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CHAPTER 22

Social virtual reality (VR) applications and user experiences

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22.1. Introduction

There is a growing need for effective remote communication, which has many positive societal impacts, such as reducing environmental pollution and travel costs, supporting rich collaboration by remotely connecting talented people. Video conferencing tools, such as *Zoom*[1] and *Google Hangouts*,[2] are low-cost, allow multiple users to have conversations at the same time, and provide face-to-face-like experiences compared to audio-only phone calls [1,2]. Some high-end video conferencing systems, such as *HP Halo* and *Cisco Telepresence* are designed to link two physically separated rooms through wall-size screens, high-fidelity audio, and video, which enable users to feel co-present in a single conference room [3,4]. However, all the video conferencing tools still restrict users in front of screens with "talking heads experiences," and limit physical activities that naturally arise from social interactions and spontaneous collaborations [2,5].

Social VR has the potential to afford more social interaction than video conferencing, such as the ability to organically break off into small groups, or interact with virtual objects in the scene [6]. Many commercial social VR platforms have implemented novel social mechanics to stimulate social activities, such as designing a virtual environment (VE) to simulate a group discussion atmosphere, implementing built-in tools to enable users to stay in VEs and focus on the social tasks. Existing social VR platforms vary widely in affordances, fidelity, scale, and accessibility. On commercial platforms, such as *Facebook Horizon*,[3] *AltSpaceVR*,[4] and *VRChat*,[5] the facial expressions, voice, eye direction, and body gestures of a user are captured and mapped to the virtual avatar of

[1] Zoom (https://zoom.us) is a video conferencing tool, enabling a large group of people meeting online at the same time.
[2] Google Hangout (https://hangouts.google.com) is a multiple-user video conferencing tool.
[3] *Facebook Horizon* (https://www.oculus.com/facebook-horizon) is an invite-only virtual community where users can explore the virtual worlds and do creative activities together.
[4] *AltSpaceVR* (https://altvr.com) is a commercial virtual reality community for virtual live shows, meetups, and classes.
[5] *VRChat* (https://www.vrchat.com) is an online massively multiplayer social environment.

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that user in real-time. Platforms such as *Mozilla Hubs*,[6] *Gather Town*[7] also enable social experiences, but result in dramatically different experiences. *Facebook Horizon* requires users to have a head-mounted display (HMD). *AlterSpaceVR*, *VRChat*, and *Mozilla Hubs* provide fully 3D environments that can be experienced on a desktop or using an HMD. *Gather Town* uses a 2D map, but incorporates video conferencing for groups to chat. *AlterSpaceVR* and *VRChat* are massively online VR communities, averaging over 10,000 users daily. In contrast, *Mozilla Hubs* and *Gather Town* support a maximum of 25 and 50 users respectively, although premium *Gather Town* rooms can host up to 500.

All these platforms have shown that social VR is a promising new medium for remote communication, which may better support social presence (e.g., intimacy and immediacy [7]), rich non-verbal communications (e.g., sign languages [8]), and immersive realistic interactions. However, the goal of social VR is not to completely replicate reality, but to facilitate and extend existing communication channels of the physical world. In this chapter, four user applications of social VR will be showcased, including a social VR clinic, a social VR cake co-design tool and birthday celebration, a social VR museum, and an immersive social VR movie. Apart from the useful and interesting applications, this chapter also discusses research methods of measuring user experiences in social VR applications.

This chapter introduces a few unique social VR applications, covering business areas, such as healthcare, food, cultural heritage, and entertainment. The social VR clinic (Section 22.2) is a remote consultation tool that enables patients who experience mobility difficulties to have fewer visits to hospitals, but still receive good surgery preparation guidance from doctors. Both doctors and patients are represented as upper-body human avatars. In CakeVR (Section 22.3), both pastry chefs and clients are represented as full-body human avatars, who can collaboratively make a 3D virtual cake together. The co-designed virtual cake will be used as a reference for the chef to make the real cake. The social VR birthday celebration steps further by live capturing the 3D videos of two remote users and a cake, and transmitting the 3D videos as photorealistic representations to a virtual café. So, the two users who were separated physically met each other in the virtual café and celebrated the birthday together. Using the same 3D video live capturing technology [9], the social VR museum (MediaScape XR) brings two remote users to experience a historical costume together in a nostalgic concert setup (Section 22.4). Last but not least, the social VR immersive movie enabled two to five photo-realistically represented users to "walk" into a 3D immersive mysterious murder movie (Section 22.5). The users can co-present in the movie scene with the movie characters, and participate in solving the crime together. Table 22.1 exhibits the main

[6] *Mozilla Hubs* (https://hubs.mozilla.com) offers private 3D virtual spaces that enable users to meet, share, and collaborate together.

[7] *Gather Town* (https://gather.town) is a remote gathering tool that combines 2D maps with video conferencing.

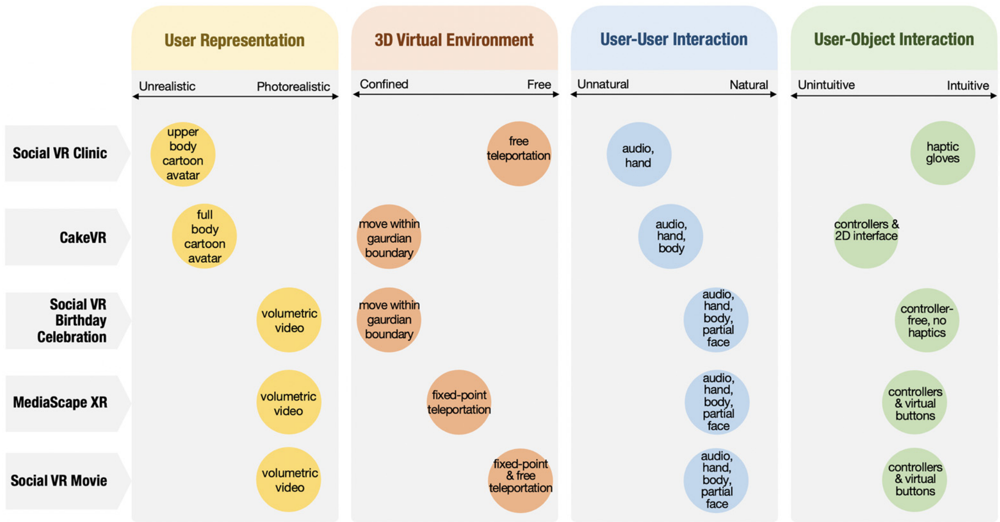

Figure 22.1 Mapping the social VR applications in terms of user representation, 3D virtual environment, user-user interaction, and user-object interaction.

characteristics of the social VR applications. Fig. 22.1 compares the realism of user representations, the 3D virtual environment, and the levels of user-user and user-object interactions. Apart from demonstrating the design and implementation process of the applications, Section 22.6 discusses methods and protocols for evaluating user experience in social VR.

22.2. The social VR clinic

A video demonstration of the social VR clinic is available at https://youtu.be/c89E98SQRqk, under the channel named "Distributed and Interactive Systems Group, CWI," with the title of "IMX2020 (demo): A Social VR Clinic for Knee Arthritis Patients with Haptics."

VR in healthcare has long been envisioned as a promising technology that can potentially approximate, or even optimize the face-to-face communication between patients and medical professionals (e.g., doctors and nurses) [10,11]. One of the pioneer VR applications in healthcare started in the 1990s, with the main purpose of visualizing complex medical data for medical professionals to prepare for the surgery [12]. So far, many VR healthcare applications have been developed for medical training [13], psychological consultation [14], and remote (psycho)therapy [15]. According to a national survey (2006–2017) in the US [16], the time people spent traveling to healthcare services was the longest compared to other professional services, such as legal services, personal care, or government activities. The time spent traveling and waiting for healthcare ser-

Table 22.1 Characteristics of the social VR applications.

Application areas	Social VR applications	Number of users	User representation	Interaction with virtual objects and 3D environment	Interaction between users
Healthcare	Social VR Clinic	2	Upper body cartoon avatar with hands	Free teleportation and haptic interaction with virtual objects (e.g., haptic virtual syringes)	Audio and hand gestures
Food	CakeVR	2	Full body cartoon avatar	Move within guardian boundary and interact with virtual objects (e.g., cakes and ingredients)	Audio, hand gestures, and body movements
	Social VR Birthday Celebration	2	Photorealistic avatar (volumetric video)	Move within guardian boundary and interact with the virtual cake (e.g., blowing candles)	Audio, hand gestures, body movements, partially facial expressions
Cultural Heritage	MediaScape XR	2	Photorealistic avatar (volumetric video)	Fixed-point teleportation, interaction with virtual objects (e.g., wearing the costume, playing with the musical instruments)	Audio, hand gestures, body movements, partially facial expressions
Entertain-ment	Social VR Movie	2–5	Photorealistic avatar (volumetric video)	Fixed-point and free teleportation, interaction with virtual objects (e.g., switch on the light)	Audio, hand gestures, body movements, partially facial expressions

vices was over 50% of the time spent receiving care. Besides the time cost, healthcare traveling can be painful for patients who have disabilities or suffer from chronic disease.

The social VR clinic aims at supporting patients with limited physical mobility to travel fewer times to the hospital, but still, communicate well with doctors and nurses. Patients with knee osteoarthritis are the target group of this application [17,18]. The social VR clinic simulates the real consultation room and facilities in the hospital, in which, patients can interact with the doctors or nurses with visualized information, such as surgery preparation procedures, 3D anatomical models, and a tour in the surgery room.

22.2.1 User journey

The user research with doctors, nurses, and knee arthritis patients provided an overall picture of a typical patient treatment journey (PTJ), which typically has three medical consultations [17]. All patients start with the first consultation with the doctor, for examination, and making decisions about the treatment. When the patient needs to have the surgery, a second consultation for patient surgery preparation and a third consultation for final before-surgery examinations will be scheduled with the nurse (Fig. 22.2).

