained a 3d model of the space to enable for occlusion of the virtual user. The Azure spatial anchor for our AR origin was set in the passage between the rooms. Additional visual features (QR markers) were attached to the floor, walls, and curtains, to ensure a stable tracking. This is mostly because the floors in our lab had no texture and therefore ARCore had difficulties tracking the area. All trials were started in a starting area in front of a cupboard, so that the user could not initially see the simulated VR user. The simulated VR user was represented by a 1.75 m tall virtual human consisting of a head with an HMD, a T-shirt, and hands.

4.2 Tasks and Conditions

The aim of our study was to investigate which of our awareness visualisations makes it easier for an AR user to find and follow a virtual user through several rooms. To explore this question in more detail, we distinguished between *finding* and *following* tasks and designed two sub-tasks for the latter. *Finding* is about how fast a participant can get a spatial understanding of the other user's position and is always the first step. *Following* is the second step because the position of the other user has to be known in order to catch up with them. However, depending on how fast the preceding user is moving, they may have to be found several times during the following process. Since the *finding* task does not require the AR user to move, it is easier to quantify and replicate the *finding* experiment than the *following* task. Therefore, the performance measures for the first task is quantitative and those for the latter two are qualitative. All tasks were conducted with the exocentric mini-map and with the egocentric compass needle with navigation path visualization. We will refer to them as *mini-map* and *needle-path* condition in this section.

4.2.1 Finding Task. In order to evaluate how both visualizations supported the user's spatial understanding of the other user's position we decided to create a local rotation task.

The goal of the local rotation task was to find out how long it takes a user to find and turn towards a peer that appears behind them. In this task, the user was standing in the starting area and had to face the cupboard. Each trial was initiated by pressing a "start" button on the mobile device. In each trial, a simulated user was randomly placed on one out of seven different locations (-90°, -120°, -150°, +/-180°, 150°, 120°, 90°) behind the subject and the respective awareness visualization indicated the spawned user's position. It was the user's task to turn in the direction of the virtual user and get him or her in the center of his field of view. A green check mark indicated the user when a trial was completed. The task completion time was measured from the start of the trial until the virtual peer was centered.

4.2.2 Follow-up Task. Our follow-up task focused on gathering qualitative insights by looking at more realistic scenarios. Steering locomotion and jumping are the most common navigation techniques for VR users. Their implications can sometimes have a strong impact on the VR user, in particular steering techniques can often cause cybersickness [8]. The VR user's navigation technique determines whether the AR user perceives their counterpart's movement as continued (steering) or discontinued (jumping). To investigate the effect of both techniques on the AR user, we developed a separate follow-up task for each technique. As a scenario, we assume that after a period of loose collaboration, the AR user revisits his virtual peer and joins in their activities until they part ways again.

Both, the steering as well as the jumping follow-up task, started in the starting area. In each trial, one of the two awareness techniques were displayed and a simulated VR user was placed in the study environment. Each trial was activated by touching a "start" button on the mobile device and considered as completed once the AR user was standing within a 1.5 m radius of the virtual user's final location. After completion, participants were instructed to move back to the start area before activating the next trail.

In the steering follow-up task, the participant had to find and follow a simulated user moving between five hidden control points in two rooms at a constant speed (1m/s). The simulated stayed at each control point for 1 second before moving on to the next one. Since distractions and focus shifts are very likely to happen in a real museum, we added a distractor to the steering task. Whenever the AR user had the virtual user in view for three seconds, the smartphone's screen went black. To unlock the screen, the user had to read a number from a screen in the room which forced them to shift their attention.

In the jumping follow-up task, a simulated user teleported to hidden control points. After each jump, the simulated peer remained at its location for 3 seconds. To avoid repeating patterns we prepared nine different paths that consisted of five control points, each of which included a room change. No distractions were used in this task as it was already difficult to keep track of the jumping user. To make the jumps of the simulated user more comprehensible, a particle trail followed it to the new location (see Figure 5).

4.3 Participants

The experiment was conducted with 20 participants (7 females, 13 males, 22-32 years, Mean (M)=25.65, Standard Deviation (σ =2.70). Two participants stated to be very familiar with AR; seven were just familiar; five had some experience and six reported having only single experiences to none. The participants were compensated with 10 Euro for their participation.

4.4 Procedure

The design of the study followed a within-subject design with the two visualization conditions: needle-path and mini-map. The order of conditions was counterbalanced to prevent order effects. However, the order of our tasks remained the same since the tasks build on each other and become more difficult.

