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Cross-Reality Interaction and Collaboration in Museums, Education, and Rehabilitation

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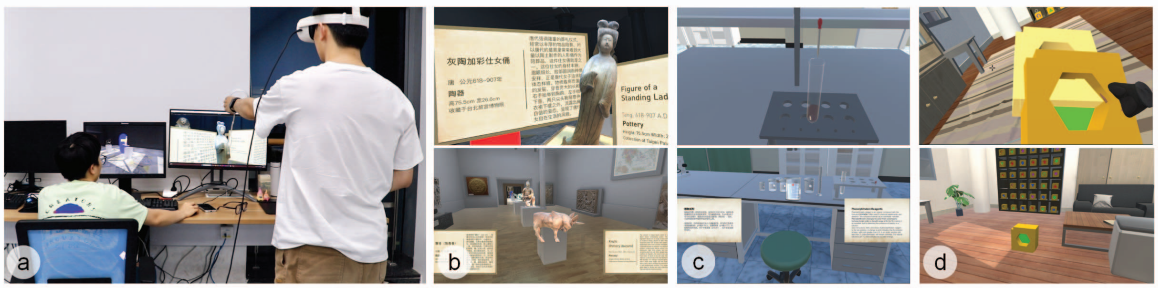

Figure 1: Demonstration of cross-reality collaboration between (a) a VR user and a PC user in (b) museum visiting, (c) chemistry education, and (d) assisted rehabilitation. The top ones are the VR views and the bottom ones are the desktop views.

Abstract

With Virtual Reality Head-Mounted Displays (VR HMDs) establishing themselves as a potent platform for collaborative tasks, their cross-reality capability and cross-domain applicability remain largely unexplored. This study intends to assess the effectiveness of cross-reality collaboration systems using a VR HMD and a desktop PC across three disparate sectors: museum visiting, chemical education, and assisted rehabilitation. The systems were designed to support social interactions and scenario-specific collaborative tasks. Evaluation of the systems showed above-average system usability and user experience. By probing into these varied environments, our study offers a comprehensive understanding of the applicability of such collaborative cross-reality systems in real scenarios, potentially fostering more immersive, efficient, and enriching multi-field applications of cross-reality technologies.

Keywords: virtual reality, museums, education, rehabilitation

Index Terms: Human-centered computing - Human computer interaction (HCI) - Interaction paradigms - Virtual reality

1 Introduction

In recent years, Virtual Reality (VR) technology has been well used in various fields. In particular, VR Head-Mounted Displays (HMDs) have become increasingly popular as a promising platform for collaborative tasks. This immersive technology is changing the way we interact, learn and work, providing opportunities to blend the virtual and physical reality. However, the exploration of VR HMDs in cross-reality and cross-domain applications is still in its nascent stages. In particular, asymmetric collaboration supports users to interact with different devices in the same virtual environment, which greatly reduces the cost of usage and constitutes an important direction for further exploration in VR.

In this project, we propose a cross-reality collaborative system design that connects users in reality and virtuality. Specifically, we implemented three cross-reality systems for three real-world scenarios: museum visiting, chemistry education, and assisted rehabilitation. Users are allowed to use either a VR HMD or a desktop to engage in the cross-reality interaction and collaboration. For **museum visiting**, we designed a virtual museum scene populated with 3D models of cultural artifacts. Users could co-visit the museum, learn about cultural artifacts, and discuss their visiting experience. For **chemistry education**, we simulate a virtual chemistry lab for a student to practice the experiments in VR, and an instructor to prepare for the experiment and provide guidance. Realistic operations and experimental phenomena were simulated to aid the practice-led learning and mitigate potential risks in chemistry education. For **assisted rehabilitation**, the PC user assists the VR user in the rehabilitation training. The VR user performs upper-body rehabilitation training by completing 3D manipulation tasks defined by the PC user. The tasks engage users in arm and hand movements, contributing to their physicality recovery. The design of the three environments has taken into account of the social nature of real-world scenarios, as well as the characteristics of different roles, devices, and tasks.