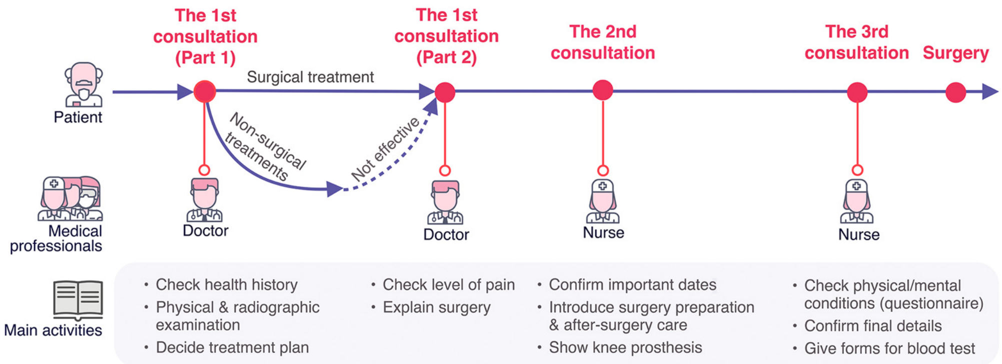

Figure 22.2 The knee arthritis patient treatment journey.

The user study also led us to focus on the second consultation of the PTJ to design the social VR clinic. The reason we choose the second consultation is that surgery preparations involve more active verbal communications and physical interactions between the nurse and the patient (e.g., showing the anatomical model) than the first and third consultation, but does not involve medical examinations that require professional equipment (e.g., X-ray). The second consultation has four main activities: (1) explain how patients should prepare for the surgery and stress the important information (e.g., dates, medications); (2) show a video about the surgery room; (3) explain the surgery process using the knee prosthesis and ask patients to feel its weight; and (4) train the patient to use an injection tool (a virtual syringe) to inject medicines to the knee.

22.2.2 Design and implementation

A combination of spoken and visual information is easier for patients to remember than only verbally explained information [19,20]. Therefore the social VR clinic maximizes information visualizations by (1) visualizing the preparation timeline and explaining the medical jargon; (2) allowing the patient to "walk into" a 3D virtual surgery room to "meet" the medical staff, and (3) enabling the patient to interact with an animated 3D knee anatomical model and a knee prosthesis to see what the differences are before and after the surgery. By wearing an *HTC Vive Pro Eye* HMD,[8] the patient can interact with the virtual nurse, teleport within the virtual rooms and operate the virtual artifacts. The nurse is represented by an avatar, which mirrors the real-time head, hands, mouth, and body movements of the nurse. The recorded social VR consultation can be replayed and shared with the patient.

In addition, the patient is equipped with mechanical VR gloves (*SenseGlove*[9]). *SenseGlove* can position hands in VR using the HTC Vive Tracker,[10] and can accurately track the fingers, hand, and wrist of the patient's hand gestures, and provide force feedback on fingers. So, the patient can have the sensation of grasping objects. With *SenseGlove*, the patient can grab, hold, and press a virtual injection tool and practice injection with realistic haptic feedback, such as feeling the resistance when pressing the plunger of the virtual injection tool (Fig. 22.3).

The prototype is implemented in Unity (version 2018.4.1f1). The *HTC Vive* and the tracker are supported by *SteamVR* Plugin, and the *SenseGlove* is integrated into Unity by the free *SenseGlove* SDK.[11] The demo project runs on a 2.20 GHz Intel i7 Alienware laptop with an Nvidia RTX 2070 graphics card. Both the *HTC Vive* and *SenseGlove* are wired and connected to the laptop.

The knee and the prosthesis model implementations were adapted based on professionally 3D scanned medical models from Thingiverse.[12] We added the material layer and motion to the models in *Unity* and incorporated them into the prototype. The surgery room is based on an asset from the *Unity Store*,[13] including a set of realistic medical devices, furniture objects, and animations. Fig. 22.4 illustrates the implemented four surgery preparation activities in social VR compared to the real-world ones.

[8] *HTC Vive Pro Eye* HMD: https://www.vive.com/eu/product/vive-pro-eye/.
[9] *SenseGlove*: https://www.senseglove.com.
[10] *HTC Vive Tracker*: https://www.vive.com/ca/vive-tracker/.
[11] https://github.com/Adjuvo/SenseGlove-Unity.
[12] *Thingiverse*: https://www.thingiverse.com/thing:340254.
[13] A surgery room asset from the Unity Asset Store: https://assetstore.unity.com/packages/3d/props/interior/operating-room-18295.

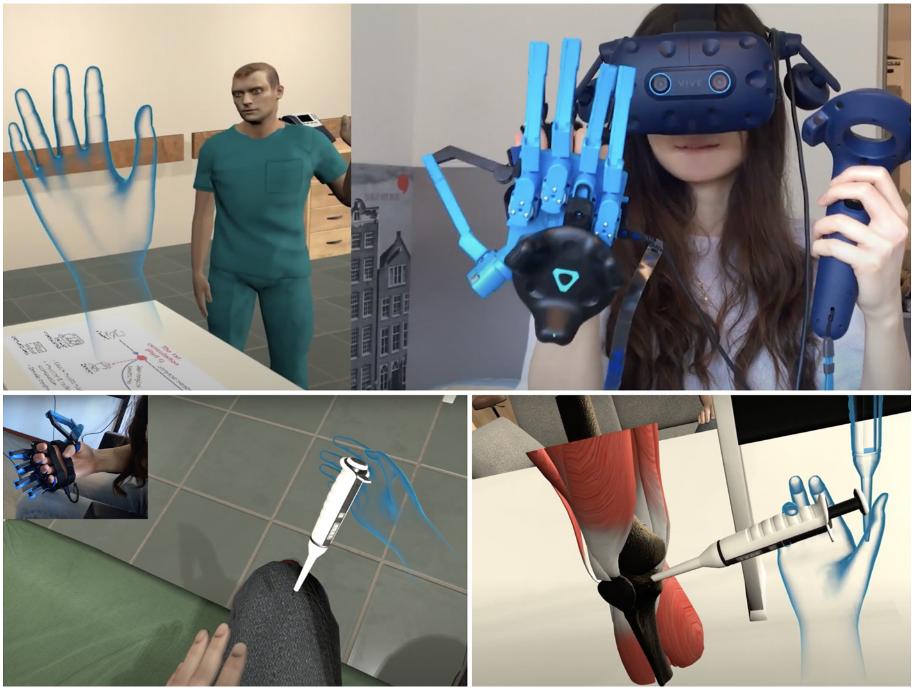

Figure 22.3 Use SenseGlove with HTC Vive tracker to position the hands in VR spaces and train the patient to use an injection tool. SenseGlove can track the fingers, hand, and wrist of user's hand gestures, and provides force feedback on fingers.

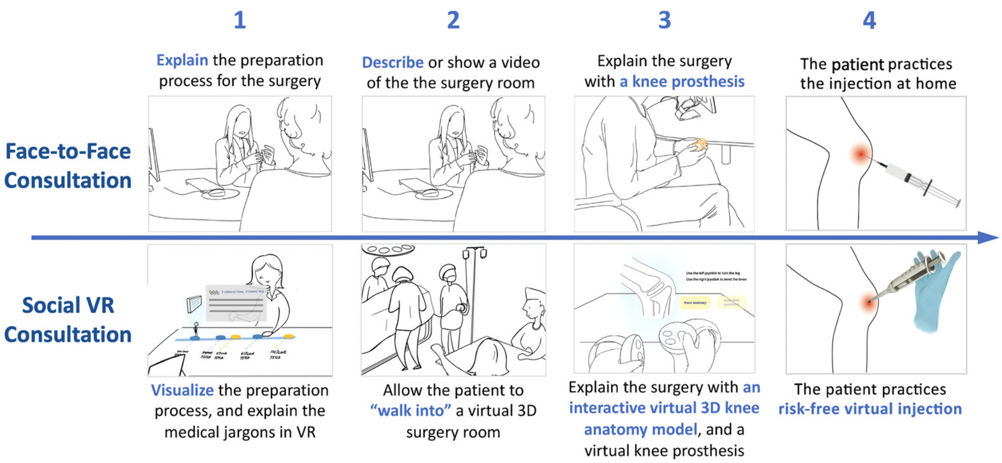

Figure 22.4 The four main activities related to a medical consultation: comparing the differences in the face-to-face consultation with the social VR clinic.

22.2.3 Real-world deployment

We set up the social VR clinic prototype in one usability lab of Delft University of Technology (TU Delft) and invited 22 user experience designers or design students from the faculty of Industry Design Engineering of TU Delft to experience both the face-to-face consultation and the social VR consultation. We made this decision due to the restrictions of visiting hospitals during the pandemic. The invited designers or design students were experienced in designing user journeys and user interfaces and can provide us with expert feedback in improving the experiences.

The results of design experts' evaluation showed the potential of social VR as a new medium to enable effective remote communications. The experts found the 3D visualizations of medical information and immersive "walk-in" experiences important. However, we noticed that, at the moment, social VR consultations cannot replace face-to-face ones, due to regulations that restrict performing medical examinations in a non-face-to-face setting [21]. Many design experts found face-to-face consultations less complicated and less distracting than social VR ones.

The social VR clinic aims at facilitating communication between two users (i.e., patient and nurse). However, in the end, we did not manage to obtain permission to set up the social VR clinic in the hospital. As an alternative, we recruited 22 non-patients for the evaluation. We as well considered the age factor when recruiting young participants. As we found in our user study [17] and literature [22], most of the elder patients are accompanied by their child or grandchild to the hospital. These young family members can be the target users of the social VR clinic, as they can attend and record the VR consultation for the patients. Our design is an initial exploration of social VR use cases in healthcare, aiming at facilitating immersive remote communication between two users. Further studies and design iterations are needed to allow elder patients to use the technology.

22.3. CakeVR and the birthday celebration

A video demonstration of the *CakeVR* application is available at https://youtu.be/HS8sN212toQ, under the channel named "Distributed and Interactive Systems Group," with the title of "CHI2021 - CakeVR: A Social Virtual Reality (VR) Tool for Co-designing Cakes."

