Emerging Immersive Communication Systems: Overview, Taxonomy, and Good Practises for QoE Assessment

Pablo Pérez, Ester Gonzalez-Sosa, Jesús Gutiérrez, and Narciso García

1 eXtended Reality Lab, Nokia, Madrid, Spain
2 Grupo de Tratamiento de Imágenes, Universidad Politécnica de Madrid, Spain

Correspondence*: Pablo Pérez
pablo.perez@nokia.com

ABSTRACT

Several technological and scientific advances have been achieved recently in the fields of immersive systems (e.g., 360-degree/multiview video systems, augmented/mixed/virtual reality systems, immersive audio-haptic systems, etc.), which are offering new possibilities to applications and services in different communication domains, such as entertainment, virtual conferencing, working meetings, social relations, healthcare, and industry. Users of these immersive technologies can explore and experience the stimuli in a more interactive and personalized way than previous technologies (e.g., 2D video). Thus, considering the new technological challenges related to these systems and the new perceptual dimensions and interaction behaviors involved, a deep understanding of the users’ Quality of Experience (QoE) is required to satisfy their demands and expectations. In this sense, it is essential to foster the research on evaluating the QoE of immersive communication systems, since this will provide useful outcomes to optimize them and to identify the factors that can deteriorate the user experience. With this aim, subjective tests are usually performed following standard methodologies (e.g., ITU recommendations), which are designed for specific technologies and services. Although numerous user studies have been already published, there are no recommendations or standards that define common testing methodologies to be applied to evaluate immersive communication systems, such as those developed for images and video. Taking this into account, a revision of the QoE evaluation methods designed for previous technologies is required to develop robust and reliable methodologies for immersive communication systems. Thus, the objective of this paper is to provide an overview of existing immersive communication systems and related user studies, which can help on the definition of basic guidelines and testing methodologies to be used when performing user tests of immersive communication systems, such as 360-degree video-based telepresence, avatar-based social VR, cooperative AR, etc.

Keywords: immersive, communication, systems, quality of experience, evaluation, virtual reality, augmented reality, telepresence

1 INTRODUCTION

Immersion is the main factor that differentiates Virtual Reality (VR) technologies from traditional computer-mediated communication systems (e.g: videoconferencing). In the last decades, and now even more since
the COVID-19 pandemic situation, many works on immersive communication systems have been proposed. The umbrella of XR technologies is very extensive, ranging from VR places [Sanchez-Vives and Slater (2005)], local spaces augmented with Augmented Reality (AR) [Billinghurst et al. (2014); Kim et al. (2018)], or even the emerging hybrid technologies of Mixed Reality (MR) and Extended Reality (XR) that exploits state-of-the-art technologies such as spatial computing, computer vision, 360 video, among others.

Despite the growing number of existing works, little efforts have been done to understand the whole spectrum of works from which to conform a general common vision. Ideally, such common vision would allow researchers to characterize any immersive communication system by their main perceptual and technological pieces, as well as make fair comparisons between systems. Likewise, there is not a common/standard Quality of Experience (QoE) assessment framework that could in turn assess the related technical and perceptual items of such systems.

As already stated by Steed (2021) in what concerns the use of MR for human communications, there is a real need establish some common metrics that can be used to establish the quality of communication and interaction between people, standardized social tasks, and the quality of the MR-base communication through time.

Overall, the contributions of this paper are:

- the proposal of a new taxonomy able to describe immersive communication systems based on key perceptual features.
- a concept map that shells out the different technological components that could conform a given immersive communication.
- a comprehensive discussion of related immersive communication works attending to the proposed taxonomy.
- a thorough analysis of the Quality of Experience evaluation methods carried out in these related works, to understand whether there is (or not) similarities in what concerns QoE methods between works that lies in the same space of the proposed taxonomy.

We believe these contributions will be of relevance to the community of immersive communication as well as VR, AR, MR, and XR, in the form of good practises and recommendations, so that they could build upon the proposed taxonomy, inspire with ideas to solve most important challenges in the field, among others.

The remainder of this review is organized as follows. Section 2 presents the taxonomy for immersive communication, as well as the conceptual map that associated technological components of immersive communications with proposed technologies. Section 3 describes related work attending to the proposed taxonomy. Section 4 describes how Quality of Experience is assessed in the related works. Then section 5 provides a discussion on important aspects of QoE assessment in immersive communication systems, as well as a set of good practises. Conclusions and future lines of work are reported in section 6.