In this work, we demonstrates the necessity and benefits of cross-reality systems based on the analysis of three real-world scenarios: museum, education, and rehabilitation. Our design and evaluation contribute to the field of knowledge. First, we verified the versatile use of VR HMD together with an easy-to-access desktop device. Second, we demonstrated the applicability of cross-reality systems across various domains, with satisfying system usability and user experience. Third, we showed that cross-reality systems exhibit strong social capabilities in multiuser scenarios, overcoming the limitations of single-user VR experiences for widespread use in real-world scenarios.

2 Analysis of the Real-World Scenarios

Cross-reality interaction and collaboration in VR has become an important research direction. Early work [21] has implicated the significant role of users around the VR HMD user as part of the coherent experience. Recent research has investigated the use of VR HMDs in collaboration with other interactive devices. Examples include collaborative learning based on VR HMDs and tablets [7], comparisons of object selection and manipulation using VR, PC, and tablet [26], and using VR social platforms to enable remote, synchro-

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nized, and collaborative VR experiments [22]. The results of these studies demonstrated the potential of cross-reality systems in supporting social interactions and facilitating effective collaborations. Here, we focus on three specific real-world scenarios.

2.1 Museum Visiting

VR offers new opportunities for museums to improve the accessibility of artifacts and exhibitions and to provide a better user experience for visitors [12, 15, 17]. An important goal of VR museums is to preserve the social aspect of the real museum experience, including exhibitions visits by groups, families and friends [18]. Many visitors to museums are primarily interested in "having an enjoyable social experience" [20]. Ch'ng et al. [6] showed that the VR museums could enhance the communication of cultural heritage, and improve the interactive experience of museum learning for the younger generation. However, user characteristics, such as gender and motion sickness susceptibility [10], were found to be related with VR sickness, meaning that VR experience may not be the optimal choice for all. Cross-reality systems could further improve the experience of museum visiting by allowing multiple users to interact and communicate in a shared virtual space. It was demonstrated that multi-user interactive exhibitions will foster social engagement and collaboration [2]. Previous work also showed that users in reality using mobile AR perceived a greater social presence than users in VR during a shared experience [16], demonstrating the effect of device on user experience. In addition, many studies have experimented with the possibility of using different devices to access VR museums, such as using smartphones to create virtual tour experiences [11, 24, 25]. Despite the benefits of immersive displays, budget considerations limit museums' choice of technology [3] and the use of devices is relevant to the accessibility of the developed content and experience.

We summarize that 1) single-user experience of VR can limit the ability of users to engage in social interactions, whereas cross-reality systems that allow multiple users to interact and communicate in a shared virtual space provide new solutions to this challenge; 2) given different user characteristics, the inclusion of other display methods aside from VR is expected in a social experience; 3) cross-reality systems that support access from a variety of devices reduce the need for expensive hardware investments and increase the accessibility of virtual museum tours.

2.2 Chemistry Education

Simulations play an essential role in education as they constitute a safe environment for students and support them in repeating processes to gain better hands-on experience [8]. Oluwatoyin et al. [1] proposed a VR system for titration experiments in a chemistry laboratory. They stated it is an effective solution that can replace a realistic laboratory in case of insufficient reagents and equipment. According to the results, this system helped students understand the acid-base titration process and improved their learning experience. Georgiou et al. [8] demonstrated the value of VR laboratories in distance education in institutions without a suitable infrastructure. In Herga et al.'s [9] study for the application of virtual laboratory in primary school chemistry, they demonstrated that virtual laboratory promotes effective learning of chemistry with dynamic visualization. However, these studies did not consider the role of instructors in education, although teacher guidance is indispensable in learning and teaching. The cross-reality system is able to provide different tasks for different identities, assisting the teacher to provide instructions while ensuring that the students perform the simulation in a safe environment.

Analysis of the education scenarios showed that 1) previous VR education systems mainly focused on students' active learning, but instructive learning and the role of teachers were not well supported; 2) there is opportunity for design of cross-reality collaborations for education based on the different user roles (student and teacher) and tasks (experimentation and instruction).