Rarely is there a celebration without a cake. Apart from being an edible art, a customized cake is often a ceremonial symbol [23,24], which is special and personal, and closely associated with social relations and emotions [25]. Customized cake services enable clients to collaboratively personalize their cake in shape, color, and flavor with pastry chefs [26]. However, the customization process is not easy for both clients and chefs, which usually starts in a face-to-face meeting. Most of the follow-up communications are through text messages with the aid of reference cake pictures, which is

Figure 22.5 The difficulties in communicating the decoration and size of a customized cake: (*a*) design keywords from the clients, (*b*) a cake reference picture, (*c*) the final cake design in a 2D photo, and (*d*) the clients only saw the final cake at the celebration.

insufficient for them to fully communicate their creative thoughts and to have a clear image of the final design [27,28]. Cake customization requires professional skills. Based on 2D reference pictures and texts, it is not only difficult for clients to express the ideal decorations they want [28,29], but also challenging for pastry chefs to immediately visualize and show the size and decorations of the cake to the clients [27]. Fig. 22.5 illustrates such difficulties.

As a new remote communication medium [30], social VR is distinguished from video conferencing tools by their capacity to portray 3D spatial information [31], to exploit users' natural behaviors, and to immerse users in the virtual world [32,33]. In this application, we demonstrate that social VR is a promising medium to support clients to remotely co-design customized cakes with pastry chefs. Social VR allows pastry chefs and clients who are physically separated to co-present in a shared virtual space and to assist their cake co-design by providing intuitive virtual interaction techniques and real-time 3D visualizations of virtual cakes. Both clients and chefs can instantly see the real-size 3D cake visualizations as their co-design results.

22.3.1 User journey

Based on the interviews with pastry chefs and clients who had experiences of ordering customized cakes [34], we identified three main phases of the current communication process of cake customization, including (1) client input, (2) ideation and negotiation, and (3) agreement (Fig. 22.6).

At Phase 1, a client usually starts the conversation with a pastry chef by describing the cake he or she needs from three aspects: the main features of the cake, the context where the cake will be consumed, and the emotion that the cake should convey. The

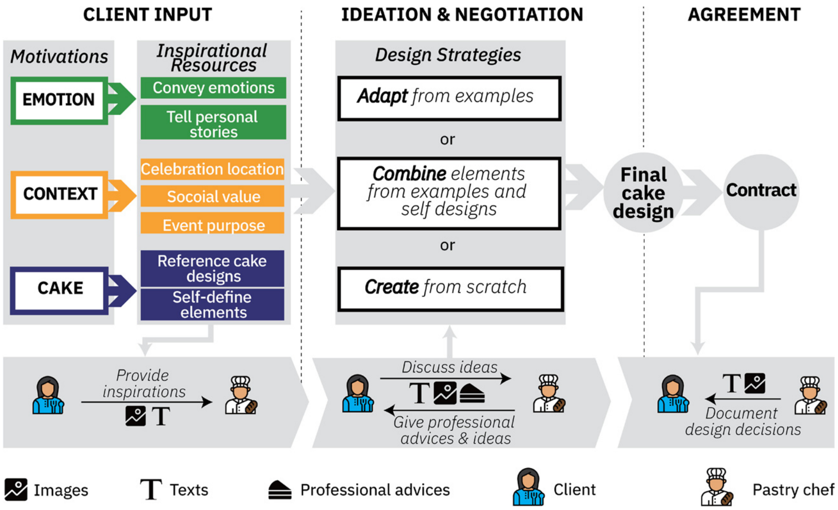

Figure 22.6 Three phases of current cake customization communication.

reference cake pictures and information obtained at Phase 1 help define the style, size, and high-level visual features (e.g., wood/forest elements) of the cake. At Phase 2, pastry chefs help clients turn the inspirations into tangible cake designs, with professional skills and equipment. We noticed that three design strategies were often applied, namely (1) adapting from examples (reference cake pictures), (2) combining elements from examples and self-designs, and (3) creating a new cake from scratch. At Phase 3, the clients and the pastry chefs agree upon the final design of the cake. The chefs precisely document all the design details into a formal contract, usually with a sketch or a collage of reference pictures.

To support Phase 1, it is essential to enable the pastry chef and the client to meet in the virtual space, and allow them to discuss with the aid of reference cake pictures, the celebration locations, and support the communication with natural hand gestures. To support Phase 2, social VR has its unique advantage in integrating different types of media to assist design activities and provide instant visualizations of the final design. It is important for *CakeVR* to support users to perform cake co-design activities in the virtual space, including making sketches, adding decorations, resizing the cakes, and instantly seeing the design outcomes. To support Phase 3, it is essential to assist in documenting the final cake with all the design details (e.g., exact colors, texture).

22.3.2 Design and implementation

We made a storyboard to describe the core functions and user scenarios of CakeVR, from preparation, initial idea discussion, ideation, and negotiation to confirmation (Fig. 22.7). The storyboard guided the implementation of CakeVR, which is a medium-

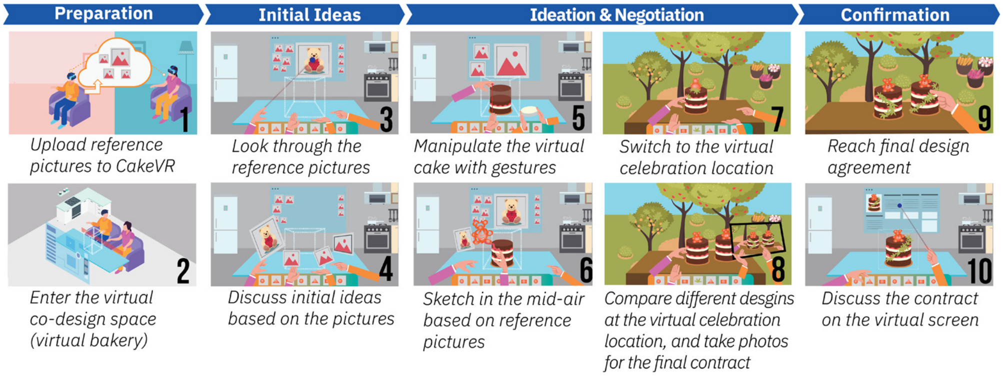

Figure 22.7 The storyboard of CakeVR, defining the core functions and user scenarios.

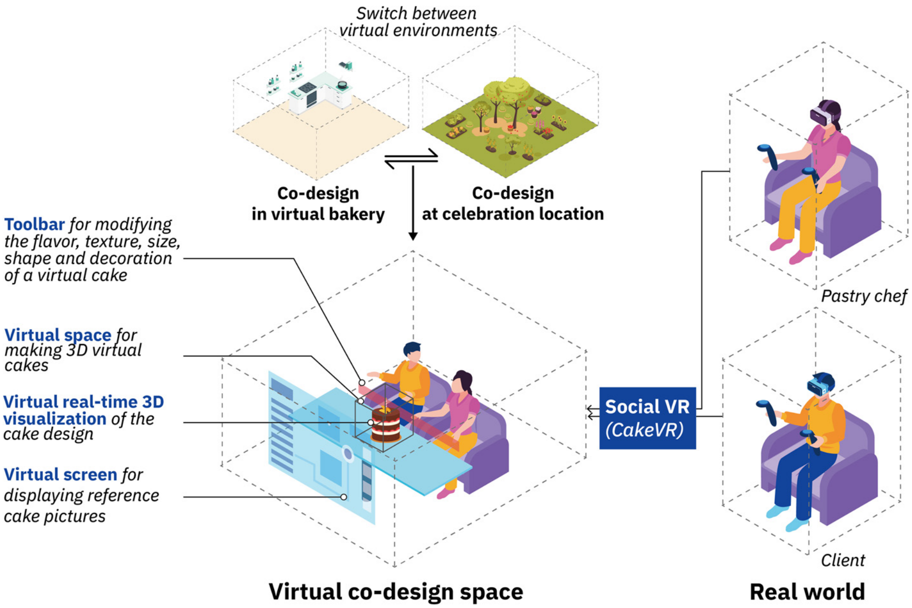

Figure 22.8 An overview of the CakeVR system.

fidelity social VR prototype for one client and one pastry chef to co-design a cake in a shared virtual space. Fig. 22.8 illustrates the system overview of CakeVR. The virtual co-design space can switch between a virtual bakery and a celebration location. Two users who are represented as cartoon-like avatars meet at the virtual space wearing HMDs. The virtual space has a graphical interface to guide them to build a 3D virtual cake together and visualizes the cake design in real-time.

The 3D cake models with textures and the pre-designed cake decoration components (e.g., different shapes of cakes, cream, fruits, flowers) were made in *Blender*,[14] and then exported into *Unity3D*[15] (version 2018.4.4f1). The virtual scenes, including the virtual café, the garden, and the two avatars were built based on selected assets from the *Unity Asset Store*.[16] How the users interact with the virtual interface and the gestural manipulations of the virtual cake were manually coded using C# in *Unity3D*. *Animation Rigging*, a plugin of *Unity3D* is applied for simulating the upper body motion of the avatars based on the spatial positions of the two hands and the head-tracked by the *Oculus Rifts* HMD. The *Oculus Rifts* HMD and the *Oculus Touch* controllers were supported by the *Oculus Integration plugin*. *PhotonPun*, a plugin *Unity 3D*, was utilized to connect two VR users and synchronize all the data (i.e., dynamic data of the 3D virtual objects, body movements of the avatars) via the Internet. Three basic gesture-based 3D manipulations were implemented in the prototype, namely moving, rotating, and scaling. By pressing the grip button of the *Oculus Touch* controller, users can virtually grab a 3D object, and change its position, orientation and size.

22.3.3 Real-world deployment

We invited six clients and four pastry chefs to use and evaluate the *CakeVR* prototype and found that CakeVR has improved the efficiency in the cake customization communication, and enhanced the shared understanding in the co-design process by allowing natural gestural interactions, intuitive manipulations of 3D objects, and instant 3D visualizations [34]. The findings also highlight *CakeVR*'s potential to transform product design communication through remote interactive and immersive co-design and to recreate (food-related) senses in social VR.

The Dutch National Research Institute of Mathematics and Computer Science (Centrum voor Wiskunde en Informatica (CWI))[17] celebrated its 75th birthday virtually, since the pandemic did not allow physical gatherings. As an extension of the *CakeVR* application, the virtual celebration brought two people to get immersed in a virtual world by wearing VR glasses and blowing candles on a virtual birthday cake together. The celebration demonstrated the state of the art of what is possible with volumetric video [9]. Each person and the birthday cake were recorded in separate locations using three *Microsoft Azure Kinect DK* depth cameras (hereinafter referred to as *Kinect* camera).[18] The volumetric videos were combined and transmitted into a virtual café in real-time so that the two people got the feeling that they were celebrating their birthday

14 *Blender*: https://www.blender.org.
15 *Unity 3D*: https://unity3d.com/get-unity/download.
16 Unity Asset Store: https://assetstore.unity.com.
17 Centrum voor Wiskunde en Informatica (CWI): https://www.cwi.nl.
18 *Microsoft Azure Kinect DK* developer kit: https://azure.microsoft.com/en-us/services/kinect-dk/#industries.