In both conditions, participants had to perform 21 (three times each angle) local rotation trials, five steering follow-up trials, and nine jumping follow-up trials. In a short warm-up session before each task, our users had the chance to get familiar with their task.

4.5 Measures

The task completion time (tct), position of the virtual peer as well as the direction in which the participants turned was recorded for the first task (finding with local rotation). In the second and third task, we measured tct and had the user's fill in a questionnaire about both visualizations (follow-up task with steering and jumping). As users followed the simulated peers differently and moved at different speeds, we later excluded the tct measurement from the follow-up tasks. In all tasks, we recorded the position and orientation of the user and their peer. In the end, the participants answered a system usability scale (SUS) questionnaire.

In addition to that, we asked participants after each task to indicate their preferred condition and to rate their confidence in following the simulated user on a Likert-Scale from 1 to 5. We also gave them the opportunity to tell us what they liked and disliked.

4.6 Controlled User Study Results

Each condition of the local rotation task resulted in 21 trials per user. Overall, 840 trials were performed in the first task. We excluded 17 (10 mini-map, 7 needle-path) trials whose tct and pose recordings indicated a violation of the experimental procedure or could be attributed to technical problems such as calibration. 13 of the removed outliers exceeded the mean (M) plus three times standard deviation (σ) of the respective condition.

When a target appears behind a user, they can turn either clockwise or counterclockwise to reach it. Except for 180°, one turn is always shorter than the other (e.g. short 90° and long 270°). We labeled each user rotation with *"short"* or *"long"* based on whether the user reached the target by turning the shorter way or not.

Out of 823 trials, 47 were marked as "long" rotations (29 for needle-path and 18 for mini-map), which corresponds to 7.02% of the needle-path rotations and 4.39% of the mini-map rotations. After labeling the user's turn direction, we analyzed the search time per awareness visualization method. On average, it took participants M = 2.28s (σ = 0.71s) to find the simulated user. A Kolmogorov–Smirnov test [21] showed that our data was not normally distributed. We therefore applied the Wilcoxon signed-rank test [45] which showed that there was no significant difference (α = 0.05, p = 0.81) in search time between the needle-path visualization and the mini-map visualization with M = 2.32s (σ = 0.75s) and M = 2.25s (σ = 0.70s) for needle-path and mini-map respectively. This means that the users' search time for the virtual companion was comparable between both visualizations. However, users were more likely to make a "long" turn with the needle-path condition. To further evaluate the search time, we grouped our data based on the absolute value of the actual rotated angle of the users as shown in Figure 6. The results show that search time increases the farther a user has to turn. While this was to be expected, it is also obvious that turning the "long" direction is less efficient.

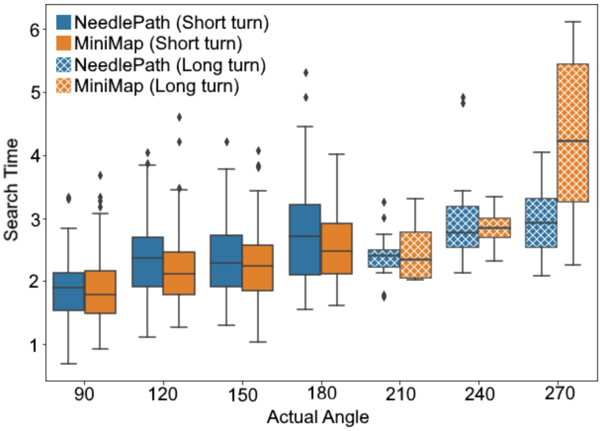


Figure 6: Search Time in [s] per actual turn angle for both awareness visualization methods.

4.7 Controlled User Study Discussion

The results of the controlled user study indicate that the needle-path and the mini-map, enabled the participants to locate the virtual companion reliably and with high confidence in the finding task.

In the follow-up task with a steering VR user, preferences for both visualizations were evenly distributed at 50%. The confidence in following the steering user was very high with M = 4.6 (σ = 0.48). Similarly, in the follow-up task with a jumping user, 55% preferred the mini-map and 45% preferred the needle-path. The confidence score for following the jumping user was slightly lower with M = 4.25 (σ = 0.69), supporting our assumption that it is easier to follow a continuously moving user.