2.3 Assisted Rehabilitation

In recent years, numerous VR applications have been explored in the field of rehabilitation. Previous work have shown that VR training systems combined with desktop computer applications have been used as an adjunct to traditional rehabilitation [19]. Broeren et al. [4] designed VR haptic games to support user interaction with 3D objects via haptic devices. They placed this system in a non-hospital setting to assess and enhance users' upper extremity motor performance. The results demonstrated the benefits of VR gaming for patient rehabilitation and are applicable to older adults. Kandalaft and Didehbani [13] designed VR social cognitive training for adolescents with autism spectrum disorders. Through the review of the literature, we found that rehabilitation often requires assistance from a therapist or a facilitator. For example, Broeren et al. [4] used Skype with a webcam as a communication tool to provide clinical and technical support to patients remotely. For Kandalaft's experiment [13], the therapist acted as a coach in a VR system that prompted participants to interact with specific locations and people.

Within the rehabilitation scenario, we found that 1) there is a growing trend for rehabilitation to be conducted in non-hospital settings; 2) therapists and facilitators should be involved in the rehabilitation training to provide verbal guidance and assign tasks.

2.4 Summary of Findings

Based on the above analysis of three real-world scenarios, we summarize the following findings:

1. **Social nature of real-world scenarios.** The real-world scenarios (museums, education, rehabilitation) often contain multiple people. The single-user experience of VR limits the user's ability to engage in social interactions, whereas cross-reality systems offer a solution to this challenge. The supported social aspects enhance teamwork, remote collaboration, and communication in real-world scenarios.

2. **User characteristics.** Cross-reality systems cater to diverse user characteristics, such as motion sickness susceptibility, making technology more accessible and inclusive. Users are allowed to freely choose their preferred interface and engage with the technology comfortably, enhancing their participation and overall experience in various real-world applications.

3. **Device characteristics.** Cross-reality systems are adaptable to a wide range of devices, from high-end VR headsets to everyday smartphones. This versatility enables users to access cross-reality experiences with devices they already own, reducing the need for expensive hardware investments. Consequently, the cross-reality systems will become more accessible to the masses, making it applicable to various real-world scenarios.

4. **Task characteristics.** Cross-reality systems enhance and optimize various real-world tasks by providing immersive, interactive, and social experiences. For instance, cross-reality systems can simulate complex scenarios, allowing learners to practice hands-on skills in safe environments and patients to perform various training tasks. In the meantime, the educators and therapists could ensure the safety of students and patients in real environments while providing guidance and instructions, leading to more efficient workflows and better outcomes.

3 Cross-Reality System Design and Development

3.1 Apparatus and Network Development

The virtual environments and network synchronization were developed in Unity (version 2021.3.6f1c1). The VR system was deployed on a computer equipped with an Intel Core i7-12700K CPU, 32GB RAM, and an NVIDIA GeForce RTX 3080 GPU. The same computer was used for the PC system, along with a 24 inch full HD display. The Meta Quest 2 VR HMD with two hand-held controllers was used as the VR display and input device, with a resolution of 1832 x 1920 pixels per eye and a refresh rate of 72Hz.

3.2 Virtual Museum

3.2.1 Environment and Tasks

The museum scenario allowed both HMD and non-HMD users to jointly visit a virtual museum displaying cultural artifacts. Users could interact with the artifacts, with associated information being displayed upon interaction. The environment simulates elements of a real museum, including the lighting and decorative settings, offering users a sense of being in an actual museum space. The museum layout comprised three simple rooms (see Figure 2). Cultural artifacts, spotlighted for emphasis, were placed along the center line of each room and served as the primary interactive elements for user. Each artifact was accompanied by two labels providing detailed bilingual information (Chinese and English), including its name, age, material, collection location, and a brief introduction.

The main task for users in the museum scenario is a co-visit task: 1) explore the museum, 2) learn about the cultural artifacts by interacting with them and reading the labels, and 3) share their thoughts with each other.

Figure 2: Virtual museum environment. (a) The virtual museum layout. (b-d) Detailed views of the three exhibition halls.