Figure 22.9 Two persons and a cake were recorded in separate locations using three Kinect depth cameras. Their real-time volumetric videos were transmitted into a virtual café so that the two people felt that they were celebrating together.

together with a cake in front of them (Fig. 22.9). This demonstration is available online: https://youtu.be/KcRpp0s50RQ.

22.4. MediaScape XR: the social VR museum experience

The video demonstration of the *MediaScape XR* available at https://youtu.be/I7kY1cMZyD0, under the channel named "Distributed and Interactive Systems Group, CWI," with the title of "MediaScape XR | OBA - VRDays2021 | Short."

Today, a trip to museums often involves looking at precious objects through a protective glass screen. The artifacts cannot be touched or approached too closely, and there is only a limited amount of information about them, usually on a small white card next to the objects [35]. No wonder for some audiences, particularly the younger generation, who have grown up in a digital world, museum-going can feel passive, lacking in interactivity, and not very exciting.

Our society is proficient at studying culture from a historical perspective and possesses impressive longitudinal datasets on arts, media culture, and audio-visual archives. These datasets or artifacts have been digitized and made available online in recent years, such as Rijks studio of the Rijksmuseum [36]. Still, the ongoing effort has mainly focused on the creation of digital surrogates, and not so much on the provision of novel manners to enjoy the artifacts or interact with them in meaningful and socially engaging ways. Museums are exploring how to make their collection accessible remotely, but in most cases, this is limited to traditional web technology, such as websites, online catalogs, social media posts, videos, with little interaction and no immersion [37]. Museum curators also lack tools to present the full story behind the artifacts to remote visitors in an immersive manner [38]. The *MediaScape XR* application aims at changing this kind of passive museum visiting to interactive and immersive experiences by enabling visitors to enjoy a remote VR museum experience with photo-realistic user representations;

The *MediaScape XR* application integrates a 3D replica of a heritage object from the Netherlands Institute for Sound and Vision (NISV)[19] in an immersive virtual museum. Museum visitors, who are in realistic representations, will wear HMDs to get immersed and interact with the virtual object, such as dressing up in a historical costume, which will enable visitors to cherish the historical accomplishments through an immersive and engaging experience.

22.4.1 User journey

The focus group sessions with the curators at the NISV directed us to focus on one cultural artifact: the costume that Jerney Kaagman, lead singer of the rock band Earth and Fire, wore in the music program TopPop in 1979. In addition, a co-design session was conducted with a group of user experience designers that helped us specify a list of design requirements that indicate what interactions and activities could be implemented in this social VR application. The storyboard describes the main activities defined at the co-design session (Fig. 22.10). The requirements are the following: (1) The *MediaScape* application allows more than two remote visitors to co-present in a shared virtual environment with photo-realistic representations. (2) It allows visitors to freely explore the 3D virtual museum (six-degree-of-freedom). (3) It offers a user interface within the virtual museum to offer multimedia content about artifact-related knowledge. (4) It allows visitors to revisit the historical scene. In this case, it is the music hall where the costume was worn by Jerney Kaagman in the TopPop music program in 1979. (5) It allows haptic interaction with the museum artifact, which is impossible in the real world. In this case, the visitors can wear the costume virtually. (6) It guides visitors to collaboratively recreate the musical performance of Jerney Kaagman's "Weekend" in 1979. (7) Visitors can take the experience home by taking virtual photos or recording the videos.

22.4.2 Design and implementation

Based on the design requirements, the implementation of the *MediaScape* experience started with creating a 3D virtual museum. To make a more realistic museum experience for NISV, we integrated the 3D model of the NISV museum building into *Unity3D*

[19] The Netherlands Institute for Sound and Vision: https://www.beeldengeluid.nl/en.

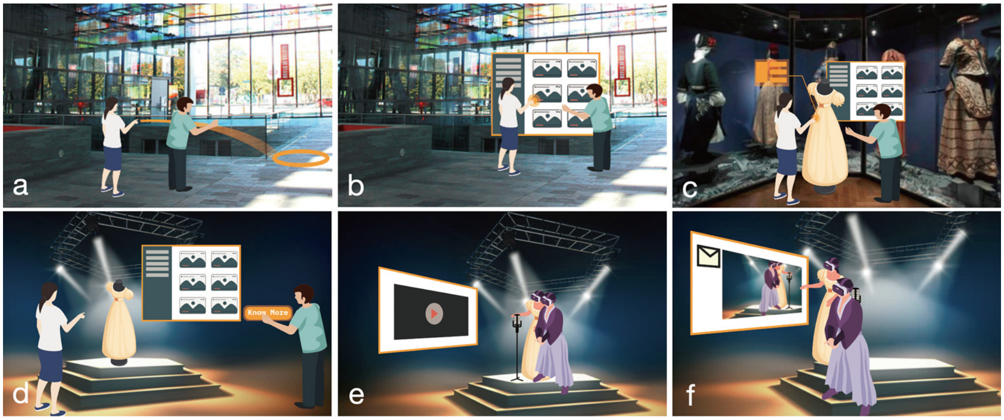

Figure 22.10 (*a*) Two remote users, captured as volumetric videos, were transmitted into the virtual museum; (*b&c*) they search for Jerney Kaagman's costume, which is shown as a placeholder costume in this storyboard, and closely "touch," examine, and rotate it; (*d*) the curated tour guide the users to a virtual stage; (*e*) they wear the costume and recreate the TopPop performance of Jerney Kaagman's Weekend; (*f*) they take home a photo of their virtual museum experience.

(Fig. 22.11). It was an open exhibit space, displaying a collection of archives representing the historical evolution of Dutch media (i.e., television, radio, costume), and letting visitors walk through among the collections. The 3D models of the NISV building and other props were built in *Cinema 4D*[20]and in *Blender*, and then imported into *Unity3D*. After that, we implemented the texture and lighting for the 3D model in *Unity3D*. Finally, we worked on the optimization of the VR viewing experience and improved the rendering efficiency by (1) baking light maps,[21] (2) activating occlusion culling,[22] (3) using the single-path rendering setting, (4) and switching the rendering quality to "VR" level. In this way, we were able to keep the frame per second (FPS) higher than 50, and significantly improve the rendering performance (Fig. 22.12).

Next, we replicated the historical scene, which is the TopPop music hall of the Weekend show in 1979. The videos of the Weekend show were used as a guideline for the spatial layout and decorations of the stage. Then, we built the 3D assets in *Blender*, and then loaded them into *Unity3D*. After that, we set the texture, lighting, and special effects (i.e., smoke) to the scene in *Unity3D* (Fig. 22.13).

[20] Cinema4D is a 3D modeling software https://www.maxon.net/en/cinema-4d/.

[21] Baking lighting is when Unity performs lighting calculations in advance and saves the results as lighting data, which is then applied at runtime.

[22] Occlusion culling is a process that prevents Unity from performing rendering calculations for game objects that are completely hidden from view (occluded) by other game objects.

Figure 22.11 The 3D architecture model in MediaScape application (*Left*); the physical space of NISV museum which is now under construction (*Right*).

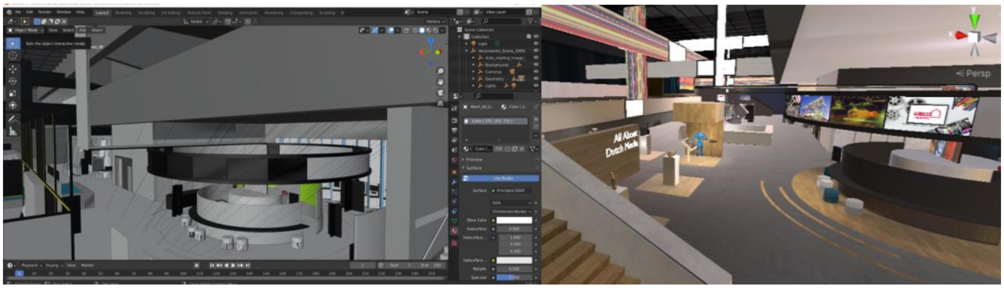

Figure 22.12 The 3D architecture model in Blender (*Left*); The 3D architecture model in Unity3D with texture and lighting (*Right*).

Figure 22.13 The replicated 1979 TopPop music hall in Unity3D.

Besides the creation of the virtual scenes, a realistic 3D model of the costume (Fig. 22.14) was built by transforming the 3D structure of the costume into 2D patterns by hand sketching. After that, we drew all the 2D textile patterns digitally, and trans-

Figure 22.14 A photo collage of the real costume.

form them into a 3D suit using *Marvelous Designer*.[23] We refined the mesh to achieve a decent textile feeling. To make it look more vivid, the texture of blue shining leather was painted on the garment digitally (Fig. 22.15).

To enable visitors to wear the costume virtually, we developed a mechanism to fuse the 3D model of the costume and the head part of the user photorealistic representation so that the virtual costume can be controlled in real time by the gestures and movement of the user. This is possible, because we bound the skeleton to the costume mesh in *Blender*, and loaded this rigged costume model into *Unity3D*. In *Unity3D*, the location and orientation of the three main joints (head, left hand, right hand) of the skeleton are controlled in real time by the joint position, captured by the HMD and the VR controllers. The rest of the joints (i.e., elbow, shoulder) are simulated using the animation rig plugin in *Unity3D*. This way, users can virtually wear the costume (Fig. 22.16).

22.4.3 Real-world deployment

Through capturing each visitor through three Kinect cameras in real time, the visitors with photorealistic representations met each other in the *MediaScape* virtual museum (Fig. 22.17). The experience is tailor-made for the costume worn by Jerney Kaagman in the *TopPop* show. In the virtual environment, visitors can freely explore the 3D virtual museum and closely examine the 3D model of the costume. They can also relive its history by watching the performance of Jerney Kaagman on the virtual screen and

[23] *Marvelous Designer* is a garment-making software with textile simulation function https://www.marvelousdesigner.com/.