Interestingly, 25% of the participants switched their preferred visualization between the two follow-up tasks. This could indicate that each visualization has its dedicated use case or that personal preferences and individual differences (e.g., different mental models [18]) influence the choice of visualization. Another possibilty is that some users initially found one awareness visualizations easier to understand but changed their preference after learning how to use the other representation.

In terms of positive user feedback, it is worth noting that both visualizations were favored for different reasons. The needle path visualization was appreciated for its clear directional guidance (Comment Occurrence (CO) = 10), ease of following and locating the user (CO = 5), easy-to-read distance (CO = 3), visual representation (CO = 2), and integration with AR (CO = 1). Participant (P) 9 commented, "It is easy to determine the direction and distance of the target without having to turn my attention away from the main view". The color-coded arrow as well as the distance indication were rated positively, and users indicated that the visualization was especially helpful when the companion was farther away.

In contrast, the mini-map received positive feedback for its overview and spatial representation: easy to locate the jumping user (CO = 6), ease of use and clarity (CO = 3), provides overview (CO = 3), distance and path information (CO = 3), visibility of the physical relation between the both users (CO = 1). P3 stated that "the VR user [being] visible in the minimap made it easy to find them, and the radius indication was very helpful." Similarly, P14 said "I knew where and how far the user was, by looking at the map. The familiarity with minimaps from games helped me use this technique much faster and better, and there was less confusion as to where I should turn."

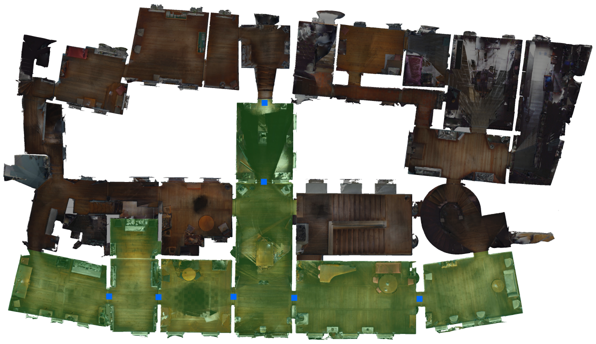
Based on the user comments, it appears that although there was no clear preference for one visualization, the mini-map was associated with fewer problems. When asked what users disliked about the visualizations, 11 out of 20 users answered "nothing" for the mini-map, while only three out of 20 had no issues with the needle-path visualization. The needle-path technique was criticized for its inaccuracies (CO = 6), difficulty in orientation at short distances (CO = 4), and the overloaded visual representation with two arrows (CO = 3). One participant stated, "the picture seems overloaded."

The evaluation of the SUS resulted in an average score of 79.5 with an σ = 13.97 for the needle-path combination and M = 83.13 (σ = 18.3) for the mini-map. The median scores are slightly higher with 82.5 and 90, respectively. A score above 68 can be considered above average [1]. Thus, we assume a good to very good usability for both visualizations.

5 MUSEUM EXPERT REVIEW

In collaboration with a cultural foundation, we set up UniteXR in a local museum and invited eight domain experts (6 females, 1 male, 1 "prefer not to say"; 18-45 years, M = 30, σ = 10.63) to perform a free roaming and a structured collaboration task. The museum has hundreds of visitors every day. To ensure controlled conditions, we conducted the study on closed days, and used experts from the museum who have an understanding of how the UniteXR experience should reflect the real museum experience. All experts have a social science background and oversee the historical reappraisal and curation of the museum. As suggested by Nielsen et al. [31], a small number of testers, such as domain experts, can effectively identify a majority of usability problems [42]. Except for one, the experts had almost no experience with AR and VR technology, thus the experts operated the system just like a regular visitor would. The available museum space included seven rooms of different sizes and different lighting conditions. Spatial Anchors were registered at all doors to allow for a recalibration as users changed rooms.

(a) Navigation Marker (b) Pointing Marker



(c) Floor plan of the museum. The rooms used for the study are highlighted in green. The spatial anchor's positions are shown in blue.

Figure 7: The pointing and visualization markers for the museum experts review task for the smartphone AR user.

After welcoming the participants and providing them with a consent form and an introduction, we divided them into dyads. In each pair, we randomly assigned the users to the on-site AR or the remote VR role. We explained the assigned roles to each participant and guided them on how to use the device and the application's features. The AR user was given a mobile device with the running application and received instructions on utilizing the awareness features, gesturing to other users, and pointing at objects in the AR space. Additionally, the AR user was instructed to demonstrate all gestures twice to the VR user, who observed them both in text and animation modes. On the other hand, the VR user was provided with an Oculus Quest 2 [24] HMD. They were guided on how to navigate within the virtual environment, switch between text-based and animation-based representations of AR gestures, and how to use the mini-map displayed on their arm. Both users could talk to each other through an audio connection. The visualizations of the AR user and the gesture representation of the VR user could be toggled throughout the whole experiment.