3.2.2 VR Interactions

For HMD users in VR, they could freely move around and interact with virtual artifacts using two hand-held controllers.

Navigation. The virtual navigation was facilitated via the teleport locomotion technique. When users push the thumbstick forward, a circle with an arrow in the center and a parabolic curve connecting to the circle will appear. The location of the circle represents the destination to which the user will be teleported after releasing the thumbstick, and the direction indicated by the arrow represents the orientation the user will be facing after teleportation.

3D artifact interaction. VR users are allowed to interact with virtual artifacts using handheld controllers. Specifically, they are allowed to 1) grab, 2) rotate, and 3) scale an artifact. By moving close to an object and pressing the grip button on the controller, users could grab an object. The object is attached to the controller if the grip button is pressed, thus rotating the hand will rotate the artifact. By pressing the grip button on both controllers, users can scale up an artifact by pulling two hands away, and scale it down by moving the hands closer together (see Figure 3a-b). The artifact will return back to its original position when the grip button is released.

Label interaction. Two information labels about the artifact will appear around an artifact if it is held in hand (see Figure 3a-b). The labels were set to always face the user's camera position.

Figure 3: Interactions implemented in the virtual museum. (a-b) VR artifact interactions using hand-held controllers. (c-d) PC artifact interactions using mouse and keyboard control.

3.2.3 PC Interactions

PC users will perform interactions using a PC with a monitor display and a set of mouse and keyboard.

Navigation. PC users navigate using the WASD keys, representing the movement forward, left, backwards, and right, respectively. They could rotate their views by moving the mouse left or right, without pressing any keys.

3D artifact interaction. Similar to the interactions in VR, the PC users can manipulate artifacts by performing grabbing, rotating, and scaling actions (see Figure 3c-d). Specifically, users can press the left mouse to grab an artifact. Upon grabbing the object, users can rotate the object by pressing the WASD keys on the keyboard, and adjust its size by pressing the Q and E keys. Different from the artifact interaction on VR, the gravity effect is disabled and the artifact is always displayed at the center of the desktop display.

Label interaction. When a user grabs an object, the two information labels will promptly appear at the left and right corners on the display (see Figure 3c-d). These labels are identical to those presented in VR. The inclusion of these labels ensures that all users, irrespective of their interaction interface, receive consistent and coherent details about the artifact, enhancing their overall engagement and comprehension during the interaction process.

3.3 Virtual Chemistry Laboratory

3.3.1 Environment and Tasks

The virtual chemistry laboratory environment mirrors a real-life chemistry lab used for teaching, incorporating orderly arrangement of items and clean operation tables (see Figure 4). This environment serves to ease the users into the role of experimental operators, ensure they receive information adhering to the safety specifications of the experiment, and practice the experiment operations.

The task in the chemistry education scenario involves two roles, an experimenter (VR user) and an instructor (PC user). Users need to work together to 1) prepare the experiment apparatus, 2) conduct the experiment following the given instructions, and 3) observe the experimental phenomena.

3.3.2 VR Interactions

For the VR users, interactions within the virtual environment mimic the actual process of chemistry experiments. Figure 5 shows an

Figure 4: Virtual chemistry laboratory. (a) The laboratory room layout. (b) Experiment equipment. (c) System menus providing experiment instructions.

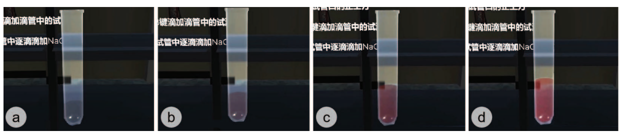

Figure 5: Interactions implemented in the virtual chemistry laboratory, showing an acid-base titration experiment: (a) phenolphthalein solution in the test tube, (b-d) adding sodium hydroxide solution using the dropper, the color gradually changed from colorless to red.

example experiment operation. Users could use a dropper to add reagents into a tube and observe the phenomena of color changes.

Navigation. Same as the navigation in the museum scenario, users can teleport to move around in the laboratory environment.