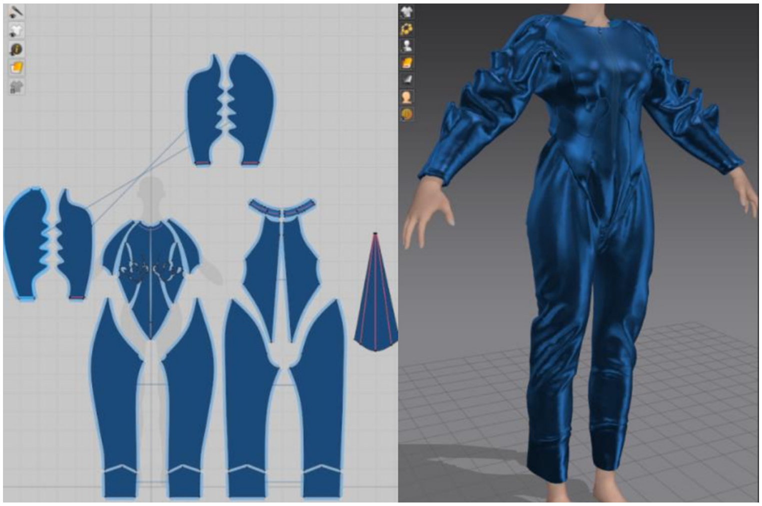

Figure 22.15 The 2D hand-sketched patterns of the costume (*Left*) and the 3D model of the costume (*Right*).

Figure 22.16 The skeleton controls the motion of the costume 3D model (*Left*); two users were wearing the costume in the virtual music hall (*Right*).

performing as the artist using the virtual music instruments. Both visitors can enjoy a curated tour of the virtual TopPop show and recreate Jerney Kaagman's *Weekend* music show with each other. The *MediaScape* application illustrates how the traditional model of a museum experience as a passive observation is shifting to active, interpretive

Figure 22.17 Two remote visitors greeting each other in the MediaScape XR virtual museum.

engagement. It facilitates novel manners to enjoy and experience the artifacts or interact with them in meaningful and socially engaging ways.

MediaScape XR was chosen to be exhibited on the main stage of the 2021 VR-Days,[24] which was held at the Amsterdam Public Library (OBA) in November 2021 (Fig. 22.18). Around 150 event visitors experienced and evaluated *MediaScape XR*. Through this event, we demonstrated that the application is robust and steady to run in an exhibit setting. We brought the application to the event visitors with diverse backgrounds and introduced the novel technology to the general public. In addition, we found that it achieved decent system usability and user experience. On the system usability scale [39,40], 6% of the visitors rated the application "best imaginable," 12% rated "excellent," 48% rated "good," 29% rated "ok," and only 5% found it "under ok." *MediaScape XR* has envisioned a future heritage experience that can be accessed remotely and socially. Through the deployment, we validated the added value that social VR can bring to the cultural heritage domain.

22.5. The social VR movie

Hunkering down on the couch and watching a movie together with friends or family is not only a nice cozy thing to do, but also enables us to share emotions, increase engagement, and social bonds with people we love [41]. However, this is not always possible if we live apart. Although people at a distance can text each other, video call,

[24] *VRDays* is an annual event in Amsterdam for exhibiting the emerging XR technologies: https://vrdays.co.

Figure 22.18 MediaScape XR was demonstrated to the public at the VRDays.

and share their screens, or even use video stream synchronization applications (e.g., Teleparty[25]), it is still far from the feeling of being together. As an emerging immersive remote communication tool, social VR has the potential to afford face-to-face-like social interactions than video calls, enabling users to feel co-present and interact with virtual objects [6,17,32,34]. The virtual space can be a computer-generated 3D scene or a 360° scene captured by an omnidirectional camera. Each user can be represented as a computer-generated avatar [42–44] or, in recently proposed systems, a user's virtual representation was live captured by depth cameras [9,45].

Recently, VR films are becoming popular, thanks to the market available and affordable HMDs. The Oculus platform offers a vast variety of immersive content, from 360° videos, immersive 3D wonderlands to interactive replicas of historical monuments. The 360° video documentary Rebuilding Notre Dame[26] immerses VR viewers with the footage from before and after the April 2019 blaze at the same locations, capturing the majestic architecture from angles that visitors usually cannot see. The Under Presents[27]

[25] *Teleparty* (https://www.netflixparty.com) is an application that synchronizes video playback and adds group chat to multiple over-the-top movie/TV content platforms, such as Netflix, Disney, Hulu.

[26] *Rebuild Notre Dame* is available at https://www.oculus.com/experiences/media/1353452644677196/210792686621494.

[27] *The Uder Presents* is available at https://www.oculus.com/deeplink/?action=view&path=app/1917371471713228&ref=oculus_desktop.

takes users to a new virtual world, where they enjoy live immersive theaters and explore novel interface-free interactions, such as the "scrunch" technique, in which users move forward by reaching out their virtual arms and pulling the destination towards them. The Anne Frank House VR[28] reconstructed the "Secret Annex," where Anne spent two years of her life hiding in. The experience invites users to wander through the rooms, immerse themselves in Anne's thoughts, and interact with Anne's belongings.

VR has increasingly become a sophisticated tool for storytelling, which guides viewers through the narrative in a novel way and invites viewers to participate [46]. Imagine a near-future scenario, where you and your friends or family who live apart can walk into the same virtual movie together and see each other as holograms. You co-present with the movie characters, interact with them, and influence the movie storylines without interrupting the watching experiences. This new type of interactive movie that supports immersive social interaction brings the co-watching experience to the next level. The conversations between us would no longer be "The detective found three fingerprints," but be "My mother and I saw the forensic report held by the detective, saying 'three finger prints'."

The social VR movie engages multiple users in such an immersive and interactive experience. Each user is captured in real-time by three Kinect cameras. The volumetric videos of users were transmitted into the virtual movie scene, so that they felt like walking into the movie and being together with each other.

22.5.1 The virtual movie production

The video demonstration of the social VR movie is available at https://youtu.be/t30ECMnocWk, under the channel named "VRTogether," with the title of "VRTogether Pilot 3: Interactive Scenario (Visit at the Crime Location)."

The 10-minute virtual movie is about the investigation of the murder of Ms. Armova, which was professionally produced by The Modern Cultural Productions (Madrid, Spain) [47]. The virtual movie invites four users to join in simultaneously, who form the Civilian Oversight Committee as the witnesses of the crime-solving process and allow interaction with the movie characters to help with the process. There are six movie characters: Sarge Hoffsteler (detective), Elena Armova (victim), Rachel Tyrell (policewoman), Evans Young (forensic technician), Christine Gerard (Elena's assistant), and Ryan Zeller (Elena's ex-boyfriend). The last two of the above characters are the two suspects. The movie characters were generated in three steps (Fig. 22.19): (1) record the full-body acting of the real actors and actresses; (2) capture movements of their faces using an iPhone and Reallusion's live face application and Character Creator[29]; (3) perform a body MoCap (full-body motion capture animation) during post-production.

[28] *The Anne Frank House VR* is available at https://www.oculus.com/deeplink/?action=view&path=app/1596151970428159&ref=oculus_desktop.

[29] Reallusion's character creator: https://www.reallusion.com/character-creator.

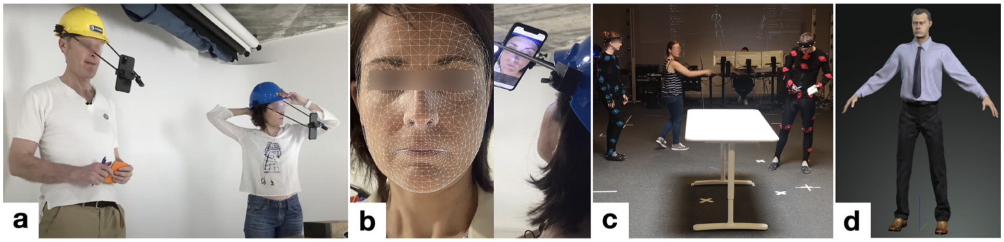

Figure 22.19 The generation of the virtual movie characters: (*a&b*) capture the movements of the actor's or actress's face using the Reallusion's live face application on an iPhone that is attached to a specially designed helmet; (*c*) perform a full-body motion capture animation (*MoCap*) of the actor or actress; (*d*) the generated virtual movie character based on the face and full-body capture.

Figure 22.20 The user-movie character interaction in the movie: (*a*) detective, Sarge, instructed one user to look for the phone finder and switch it off; (*b*) one HMD user found the phone finder on a lower table next to the window; (*c*) she switched it off.

Users can access the virtual movie either by using an HMD or using a screen with a game controller. HMD and screen users can use voice to answer the questions raised by the movie characters. However, the HMD users can only teleport between blue circles inside the virtual apartment, but can interact with the environment, such as switching on the light and clicking on buttons (Fig. 22.20). The screen users can use the game controller to freely navigate inside the apartment, but cannot interact with the environment. These differences were pre-defined by the movie production company, aiming at (1) reducing the motion sickness of the HMD users by limiting their movement to teleportation (e.g., joystick walking in VR may largely increase motion sickness [48]), and (2) increasing the collaboration opportunities between HMD and screen users, because they have to find out who can interact with the environment or talk to the movie characters to move on in the story.

The virtual movie takes place in the luxury apartment of the victim Elena. The first part of the movie happens in the living room (Fig. 22.21*a*), where four users are observing the crime-solving and interacting with the movie characters (e.g., help switch on the light or click on the phone finder). In the second part, the four users are separated into

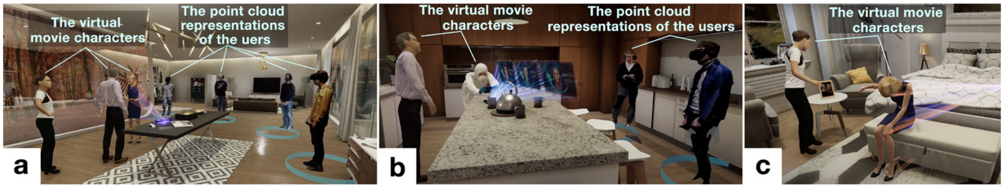

Figure 22.21 The luxury apartment of the victim Elena Armova: (*a*) the living room with four users represented as point clouds and three virtual characters: (*from left to right*) Rachel, Sarge, and the hologram of Elena; (*b*) the kitchen with two users, Sarge and Evans; (*c*) the bedroom with Rachel and Elena.

two groups. Two users follow Sarge to the kitchen, where technician Evans is checking the evidence (Fig. 22.21*b*). The other two users follow Rachel to the bedroom, where the hologram of Elena confesses some secrets (Fig. 22.21*c*). The users are represented as hologram-like point clouds (Fig. 22.21*a*).