2 A TAXONOMY OF IMMERSIVE COMMUNICATION SYSTEMS

Immersive communication systems are used to elicit place presence, social presence, co-presence and other psychological concepts. This is done through several technical features: use of large or head-mounted displays, volumetric capture and representation of participants, transmission of immersive video from a remote area, etc. As the technology is evolving quickly, there are dozens of different proposals, mostly
experimental, of such systems. Therefore a taxonomy is needed to classify those systems according to their most relevant characteristics.

To build such taxonomy, we have studied the state of the art of immersive communication systems, analyzing their technology and proposed use cases, searching for similarities and differences. For the sake of the clarity of the presentation, we will describe first our proposed taxonomy, which we will use to structure the description of the related work in section 3.

A possible analysis line would be to detail the different technology blocks involved in each system, as proposed by Park and Kim (2022). However, this easily results in a large number of classification elements, and therefore a much larger number of categories. A different approach would be focusing on the different psychological and QoE values they provide, e.g. place presence, social presence or avatar embodiment. However, as totally different systems may elicit similar psychological properties, this would not be a very effective classification criterion. Besides, subjective mental states such as presence are heavily influenced by context factors completely independent of the system itself.

In an intermediate approach, our taxonomy is based on perceptual features provided by the system. Our idea is that immersive communication systems try to emulate in-person communication, ideally aiming at achieving total equivalence to a physical meeting. As this task is not achievable in general, different systems focus on different aspects of the communication. Based on this idea, it is possible to identify four basic communication elements (depicted in Figure 1) that are the building blocks of those systems: Face, Visit, Meet and Move.

**Table 1.** Fundamental elements of an immersive communication system

| Element | Face | Visit | Meet | Move |
|---------|------|-------|------|------|
| Perceptual prop | Visual communication | Remote presence | Shared immersion | Embodied interaction |
| Experience | I see you | I see what you see | I am with you | I control objects |
| Paradigm | Face-to-face | Shoulder-to-shoulder | Hand-in-hand | Hand-to-world |

1. **Face** is the property of the system to transmit in real time a visual representation of the other person, e.g. through a video-conferencing system. This element enables **visual communication**. Seeing the other person is key to transmit non-verbal communication cues, including showing objects of the personal space.
Figure 2. Components of an immersive communication system. It include the main categories, a two-level classification of technologies within those categories, and one example for each of them, mostly from commercial products. Categories intend to be exhaustive; examples do not.

2. **Visit** is the property of the system to transmit in real time a visual representation of the surroundings of the other person. This enables remote presence: seeing the physical environment of the other person and being able to operate and discuss about it.

3. **Meet** is the property of the system to represent the other person in the same (virtual or physical) space as the user. This enables shared immersion: being immersed in the same (virtual or physical) environment and interacting with the same (virtual or physical) objects.

4. **Move** is the property of the system itself to represent the user within it and enable its embodied interaction. It means that the actions of the users are represented within the system and allow the user to interact with it.
Table 1 describes these elements from several perspectives. First of all, by describing the main perceptual property provided by each element. Those properties are purely perceptual, i.e., they describe what the user *can see* (or do) in the system. They are related with the psychological properties of immersive communication experiences, such as spatial presence, social presence or avatar embodiment. However, since the relationship between the technology and the these psychological aspects is not trivial, we will not use them in our taxonomy. Other perspective that is used in Table 1 is the description of the most relevant communication feature which is enabled by each of the elements. This is done by describing the communication *experience* (e.g. “I see you”) and *paradigm* (e.g. “face-to-face”) associated to each of the elements.

Besides the different combination of fundamental elements they implement, immersive communication systems can be characterized by the technological components they are composed of (Figure 2):