Object interaction. Direct selection and manipulation through the hand-held controllers are supported to interact with the objects in the scene, such as tubes, droppers, beakers, and chemical reagent. They could grab the instruments by pressing the grip button.

Reagent interaction. VR users can press the 'b' button on the controller to release the reagent in the dropper upon grabbing it.

3.3.3 PC Interactions

The PC user acts as the instructor and help prepare experiment apparatus for the VR user.

Navigation. PC users can move around in the laboratory environment using WASD keys.

Object interaction. PC users can press the left mouse to grab an object. Users read the experiment instruction label and prepare the apparatus for the VR user. By pressing the 'T' key on the keyboard, they could 'transmit' the selected instrument to the VR user. These interactions thus provide an effective way of bridging the gap between users in the virtuality and reality, ensuring a cohesive collaborative experience.

3.4 Virtual Rehabilitation

3.4.1 Environment and Tasks

The virtual rehabilitation scene simulates a family living room, aiming to emulate a typical real-life rehabilitation scenario, where patients engage in physical activities beneficial for recovery and improvement of physicality after an injury. The environment incorporates warm and cozy lighting, along with common living room objects, such as sofa, carpet, and plants, to cultivate a relaxing ambiance (see Figure 6).

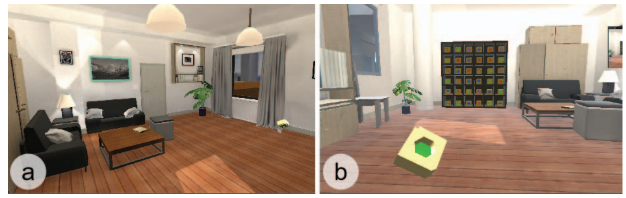

Figure 6: Virtual rehabilitation environment. (a) The virtual living room. (b) The training task system with a shelf of target objects.

The task in the rehabilitation scenario involves two roles, a patient (VR user) and a facilitator (PC user). The patients are required to execute designated tasks based on the facilitator's guidance. Specifically, there are two fundamental tasks: 1) the facilitator defines training tasks by selecting and moving an object to a random location, and 2) the patient moves the object to map it with the target position and rotation in the scene.

3.4.2 PC Interactions

The PC user acts as the facilitator and define tasks for the VR user.

Navigation. The movements are achieved using WASD keys.

Object interaction. PC users can select a 3D object and move it to a random position around the VR user's arm reach. By pressing the space key on the keyboard, users could select or drop the 3D object. This interaction allows non-HMD users to actively engage in the rehabilitation process, thereby contributing to a more effective and personalized rehabilitation experience.

3.4.3 VR Interactions

VR users complete the object placement tasks defined by the facilitator. To focus on arm movements required for upper-body rehabilitation, it was set up as a seated experience.

Object interaction. Same as the previous two scenes, users can grab and move objects by pressing and holding the grip button on the controller. In this scenario, users should map the transform of an object to the target position and rotation (see Figure 7).

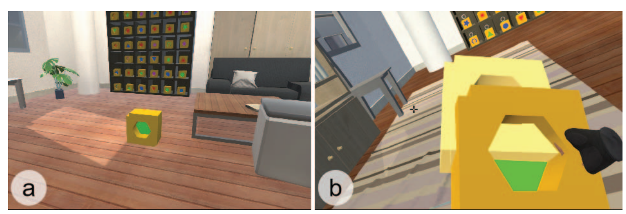

Figure 7: Interactions implemented in the virtual rehabilitation. (a) PC interactions: select a 3D object and pass it to the VR user. (b) VR interactions: map the object transform position and rotation to the target area.

4 Evaluation

4.1 Study Design and Procedure

We evaluated the usability and user experience of our designed systems. In particular, we chose the System Usability Scale (SUS) [5] and the short version of the User Experience Questionnaire (UEQ-S) [23]. Prior to the experiment, the researcher collected informed consent and provided a tutorial for participants to get familiar with the device and system operations. A within-subjects design (2 Devices $\times$ 3 Environments) was adopted, resulting in six sessions in total. In each session, the participant used the system together with the researcher and completed the SUS and UEQ questionnaires.