22.5.2 Real-world deployment

We set up four separate rooms, Room A, B, C, and D, located on the 3rd floor of the CWI building (Science Park, Amsterdam). Room A and B had an Oculus Rifts HMD. Room C and D had a desktop computer, a 50-inch monitor, and a game controller. Each Room had three *Kinect* depth cameras to capture users' volumetric representations and deliver them to the virtual movie as point clouds (Fig. 22.22). For each social VR movie session, we invited four users. The two HMD users were in Room A and B, and the two screen users were in Room C and D. There are two interactive objects in the virtual movie: a light switch and a phone finder. HMD users must interact with them as instructed by the detective to move forward with the story.

We recruited 48 participants (23 males, 25 females), with age range of 21–56 years ($M = 34.9$, $SD = 10.3$). 12 females and 12 males were HMD users; 13 females and 11 males were screen users. Thirteen (13) of them had never used VR, 33 had used it 1 to 3 times, and two were experienced VR users. They came to the social VR movie session in groups of four persons. In addition, 14 VR experts, from 9 companies/institutes[30] were invited to evaluate the photorealistic social VR movie. We set up two rooms equipped with an HMD and one room with a screen. The 14 experts came in two groups: Group 1 had 8 experts, and Group 2 had 6 experts. After all the experts rotated and experienced both the HMD and the screen version of the virtual movie, they were gathered in a spacious meeting room for a 30-minute focus group discussion (audio-

[30] The 9 companies/institutes are The Netherlands Institute of Sound and Vision, Medical VR, The Virtual Dutch Men, NEMO Science Museum, Erasmus University Medical Center, Sensiks, PostNL, Buitenboord Motor, and Interface.

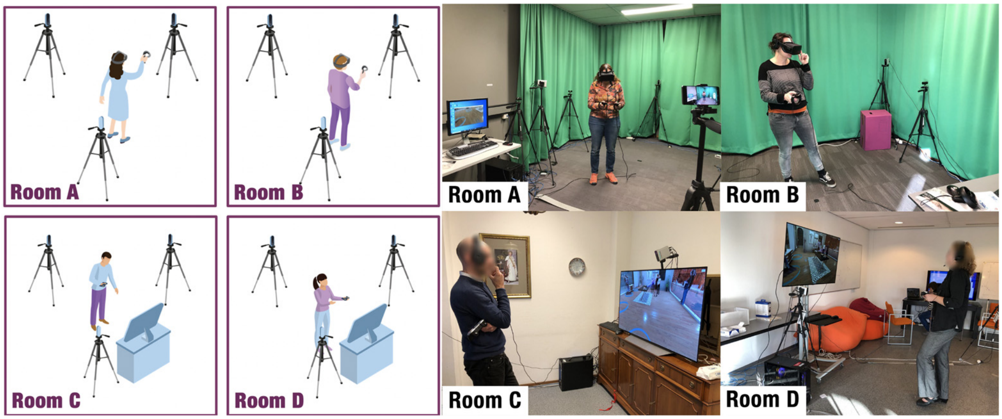

Figure 22.22 The (*left*) illustrations and (*right*) photos of the 4 rooms. Room A and B had an Oculus Rifts HMD. Room C and D had a screen computer, a 50-inch monitor, and a game controller. Each room had three Kinect depth cameras to capture users' volumetric representations.

recorded) about the potentials and challenges of the photorealistic social VR experiences [49].

The results showed that whereas HMD users reported a higher sense of presence and immersion, screen users reported a lower workload and could more easily explore the virtual environment. Both HMD and screen users did not report any difference in cybersickness. In addition, we found that males rated the "possibility to act" higher than females, indicating that they could more easily and more actively control and interact with the virtual environment. For the evaluation of the volumetric representations, we found that, within the HMD group, the ratings for self-representations were worse than the ratings for others' representations. However, no differences were found within the screen users between the ratings for self and others' representations.

All 14 experts (E1–E14) were impressed by the simple setup of the "hologram" capturing system and were excited to see the photorealistic representations, which enabled them to feel co-present in the same space. As we observed, they were waving at each other in the virtual space and talking about the texture of their clothes, and the possible scenarios for applying the social VR system. The virtual movie was short (about 10 minutes), but all the experts spent a much longer time exploring all the details. They saw the full potential of our social VR system in many market sectors, such as medical care, education, immersive meetings, family reunion, virtual dating. As E8 commented, "It doesn't feel like an avatar, but the real person. Despite the quality, it still needs a lot of improvement, but you go beyond the uncanny valley, and it's the person there. That's amazing. That's more than I expected. I expected it to be a nice virtual environment with a Skype-like interface, but you go way beyond that." The experts also pointed out challenges that we need to consider in our future work. E6 is a physician, she mentioned, “The realism level of the virtual objects needs to be much higher in a clinical context. Suppose we are going to reconstruct the breast of a cancer patient, not only the visual quality needs to be fully realistic, but the haptic feelings of the 3D reconstruction also need to be realistic. In this way, patients can have a correct expectation towards the surgery.” E11 suggested, based on the comparison of the two devices, “The HMD was very immersive, but on the other hand, the screen with a game controller was more practical, perhaps also more addictive. I am curious to see the effects on 3D screens.”

Overall, both users and VR experts found that photorealistic volumetric representations enhanced co-presence. We additionally found that gender influenced interactions with the movie.

22.6. Measuring user experiences in social VR

Instead of watching a film together on a screen, social VR can be experienced as if viewers are co-present in the same space. Although research interests in understanding social VR experiences are growing, there is no theoretical frameworks or experimental protocols to depict what factors influence social VR experiences and how to measure them. Many studies identified the importance of user representations for providing immersive experiences. Latoschik et al. [50] found that realistic avatars were rated significantly more human-like and evoked a stronger acceptance of the virtual body. Similarly, Waltemate et al. [51] concluded that personalized avatars significantly increase the sense of body ownership, presence, and dominance. Cho et al. [52] compared the actor captured by volumetric videos with the actor captured in 2D videos, and another 3D avatar obtained by pre-scanning the actor. The results show that users have the highest sense of social presence with the volumetric actor when performing dynamic tasks.

Apart from user representations, there are metrics (e.g., surveys, questionnaires) and experimental protocols that can be adapted to understand social VR experiences. Metrics for evaluating presence and immersion have been developed and widely validated, such as the presence questionnaire by Witmer and Singer [53] and the Slater-Usoh-Steed questionnaire [54]. Jennett et al. [55] suggested in their immersion questionnaire to include factors such as lack of awareness of time and involvement. Some other studies have explored user experiences in VR using different devices (e.g., 2D screens, HMDs). Srivastava et al. [56] examined how HMD and desktop would affect spatial learning when the ambulatory locomotion in HMD was restricted. They found that users spent more time and perceived less motion sickness and task effort using desktop than HMD. In their virtual earthquake training, Shu et al. [57] found that users reported a higher sense of spatial presence and immersion while using HMD than using a desktop.

Quality of experience (QoE) assesses the degree of delight or annoyance of the user of a system [58] and takes into consideration of a wide range of factors that contribute to a user's perceived quality of a system, including human, system, and context factors [59]. User experience (UX) research aims at investigating a user's perceptions and responses that result from the use and/or anticipated use of a system (ISO 9241-210:2019 [60]). UX includes both subjective evaluation of hedonic and/or meaningful experiences and emotions, and objective evaluation of the user-system interactions, such as task execution time and the number of clicks or errors. Users' expectations and motivations are important factors in UX evaluation [61]. A growing research effort is to combine the QoE and UX measurements to have a comprehensive understanding of the perceptual and experiential quality of user-system interactions in an immersive virtual environment [62]. Chessa et al. [63] combined objective measurements (i.e., heart rate and head movement) and subjective self-reports to assess how users perceived and experienced an immersive VR system, and found positive correlations between the two measurements. Chamilothori et al. [64] evaluated the adequacy of a virtual space as an alternative environment for subjective experiments by combining three metrics, namely the subjective evaluations of perceptual accuracy, the users' physiological reactions, and the presence questionnaire. Egan et al. [65] presented an evaluation study comparing immersive VR and non-VR environments, using objective metrics, including heart rate (HR) and electrodermal activity (EDA), and a subjective post-test questionnaire for evaluating immersion and usability. They found correlations between objective metrics and self-reported QoE. Further research is needed to develop a social VR experience model that combines objective and subjective metrics for measuring and predicting social VR experiences.

Though many works have attempted to measure interaction experience, presence, and immersion across real [55,66] and virtual interactions [53,67,69,70], only recently has some work address the social VR medium in general [68,71]. And though social presence measurement tools can vary (e.g., subjective self-report measures [72] or non-verbal signals such as gestures [43]), we do not yet have a validated questionnaire that can capture the richness and social interaction nuances of activities in social VR. It can get tedious to use many existing questionnaires in one single experiment. Therefore the challenge is how to combine the measurement metrics into one single questionnaire that is intended for social VR experiences. The challenge leads to two goals of the study: (1) develop a questionnaire to measure social VR (photo sharing) experiences; and (2) validate the social VR questionnaire by a (photo sharing) comparative study social VR, Skype, and Face-to-Face (F2F).

22.6.1 Developing a social VR questionnaire

We adopted a mixed-methods approach (Fig. 22.23) that combines a user-centric approach [73] and statistical techniques to develop an accurate and consistent questionnaire instrument (i.e., ensures test validity and reliability) for measuring social VR photo sharing [33].