Once both participants were familiar with their device, they were given five to seven minutes to freely explore the museum on their own behalf without following specific tasks. This task aimed at simulating a real museum visit while also allowing users to get more familiar with their devices. After the free roaming was completed, the study could be started via a button in the application. Since we were interested in the awareness and social presence that UniteXR provides, we chose an experiment design that consisted of loose and tight collaboration phases and resembled a regular museum visit as close as possible.

Table 1: Initial impressions of the User Experience Questionnaire, filled in by the experts (mean values, min = 1, max = 5)

Impression Scale	VR	AR
Obstructive - Supportive	M=4.17(σ =1.17)	M=3.83(σ =0.75)
Complicate - Easy	M=4.50(σ =0.84)	M=4.33(σ =0.82)
Inefficient - Efficient	M=4.17(σ =0.41)	M=4.50(σ =0.55)
Confusing - Clear	M=4.17(σ =0.75)	M=4.50(σ =0.84)
Boring - Exciting	M=4.83(σ =0.41)	M=4.33(σ =0.84)
Not interesting - Interesting	M=4.83(σ =0.41)	M=4.50(σ =0.55)
Conventional - Inventive	M=4.50(σ =0.55)	M=4.67(σ =0.52)
Usual - Leading edge	M=3.83(σ =0.75)	M=4.17(σ =0.41)

In turns, users had to first meet at a certain point that was only shown to one user via a navigation maker (cf. 7a) and then point together at an object in their vicinity, highlighted via another marker (cf. 7b). Here, the person seeing the point was the navigator. After an accomplished meet-and-point-task, the navigator role changed, and a new navigation marker was shown to the other user. After both users had completed the meet-and-point-tasks, they were given individual navigation tasks to different rooms. Subsequently, in the next meet-and-point task, we were able to observe how users navigate and reunite with each other. In total, a complete run stretched across seven rooms of the museum (see Figure 7c) and consisted of twelve meet-and-greet tasks and five individual navigation tasks. After each run, AR users were asked which visualization they preferred while the VR users were asked which gesture and pointing mode they favored. Furthermore, all users rated how well they could follow and find their peer and how aware they were of their peer's position on a 5-point Likert-type scale. At last a Networked Minds Social Presence Inventory [5] and a short user experience questionnaire (UEQ-S) [36] were answered by the users before they switched roles.

5.1 Expert Review Results

Even though results from these questionnaires were not evaluated statistically due to the small sample size, they provide us with an initial impression with regards to usability and social presence. We used a total of 8 questions from the UEQ-S. Table 1 shows the results (the higher the better), with all values being above 3 (the neutral value). For the social presence questionnaire, both groups scored an overall high social presence score. Surprisingly however, AR users had a higher score with $M = 4.19$ ($\sigma = 0.45$) than VR users with $M = 3.96$ ($\sigma = 0.59$). Due to the few data points, the reason for the lower score for VR users is unknown. We speculate that it might be related to the stereotypical looks or the simple behaviour of the IK avatars.

5.2 Expert Review Discussion

We discuss our results from our qualitative interview and survey from our expert review session.

5.2.1 VR Feedback. When asked about the pointing gestures, six VR participants preferred the gesture-based pointing and described it as "more comprehensible" (CO = 3), "realistic" (Comment Occurrence (CO) = 2) and "personal" (CO = 1). Five participants preferred the gesture-based communication for similar reasons: they perceived it as "more realistic and natural" (CO = 2), "more personal"

(CO = 1) and "clearer message" (CO = 1). However, P5 stated that "for understanding it helps to turn on the text (at least at the beginning once)". On a 5-point Likert scale five experts reported a very good ability to follow, and six experts reported a very good ability to find the AR user, which indicates that the VR user had a good spatial awareness of their AR peer. This confirms our observations that VR users used the provided mini-map when their peer was out of sight. When asked about the overall experience, VR users felt a sense of connection with the AR user and mentioned that the experience seemed surprisingly real and pleasant. However, they did not feel comfortable when they were too close to the AR user, which is to be expected as this violates established proxemics.