- **Display**: Immersive systems typically use Head-Mounted Displays (HMDs) of any kind: AR, VR, or XR (VR display with attached camera to allow video pass-through). Large size screens, either 2D or 3D (light field displays) may also be used.
- **Avatar view** (how the user sees the other person) can be a Computer-generated imagery (CGI) model, animated by the application engine, or a real-time stream coming from a set of cameras. Different technologies are possible in either option.
- **World view** (how the user sees the surroundings of the other user). Again, the other user can be seen as part of an immersive video capture, or just immersed in a CGI environment, which may be a representation of the physical environment around the user or a completely virtual world. Some systems (e.g. AR) do not show any remote/virtual world at all.
- **Self-view** (how the user sees her/himself). VR/XR displays block the user direct self-view, resulting in the user not seeing him/herself, or getting a mediated view: either an avatar representation or a video pass-through. AR HMDs and screens keep direct view of users’ self.
- **HCI** interface (how the user can interact with the system). Different Human-Computer Interaction (HCI) technologies are possible: eye or head tracking, hand tracking/gestures, or different types of controllers.
- **Action**. Which *types* of actions are allowed in the system: whether they allow the user to move (locomotion), to interact with objects, or to point to specific locations. Besides, whether the action has *effect* in the physical world (e.g. by moving a physical robot), just in the virtual environment, or in a virtual representation of the physical world (twin).

It is worth noting that both the communication elements in Table 1 and the system components from Figure 2 are described from the perspective of the *receiver* of the communication. This distinction is important because some communication systems are not symmetrical, and therefore they may provide different fundamental elements, as well as use different types of technologies, to each side of the communication. E.g. transmitting the user environment in one direction (*Visit*) and the user image in the other (*Face*).

The first three fundamental elements (**Face**, **Visit**, and **Meet**) are related with human communication. They are not easy to fulfill simultaneously, and therefore they allow to classify systems between whether they focus in fulfilling one or the other. In fact, they allow us to define seven *archetypes* of immersive communication systems (plus two non-immersive), not only from the perspective of the fundamental
elements, but also from some of the implementation components. Figure 3 shows graphically those archetypes and their relations, and Table 2 shows which technical components are used in each of them.

Table 2. Implementation of the immersive communication system archetypes.

| Archetype                     | Elements† | Display   | Avatar View | World View | Action* |
|-------------------------------|-----------|-----------|-------------|------------|---------|
| Face-to-face Window           | F         | 2D/3D Screen | 2D/3D Video | N/A        | -       |
| Shared VR                     | M         | VR HMD    | CGI         | O, P, L (virt) |
| Remote Assistance            | V         | VR HMD    | N/A         | 2D/360 Video | P (twin/phy) |
| Social XR                     | F, M      | HMD       | 2D/3D Video | CGI        | O, P, L (virt) |
| Immersive Digital Twin       | M, V      | VR HMD    | CGI         | 3D Photo   | O, P (twin) |
| Immersive Telepresence        | V, F      | HMD       | 360 video   | O, P (twin) |
| Distributed Reality          | F, M, V   | Concept Only |            |            |         |
| AR Host                       | M (simple)| AR HMD    | CGI cues    | N/A        | P (twin) |
| Audio conference              | -         | Screen    | Icons       | -          | -       |

†F(ace), V(isit), M(eet).
*O(bject), P(ointer), L(ocomotion); phy(sical), virt(ual), twin.

Three archetypes refer to communication systems focusing on only one of the fundamental elements. They are the simplest ones and, in fact, several commercial systems already exist for all of them:

- **Face-to-face window** systems are typically based on video-conference screens and cameras. Conventional videoconferencing software follows this paradigm, but in this article we will refer to more immersive solutions involving natural-size appearance.

- **Shared Virtual Reality** (also known as Shared Virtual Environment) are multi-user VR applications where each user is represented by an avatar in a common virtual space.

- **Remote Assistance** applications allow a remote on-field person (the “host”) to point a camera to the scene of interest so that the system user (the “visitor”) can see it in real time. Both users share the same point of view.

Three more archetypes cover two fundamental elements simultaneously. These systems are typically experimental, and are mostly described in scientific literature; although some start-up companies also implement commercial prototypes:

- **Social eXtended Reality**. It is the integration of real-time capture of a person, typically using volumetric video systems, into a shared virtual environment.

- **Immersive Telepresence**. It is the extension of remote assistance applications by using an immersive camera (360) which is separate from the “host” user, so that the “host” is also seen in the video scene and therefore visual communication is possible (together with shared exploration of the remote environment).

- **Immersive Digital Twin**. It is an extension of a Shared VR experience where the virtual environment is a digital representation (“digital twin”) of a physical location, at least from a visual representation perspective. Actions on the digital twin should have also effect on the physical world.