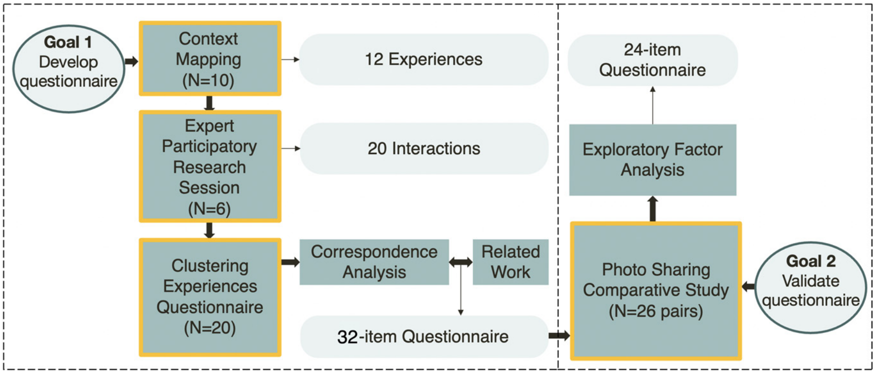

Figure 22.23 Methodological approach for constructing the social VR questionnaire.

We started with a series of user-centered studies with photo-sharing users, VR experts, and UX researchers. First, we conducted context mapping, which is a research method that involves users as "experts of their experience" [74]. With techniques such as workbooks and generative sessions, participants are facilitated to observe and reflect on the experiences of use. In the context mapping sessions, users mapped 12 typical experiences of F2F photo sharing. Based on the results of context mapping, the expert participatory session mapped 20 categories of relevant social interactions that can happen during F2F photo sharing in both the real world and in VR. Next, we designed an online questionnaire for clustering the 12 experiences based on 20 interactions, and we invited 20 UX researchers to participate [33]. Correspondence analysis of the clustering questionnaire resulted in three components of experience that are relevant to social VR, namely quality of interaction (QoI), presence and immersion (PI), and social meaning (SM).

Using the three components as guidance, we composed a 32-item social VR questionnaire.[31] The questions use a 5-point Likert scale. The question items are either derived from the well-validated questionnaires or composed based on the typical experiences mapped in the context mapping sessions.

Questions 1–11 are about QoI in social VR, which is defined as the ability of the user to interact with the virtual world and to interact with other users in that virtual world [75,76]. It assesses the quality of communication, mutual sensing of emotions, and naturalness between virtually represented users. Items 1, 2, 8, 9 were developed based on two experiences identified in the QoI cluster (i.e., feeling understood, feeling others' emotions). Items 3–7 were adapted from [67], and items 10–11 were from [77].

[31] The 32-item social VR questionnaire is available at https://www.dropbox.com/s/xhcb3zrt4fdjpkn/chi2019_32i_questionnaire.pdf?dl=0.

Questions 12–22 measure SM in social VR, which is defined as the experience of "being together," both mentally and physically. Items 12–16 were adapted from [78]; items 19–21 were from [79], and item 22 was from [76]. Items 17–18 were developed based on two experiences identified in the SM cluster (i.e., recall and recreate memories; and create stronger bonds).

Questions 23–32 measure presence and immersion. Witmer and Singer [53] defined immersion as a subjective and psychological state characterized by perceiving oneself to be involved in and interacting within a virtual environment. Item 23 was adapted from [69]. Items 24–25 were from [70]; item 26 was from[53], and items 27–32 were from [55].

22.6.2 Validating the social VR questionnaire

A within-subject controlled user study was conducted to compare photo-sharing experiences in three conditions: Face-to-Face (F2F), Facebook Spaces (FBS), and Skype (SKP). The resulting data is (a) used in the exploratory factor analysis (EFA) [80] to validate whether the three factors (i.e., QoI, PI, and SM) are indeed important to construct our social VR questionnaire, (b) provide empirical findings comparing photo sharing across study conditions using our social VR questionnaire [33].

We recruited 26 pairs of participants ($N = 52$, 23 females, $M_{age} = 27.6$, $SD_{age} = 7.9$), who are friends or colleagues. In the F2F condition, two participants were sitting together and showing each other photos on their smartphones. In the SKP condition, two participants were sitting in different rooms, and sharing photos on their smartphones through SKP. In the FBS condition, the photos were uploaded to the FBS. Two participants were sitting in different rooms, but they entered the same virtual space to share their photos represented in a smartphone display manner. After each condition, every participant filled in a social VR questionnaire.

We ran an exploratory factor analysis (EFA) [80] to better understand the important factors in our questionnaire. EFA is a statistical technique within factor analysis commonly used for scale development involving categorical and ordinal data and serves to identify a set of latent constructs underlying a battery of measured variables [81,82]. Given that our focus was to evaluate a complete list of questions, we ran our analysis only on data from the SKP and FBS evaluations (i.e., questions 24–33 for evaluating PI were removed for the F2F condition). Bartlett's sphericity test was significant ($\chi^2(2, 496) = 2207.187,\ p < 0.001$) and Kaiser–Meyer–Olkin was greater than 0.5 ($KMO = 0.85$); our data allowed for EFA. Given our earlier correspondence analysis that showed a grouping of three factors, we tested our model fit based on three factors corresponding to each set of questionnaire items. Furthermore, since we assumed that factors would be related, we used oblique rotation "oblimin" along with standard principal axes factoring. Standardized loadings are shown in Table 22.2.

Table 22.2 Exploratory factor analysis (EFA) was applied to our 32 questionnaire items. Questions in bold were kept for the 24-item social VR questionnaire.

No.		Factor 1 (PI)	Factor 2 (SM)	Factor 3 (QoI)
1	**"I was able to feel my partner's emotion during the photo sharing."**			**0.61**
2	**"I was sure that my partner often felt my emotion."**			**0.67**
3	"It was easy for me to contribute to the conversation."	0.17	0.44	0.37
4	"The conversation seemed highly interactive."	0.36	0.26	0.33
5	**"I could readily tell when my partner was listening to me."**			**0.60**
6	"I found it difficult to keep track of the conversation."	-0.12	0.45	0.36
7	"I felt completely absorbed in the conversation."	0.33	0.44	0.18
8	**"I could fully understand what my partner was talking about."**		0.18	**0.71**
9	**"I was sure that my partner understood what I was talking about."**			**0.73**
10	"The experience of photo sharing seemed natural."	0.51		0.41
11	**"The actions used to interact with my partner were natural."**	**0.36**		0.24
12	**"I often felt as if I was all alone during the photo sharing."**		**0.62**	0.20
13	**"I think my partner often felt alone during the photo sharing."**		**0.62**	0.20
14	**"I often felt that my partner and I were sitting together in the same space."**	0.82		0.16
15	**"I paid close attention to my partner."**	0.14	0.12	**0.38**
16	**"My partner was easily distracted when other things were going on around us."**	-0.20	0.32	0.26
17	**"I felt that the photo-sharing enhanced our closeness."**	**0.42**	0.21	
18	"Through the photo-sharing, I managed to share my memories with my partner."	0.11	0.41	0.37
19	**"I derived little satisfaction from photo sharing with my partner."**	0.12	**0.56**	
20	**"The photo-sharing experience with my partner felt superficial."**		**0.54**	0.18
21	**"I really enjoyed the time spent with my partner."**	0.18	**0.43**	0.29
22	"How emotionally close to your partner do you feel now?"	0.13	0.23	0.25

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Table 22.2 (*continued*)

No.		Factor 1 (PI)	Factor 2 (SM)	Factor 3 (QoI)
23	**"I had a sense of being in the same space with my partner."**	**0.92**		
24	**"Somehow I felt that the same space was surrounding me and my partner."**	**0.87**	0.12	-0.15
25	**"I had a sense of interacting with my partner in the same space, rather than doing it through a system."**	**0.88**		
26	**"My photo sharing experience seemed as if it was a face-to-face sharing."**	**0.80**	-0.22	0.27
27	**"I did not notice what was happening around me during the photo sharing." ⋆**	**0.52**	0.30	-0.12
28	**"I felt detached from the world around me during the photo sharing." ⋆**	**0.71**	0.20	-0.20
29	"At the time, I was totally focusing on photo sharing."	0.36	0.38	
30	**"Everyday thoughts and concerns were still very much on my mind."**		**0.69**	-0.16
31	**"It felt like the photo-sharing took shorter time than it really was."**	0.25	**0.31**	
32	**"When sharing the photos, time appeared to go by very slowly."**	-0.10	**0.54**	
	SS loadings	5.67	3.83	3.65
	Proportion Variance	0.18	0.12	0.11
	Cumulative Variance	0.18	0.29	0.41

To ensure the factors are meaningful and redundancies eliminated (removing collinearity effects), we only took items with factor loadings of 0.3 and above, and with cross-loadings not less than 0.2 across factors. The cumulative explained variance of the three factors is 41%. The 24 questionnaire items[32] in bold were used for the evaluation of the three conditions (F2F, FBS, and SKP) along with the identified concepts: quality of interaction (QoI), social meaning (SM), and presence/immersion (PI). We furthermore tested each set of items for internal reliability by measuring Cronbach's alpha, and our final item sets show high reliability coefficients: F2F QoI ($\alpha = 0.8$), F2F SM ($\alpha = 0.89$), F2F PI ($\alpha = 0.74$), FBS QoI ($\alpha = 0.79$), FBS SM ($\alpha = 0.83$), FBS PI ($\alpha = 0.76$), SKP QoI ($\alpha = 0.78$), SKP SM ($\alpha = 0.79$), SKP PI ($\alpha = 0.75$).

As a first step towards external validity, we ran a controlled user study to compare photo-sharing experiences under F2F, SKP, and FBS. The detailed data analysis and results were presented in [17]. Based on our developed social VR questionnaire, we found

[32] The 24-item social VR questionnaire is available at https://www.dropbox.com/s/xnnn6b6i3kyl45r/chi2019_24i_questionnaire.pdf?dl=0.

that social VR is capable of closely approximating F2F sharing. Our questionnaire contribution and our empirical findings concerning photo-sharing experiences can provide researchers and designers with a tool to measure such reality-grounded activities.

Factor loadings of 0.3 and above and without cross-loadings of >0.3 are marked in bold.

22.7. Discussion

This chapter introduces the design, implementation, and evaluation of a series of social VR applications, covering healthcare, celebration, cultural heritage, and entertainment domains. We also presented a user-centered process of developing a social VR questionnaire and conducting a user experiment in a social VR environment (i.e., Facebook Spaces) to validate the questionnaire. This section discusses the lessons learned and provides several design recommendations.