5.2.2 AR Feedback. Similar to the follow-up study, no clear favorite emerged among the visualizations in the expert evaluation. On the one hand, the participants that preferred the mini-map visualization stated that they liked seeing an overview of the other rooms around them (CO = 2) and preferenced less clutter on the screen (CO = 1). On the other hand, users who preferred the needle path indicated that it was easier to follow remote users with the help of the arrow (CO = 2). In terms of spatial awareness, the participants reported being able to track and locate the VR user, even when they jumped to different rooms. Among the experts, four noted a very good ability to follow, and five reported a very good ability to find the VR user. Furthermore, the AR users also stated that they could easily show each other objects with the pointing gestures. When asked what they liked about the application, two experts emphasized that the app provided them a "new way to explore a familiar museum".

5.2.3 Further Anecdotal Observations. The free roaming phase showed that UniteXR could even be used internally at the museum, as one VR participant used the time and far exceeded it to explain a new exhibit concept to their AR peer. The schedule of the next participant group had to be adjusted for this reason. Another memorable moment occurred with a VR participant with no prior VR experience who wanted to walk straight to their AR peer after they beckoned them with gestures. Altogether all the participants seemed to enjoy getting a new perspective of their museum with one user stating verbally that he "could do this all day long".

6 DESIGN GUIDELINES

Based on the results and observations of this work, we derived basic design guidelines for developers of hybrid co-exploration experiences of larger spaces with more than one room.

1. *Alignment and coherence:* An accurate alignment of the digital twin and the real world is crucial. We suggest to use at least spatial anchors at the doors between rooms to compensate for drift and tracking loss. Moreover, since the alignment is the central factor for a coherent experience for VR and AR user and their actions, it is essential to provide feedback to the user about the accuracy of the alignment. We found displaying door sills in our app helpful to convey disparities in the coherence.
2. *Supporting awareness:* When collaborating in spaces with several rooms, it is important to show both relative direction and direct paths to users in the awareness visualization.
3. *Expressive embodiment:* To improve collaboration in hybrid experiences, users must see each other and be capable of expressing similar actions regardless of their device. Moreover, we believe that enabling natural expression through avatars in the form of gestures further increases social presence.

7 CONCLUSION AND FUTURE WORK

Our UniteXR system fosters enjoyable social experiences between on-site and remote visitors of a museum and its registered digital twin. Through the use of AR and VR technologies, users can collaborate with each other across multiple rooms and easily find back to each other after periods of loose collaboration. The two awareness visualizations, the mini-map and the needle-path visualization, helped for reliably and quickly locating and following a companion, both in our follow-up task as well as in a real multi-room museum scenario. The use of an IK avatar to display gestures such as waving and nodding was reported as natural and more comprehensible, and it was preferred over text messages.

We found that pointing was the most commonly used gesture for referring to objects, even though verbal communication was possible in our scenario. Our expert review provided typical indications of social presence of both the VR and on-site AR users, indicating that the awareness visualizations and the embodiment of the AR user as an IK avatar were successful in enabling communication and collaboration between on-site and remote visitors.

While our initial study provided promising results with respect to the proposed awareness techniques for AR users, a more comprehensive evaluation of UniteXR in a public museum is an important next step. Key aspects in such a study would be the evaluation of other awareness visualizations than the mini-map for VR users and the assessment of co-presence and social presence between multiple remote and on-site users to judge the effectiveness of establishing and maintaining their connection. While the accuracy of the spatial alignment between the museum and its digital twin did not pose any problem in our studies, it may be a challenge in a populated museum which needs to be quantified and addressed.

Even though our system did only consider dyads, our positive experiences motivated us to continue our development towards techniques and practices for larger groups of on-site and remote visitors. The scaling to such scenarios comes along with a number of research challenges such as the use of smartphones and stable tracking in a crowded room, finding and collecting group members or squeezing a large number of virtual visitors in a small room without significantly violating proxemics. This is an exciting area of research, as museums have an educational mission and therefore must remain attractive to a broad audience in the coming Metaverse era. A connected real-world and three-dimensional online presence are first steps in becoming an attractive node in the envisioned interoperable network of real-time rendered 3D virtual worlds.

ACKNOWLEDGMENTS

Our research received funding from the German Federal Ministry of Education and Research (BMBF) under the grants 16SV8716 and 16SV8922 as well as the Thuringian Ministry for Economic Affairs, Science, and Digital Society under grant 5575/10-5.

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