Participants were encouraged to provide their comments and suggestions during and after the experiment. The experiment lasted for about 50 minutes on average. Six participants (2 females and 4 males) aged between 21 and 24 (M = 22.33, SD = 1.37) evaluated the systems. As a result, we collected 36 sets of SUS and UEQ data.

4.2 Results

4.2.1 System Usability Scale

We calculated the scores of the SUS for the three scenarios (see Figure 8). All mean scores exceeded the threshold score of 68, indicating that the three cross-reality systems had satisfying usability.

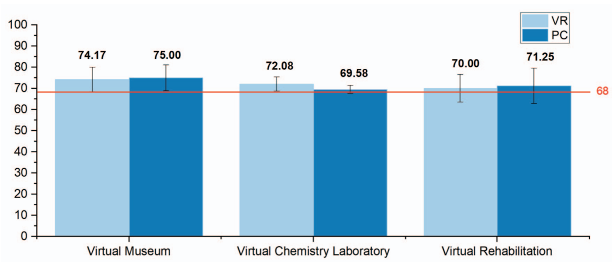

Figure 8: The SUS scores of the three systems. The red line is the SUS reference score (68).

4.2.2 User Experience Questionnaire

The results of UEQ showed positive ratings (see Figure 9). For the virtual museum, the pragmatic quality, hedonic quality and overall experience for both VR and PC exceeded the suggested value of 0.8 [14], indicating that users had a positive user experience with both devices. The same results were obtained for the virtual chemistry laboratory. However, the value for the PC-based virtual rehabilitation was 0.71, slightly below the reference value of 0.8. This identified an area of improvement for the user experience of rehabilitation facilitator (PC user) in hedonic quality.

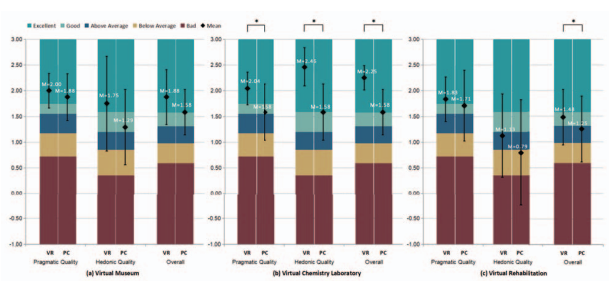

Figure 9: The UEQ scores of the three systems, showing the pragmatic quality, hedonic quality, and overall experience. $*p < 0.05$.

Comparing our results against other studies [14], users had an *Excellent* (top 10%) overall user experience using VR in virtual museum and virtual chemistry laboratory, and a *Good* (top 25% to 10%) overall user experience in virtual rehabilitation. The PC user experiences were *Excellent* for virtual museum and virtual chemistry laboratory, and *Above Average* (top 50% to 25%) for the virtual rehabilitation scenario.

Paired-samples t-test showed no statistically significant difference in the overall user experience in the virtual museum ($t(5) = 1.945, p = 0.109$), while there were significant differences in virtual chemistry laboratory ($t(5) = 3.107, p = 0.027$), and the virtual rehabilitation scenarios ($t(5) = 2.580, p = 0.049$). Participants had an overall better user experience in VR than using PC.

5 Discussion

5.1 Reflections on Cross-Reality System Design

We discuss the system usability and user experience results of the three scenarios obtained from the user study, as well as the comments provided by the users while experimenting with the systems. Overall, both the VR and PC versions of the systems demonstrated above-average usability and overall user experience. These findings indicate that the systems exhibited a satisfying usability and are capable of delivering the expected user experience.

Museum visiting. The cross-reality virtual museum system allows multiple users with different devices to co-visit the exhibition, significantly enriching the interactive and social experiences of museum visiting. The VR platform supports artifacts interactions (e.g. grabbing, rotating, and scaling), which was found easy to learn and of high pragmatic and hedonic quality. However, interactions on the PC platform, particularly object rotation and scaling, were found relatively more complex. Some participants expressed confusion in the experiment, stating that *"controlling movement and artifact rotation on the PC using the same WASD keys was a bit confusing. I couldn't move around in the museum while holding artifacts."* The UEQ results indicated that both VR and PC users had an *Excellent* user experience in the virtual museum.