22.7.1 Lessons learned and opportunities of social VR

22.7.1.1 Controlled experiments versus real-world products

The design and implementation of the applications focus on optimizing the user experiences, but are not all intended for laboratory experiments. Therefore not all aspects were fully controlled during the evaluation experiments. For example, the novel virtual movie was professionally produced by cinematography experts, which was not designed for laboratory experiments. The locomotion and interaction techniques used by HMD and screen users are not the same. To minimize the cybersickness, HMD users can only teleport among fixed locations in the virtual apartment, but screen users can move freely using the joystick on the controller. However, the goal of our evaluation studies is to exploratively evaluate possible user experiences in these novel immersive applications. We had to find the right balance between the "controlled experiments" and the "real products or applications." These real products or applications are not only operable in the laboratory, but also deployable to the real environment. We primed the aesthetics and user experience aspects over the perfectly controlled aspects. We find this important since we can derive important insights about user experiences in real-world setups.

22.7.1.2 Virtual representation and privacy

Privacy as a topic emerged during most user interviews. For example, in the social VR clinic evaluation, many users mentioned that they felt more relaxed and private in the social VR clinic than the F2F consultation, because their faces were hidden from the nurse. They do not need to pay attention to whether they look decent or whether their homes are tidy as they usually care during a video consultation [83]. However, the nurses or doctors stress, during remote consultations that it is necessary to see the patients' faces, to better understand their physical and mental conditions

[83]. The growing prevalence of real-time photorealistic human representations in VR (e.g., [9,84]) and research works on HMD removal [85] are all trying to make the user face visible to enhance the presence and immersive experience. However, the trade-off between the realism of the user representations and the privacy protections should be considered in future work.

22.7.1.3 Social VR as an extension of 2D video conferencing

As an extension to technology-mediated communication technologies, such as 2D video conferencing, social VR provides many benefits. First, social VR immerses the users in the same virtual world, providing a more realistic experience [86]. Li et al. [17] commented that the screen in video conferencing is like a "curtain" between two users, cutting off the sense of co-presence. Second, social VR uses virtual representations to offer embodiment experiences to users, and abilities to interact with the virtual environment and 3D virtual artifacts [87]. As we observed in the user evaluation of the social VR clinic, the guided "walk-in" experience, and 3D interactive anatomical models are more appreciated than watching the same content on a TV screen. Not only co-presence, but social VR also brings social connectedness and empathy to the experience, allowing people to see and feel from other persons' perspective. For instance, social VR can be used to train young physicians by simulating the circumstances the patients are going through, increasing their empathy and bonding towards the patients. Further use cases are needed to explore the potential of social VR.

22.7.1.4 Opportunities for controlled experiments

We identified many potential factors that require further investigation in a controlled manner, such as the influence of locomotion methods on users' cybersickness, (social) presence, and quality of interaction. In the social VR movie application, many users mentioned that they would have more interaction possibilities with the movie characters, the other users, and the virtual environment, indicating another research opportunity to investigate the influence of interactions on users' experiences. In addition, we also observed that there were differences in users' movement trajectories and differences in users' experiences using the devices. For instance, we noticed that male screen users moved more quickly and more frequently than female screen users, and their trajectories covered the whole virtual apartment. It also seemed that experienced VR game users finished the tasks faster than inexperienced users (e.g., find and switch on the light). We would like to further collect and analyze objective data from the users, such as movements, trajectories, gaze directions, operation errors, completion time, and audio sentiments to understand users' proxemics, social interactions, and emotions in virtual spaces. To do so, we need new production workflows that can create virtual movies that allow more interactions and can be instrumented to run controlled experiments.

22.7.1.5 Production opportunities for immersive narrative experiences

Recently, many novel media-watching experiences have been developed, such as interactive narratives that invite viewers to choose paths for lead characters (e.g., Black Mirror: Bandersnatch [88]); social TV or multiscreen TV that enable viewers to customize their viewing content and to comment during a show [89]; and cinematic VR with 360° videos that allow users to choose viewports [90]. However, these experiences were either limited at the interaction level or lacked narrativity. We expect that immersive and interactive movies with volumetric user representations will be the next innovation of media watching, where viewers are represented realistically and have the opportunity to sing along with the artists, re-watching a movie "inside," or even become a character in it. Schreer et al. [91] concluded the production challenges after one year of commercial volumetric video production, such as recording fast movements (e.g., basketball players); enabling a convincing integration of an actor into a virtual scene; recording extensive movements (e.g., walking along a road). Apart from volumetric videos, we are facing challenges in many other aspects of cinematic productions, including spatial audio design [92], attracting and directing viewers' attention [93], and creating interactable virtual objects and environments [94]. Crafting such new experiences requires incorporating interactive narratives, viewers' co-presence, interactive virtual environments, and social communications into production workflows.

22.7.2 Design recommendations for social VR

22.7.2.1 Conveying emotions in social VR

In many real-world deployments of our social VR applications, we found that the lack of facial expressions reduced the emotional connection between users, which negatively influenced the engagement of some participants. We recommend that it is important to enable the virtual human representations to show facial expressions or to implement a virtual interface for users to express visually their emotions. There is an increasing number of researchers working on removing the HMD to show the user's whole face in these volumetric representations [85], and training machine learning models to estimate emotions from the images of human faces wearing an HMD [95]. Another direction is to include visual cues of emotions in social VR. For example, emoticons and emojis are effective in conveying emotions in text messages [96]. We foresee the opportunities for designing new emoticons and emojis specifically for the virtual world, where users can experience new ways to use and interact with emoticons and emojis (e.g., throw an emoji to the air). Obrist et al. [97] investigated innovative mid-air haptic descriptions of specific emotions (e.g., happy, sad, excited, afraid), which inspires us to think about including these haptic descriptions in the next generation of virtual input devices (e.g., hand controllers).

22.7.2.2 Creative virtual environment

Users often comment that even the virtual environment looks realistic; it offers limited interaction resources, and there is a lack of serendipity to inspire them. We recommend that future social VR applications should, on one hand, provide sufficient resources (e.g., including an Internet search engine or various datasets for 3D models), and on the other hand, facilitate users to self-create virtual objects. For example, enable real-size 3D modeling or facilitate the interaction through brain-computer interfaces (BCIs) [98,99]. We see the potential of BCIs in automatically navigating users through the virtual space, enabling them to interact with virtual objects through mind-controlling, or in a more advanced manner, generating virtual visualizations based on users' thoughts.

22.7.2.3 Recreating the senses in social VR

In the *CakeVR* application, the users agreed that the 3D real-size virtual cake visualizations provide an instant overview of the co-design outcome. However, the fidelity of the virtual cake is not sufficient for them to imagine the flavor and texture of the cake. We would like to research recreating food-related senses in social VR, such as feeling the texture of a soft chiffon cake and a fluffy velvet cake, or even simulating the taste of the flavors. With incorporating haptic devices [100], the simulation of grasping, squeezing, pressing, lifting, and stroking in VR is getting promising. The handheld controllers developed by Benko et al. [101] enable users to feel 3D surfaces, textures, and forces that match the visual rendering. Apart from the multi-sensory experiences interacting with virtual objects, recreating the senses in the virtual environment is also an interesting direction to enhance the presence of social VR users. For example, the HMD accessories developed by Ranasinghe et al. [102] provide thermal and wind stimuli to simulate real-world environmental conditions, such as ambient temperatures and wind conditions.

22.7.2.4 Depth of interaction and fatigue

Many of our social VR applications aimed to cover the breadth of interaction to ensure users can have a complete virtual cake co-design, virtual clinic, or virtual museum experience. However, it is interesting to consider each sub-aspect of this experience. For example, what is the impact of creating impossible cakes or creating beyond-reality experiences, and how does that push designers to think more imaginatively inside the HMD? How can specific interactions (e.g., object snapping or finalizing a scale, and by whom) create more seamless interactions? In all the deployments, no users reported fatigue in using our applications. However, this needs further study for longer interaction periods, which may affect some users (e.g., older adults) [103].

22.7.2.5 Beyond reality experiences in social VR

During interviews of the social VR questionnaire validation study, a quarter of users stated they would like to perform activities in social VR that are not possible in the real world. Though exploring imaginary activities was not in our scope, it raises an important question about the role of social VR: are we more concerned with adapting our real-world social activities to social VR as is, or do we want to infuse our social environment with imaginary elements (e.g., do activities together on a virtual mountain)? Relatedly, should we relive the actual photo content, and will that exceed our experiences of collocated photo sharing? Though such questions may seem far away from current social VR technology, it highlights not only the role of embodiment in activities, such as photo sharing, but also what type of embodiment we assume [51]. For example, Schwind et al. [104] showed that women perceive lower levels of presence while using male avatar hands. Within our context, if a person shares a photograph of a time he was in the hospital with his friend, should the friend relive this memory by also being in the hospital, or from a 3rd person's point of view? Whose perspective do we take, the person as a patient or that of a supporting friend, and how does this affect the sense of presence? We can speculate whether our future communication tools (e.g., 3D video conferencing) should simulate physical F2F interactions as realistically as possible, or instead push activities only possible in the virtual world. For our social VR questionnaire, though it can be adapted to other social activities (e.g., collaborative tasks, gaming), these adaptations are assumed to be grounded in social interactions we draw from experience. The foregoing brings to question the underlying assumption that our current "gold standard" of comparing against F2F interactions will be the baseline of the future.

22.8. Conclusion

To achieve a more sustainable way of living, we are facing increasing pressure to reduce travel. Still, as a society, we need to efficiently and effectively, remotely and naturally, access healthcare and educational resources and collaborate. This first part of the chapter provides an overview of the design, implementation, and real-world deployment of social VR applications of multiple domains, supporting the remote communication of personalized healthcare, celebration, interactive access to cultural heritage, and immersive entertainment. The second part presents two experimental protocols: one is for developing and validating a social VR questionnaire based on a user-centered process; the other is for evaluating the visual quality of photorealistic digital humans in 3DoF and 6DoF conditions. As an emerging technology, social VR requires (1) the development of a standard protocol, including a set of qualitative and quantitative metrics for evaluating user experiences, and (2) a standard procedure of deploying social VR applications in the real world (e.g., hospitals and museums).

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