The **Distributed Reality** archetype covers all three elements simultaneously. So far, no system can cover the three of them in a significant way: only some conceptual design exists, together with fictional systems in fiction works, such as books or movies.
Archetypes which contain the *Visit* element are typically asymmetric: the “visitor” user feels immersed within the environment of the “host”, but not the other way around. The reverse side of the communication (“visitor” to “host”) normally follows one of the two paradigms:

- **AR Host.** The host user wears an Augmented Reality HMD. Some visual cues are represented in the AR scene to represent the “visitor” user (i.e., there is a simple version of the “Meet” element), but not a full embodied avatar. Such cues can be also presented in regular phone or tablet displays or through the use of projectors.

- **Audio Conference.** In those systems, all the communication is done through audio, although some visual information may also be included: list of participants, presence status for each of them, who is speaking, etc.

Finally, the **Move** element is somehow orthogonal to the other three. Regarding the technological components, it is mostly related to the self-view and HCI technologies. There is a basic dependency between the display technology and self view: screen and AR HMD displays allow direct self-view of the user, while fully occlusive HMDs (VR/XR) impose a mediated representation, or no self-view at all. Except of that (relevant) restriction, different self-perception and interaction technologies can be integrated with any system, independently of the communication paradigm which is applied.

## 3 OVERVIEW OF SYSTEMS

This section intends to describe related works following the taxonomy presented in section 2. It is our objective to focus exclusively on research or industrial attempts that move forward from the traditional video conferencing systems by enhancing some of their limitations. However, this overview does not claim
Figure 4. Representative examples from the different immersive communication archetypes: from top to bottom and left to right: a) Google Starline by Lawrence et al. (2021) for Face-to-face window, Horizon Workrooms by Meta for Shared Virtual Reality, Remote Collaboration by Gao et al. (2018) for Remote Assistance, VR Together by Prins et al. (2018) for Social Extended Reality, The Owl by Kachach et al. (2021) for Immersive Telepresence, and Mini me by Prumsomboon et al. (2018) for Digital Twin.

to be an exhaustive state of the art, but rather a selection of key representative systems that showcase the different archetypes of immersive communication systems. It also shows that most of the immersive communication systems existing both in the scientific literature and in commercial services closely map to one of the archetypes that we have described, as depicted in Figure 4. Likewise section 2, notice that all system descriptions are done from the perspective of the receiver of the immersive communication.

Systems that prioritize visual communication, that lies in the face-to-face window archetypes focus all their efforts on achieving a very realistic representation of the user appearance and the counterpart dynamics that convey non verbal communication cues. Kauff and Schreer (2002) were one of the first one to propose a solution in this line: 3D video-conferencing systems. This system was built around the idea of having meetings using a shared real/virtual table. At the real half of the table, local participants are sat down. The remote part of the table is captured and displayed using a 2D screen placed in such a way that creates the illusion that the real table is extended with the remote table. Even tough remote users are captured using conventional 2D video cameras, their efforts towards making the display to look as an extended 3D space, creates the illusion of a 3D immersive system. This 3D video conferencing system has been later converted into a product by Cisco, with their Cisco telepresence system Szigeti et al. (2009), that continues to be commercialized nowadays. More recently, Lawrence et al. (2021) proposes Google Startline, a more sophisticated and advanced system that enables 3D high resolution capturing through three synchronized stereo RGB-D cameras and audiovisual fidelity through the lenticular display that combines the different video streams using appropriate blending weights. This way, Google Startline ensures stereopsis, motion parallax, and spatialized audio. Other related factors and systems are under development within academic research groups, such as showing the remote partner near the user gaze point (Kim et al., 2019b), or aiming at allowing real-time communication and exploration of the remote environment through Free Viewpoint Video systems (FVV) (Carballeira et al., 2021). All these systems have as their final aim to maximize the face to face communication.
Shared Virtual Reality is the archetype that focuses on shared immersion as fundamental element. The idea was already explored in the early days of Virtual Reality, as described in Durlach and Slater (2000), and today it is mature enough to be widely available commercially. This is the case of Shared VR platforms such as Mozilla Hubs from Mozilla, Virbela by Virbela, Facebook Spaces or Horizon Workrooms from Meta, AltSpace from Microsoft, to name a few. What all these platforms offer to users is the possibility to meet with other people in a virtual space, normally computer generated. Communication can revolve around a conversation on any topic, or it can revolve around the joint observation of an element (e.g. a video, a virtual object) within the scene, or the scene itself. User representations are normally computer generated, but differs in the level of realism and personalization. Hubs uses cartoonish avatars ranging from robots, animals, or human with combination of different demographics and face accessories that might be aligned with user’s profile; Horizon Workrooms and Virbela allow to use as their virtual representation a fully customized avatar of their own person. Some academic works have also explored this type of systems, such as Pan and Steed (2017); Li et al. (2019). A detailed study on several Shared VR platforms can be found in McVeigh-Schultz et al. (2019).