Chemistry education. Unlike the almost symmetric task control in the museum visiting scene, the chemical experiment was set to have asymmetric collaborations. The teacher, operating on the PC, can provide instructions and 'transmit' instruments without the need to enter the VR environment. On the other hand, the student in VR can directly conduct chemical experiments and observe various changes in chemical reactions within the virtual environment. There was a significant difference in user experience between the use VR and PC, and the ratings of usability and user experience were higher in VR compared to PC. One participant expressed, *"With PC, I can only transfer objects to VR but not directly conduct the experiment, which was less interesting"*. It seems that the asymmetric design in task control could be reconsidered to improve user experience on the PC side. Additionally, it was found challenging for the participants with limited knowledge of chemistry (e.g. not recognizing an instrument) to take on the guide role during the experiment. This could lead to the perception of PC being less engaging.

Assisted rehabilitation. In the rehabilitation scenario, both the VR and PC platforms were designed to offer higher interactivity, enabling facilitators to customize rehabilitation tasks based on patient needs. However, in terms of user experience, the PC platform still lags behind the VR platform, and had the minimum hedonic quality. One of the reasons for this discrepancy is the repetitive selection actions for the PC user. Future work could incorporate some game elements to motivate users and increase the hedonic quality of the facilitator experience. In contrast, VR users found the process of grabbing and object repositioning intuitive to use. This efficient manipulation in VR is particularly beneficial for users in arm rehabilitation training. Furthermore, one participant expressed *"it would be more interesting to map not only the position and rotation, but also the trajectory of 3D object movements in the VR task."*

In summary, users had an overall better user experience in VR than using PC in the chemistry laboratory scenario and the rehabilitation scenario. Participants reported that the asymmetry in task control (e.g. hands-on interactions v.s. instructive roles) may lead to differences in user experience. Areas of improvements were identified in the evaluation, such as avoiding same key controls for different operations in PC, and improving the task settings in rehabilitation tasks to include more complex controls.

5.2 Limitations and Future Work

This study has several limitations that can be addressed in future research. First, the current cross-reality systems only support two users embodied in simple capsule avatars. Future systems should be scaled up to accommodate more users and include more vivid and realistic avatars in social interactions. In addition, we only examined the two ends of the reality-virtuality continuum. Other levels such as augmented reality (AR) and augmented virtuality (AV) were not considered. The evaluation study is also limited in the number of participants. More diverse samples should be recruited to obtain more generalizable results. Moreover, our experiment only focused on the system usability and user experience, lacking the systematic evaluation of specific collaboration tasks and training effectiveness in three scenarios. Future work could extend to include more levels of virtuality and physicality (e.g. AR and AV) and different types of devices (e.g. smartphones, tablets, and AR glasses). Specific tasks measures (e.g. learning outcome, time, and efficiency) can be adopted to investigate the performance and training effectiveness of the cross-reality system under different scenarios.

6 Conclusion

We presented a cross-reality system design and tested it in three real-world scenarios: museum, education, and rehabilitation. Our analysis of the scenarios showed the potential of cross-reality systems in supporting social interactions and taking advantage of the characteristics of the users, devices, and tasks. In the museum scenario, users could co-visit a virtual exhibition using different devices. Users on both sides can freely move around the environment and interact with museum artifacts. In the chemistry laboratory scenario, we set asymmetric interactions and task controls for an instructor and an experimenter. Users in the real world could act as the instructor to complete experiment preparations, and users in VR can perform the experiment operations. In the rehabilitation scenario, the PC user acts as the rehabilitation facilitator to define training tasks for users in VR to complete. Our design of cross-reality interactions and collaborations in three scenarios demonstrated satisfying usability and user experience, showing the potential of cross-reality systems to extend to multiple fields.

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