Social Extended Reality is a system archetype that addresses both visual communication and shared immersion. Microsoft Holoportation system developed by Orts-Escolano et al. (2016) and its foreseen evolution Mesh (Microsoft, 2021), as well as VR Together solution studied in Gunkel et al. (2018); Li et al. (2021), are examples of these immersive communication systems that maximizes both user realism and the possibility to see things together virtual. Differing from the given examples of pure visual communication, here the use of a Virtual Reality or Augmented Reality HMDs are required. Also, unlike the given examples of pure shared immersion, the realism of users is important. Earlier versions simply inserted a 2D video of the remote user within the AR or VR environment, as in Lawrence et al. (2018); Prins et al. (2018). In more advanced implementations, such as the aforementioned Holoportation and VR Together, users are represented using 3D point clouds obtained from volumetric video capture. Should there are spatial constrains for full-size avatar placement, the use of miniature versions is becoming a common practise (Pliumsomboon et al., 2018), yet eye contact needs to be carefully designed (Anjos et al., 2019).

Immersive communications focusing on exploration tasks benefits more from the use of remote assistance systems. In this context, the user (the “visitor”) provides practical expertise to the remote use (the “host”) who is physically located in an area of interest. Usually a 360° video camera is capturing the area of interest and is transmitted so that the user wearing VR HMD can explore. Kasahara et al. (2017) proposes Jack in Head, a telepresence system in which the host is wearing a head-mounted omnidirectional camera, composed of nine cameras around the user’s head and backpack containing laptop computer. As already mentioned, system archetypes which contain the Visit element are typically asymmetric (see Figure 5). In the particular case of Jack in Head, the reverse side, that is communication that the host received from the visitor, is purely based on audio cues.

The work by Wang et al. (2020) relies on the use of a 2D conventional camera capturing at 1280 × 960. Although not immersive, the 2D camera feed is rendered in Unity 3D in a particular plane, allowing the user to see it while wearing the HMD. In this case, the reverse side falls in AR Host archetype, yet using a standard projector and not AR goggles. In this work, apart from audio communication, the host might has further visual cues such as cursor pointer, head pointer or eye gaze from the visitor.

Most remote assistance related works rely on the use of a commercial 360° video camera placed on the head of the host. Representative examples are the work by Lee et al. (2018); Teo et al. (2019a); Young et al. (2019), who proposed the use of a Ricoh Theta S 360° to capture 360° video and stream it to the visitor. For those use cases where the area of interest is mainly static, there are also hybrid immersive approaches.
resulting from the combination of 3D reconstructed environment and live 360° video panorama camera (Teo et al., 2019b, 2020). In turn, all these systems share the use of AR Host archetype with AR googles as the mainstream system for the reverse side. In particular, AR google can render visual cues made by the user such as: gaze, user awareness, hand gestures (Teo et al., 2019a) (easily inferred through the use of hand trackers such as Leap Motion), hand pointing (Kim et al., 2020) or annotations through the use of VR controllers (Teo et al., 2019a).

One important concern related to these systems is how to impair the cybersickness resulting from the movement of the host user wearing the omnidirectional camera. As reported by several authors such as Singla et al. (2017); Pérez et al. (2018), the onset of cybersickness in 360 video is mostly triggered by the accelerated motion of the capture camera. In this sense, the system by Kasahara et al. (2017) proposed the use of some image-processing algorithm to diminish the rotational motion and achieve therefore real time camera stabilization and cybersickness alleviation.

In the intersection between remote assistance and face-to-face window archetype lies immersive telepresence systems. This type of immersive systems are characterized by the use of a 360 camera that, unlike the remote assistance systems, is not placed on the user’s head (which allows having the same vision as the user), but rather placed using a tripod, held by the hands of a user, or even placed on top of a robot (Zhang et al., 2020). While communication happening in remote assistance or face-to-face window systems is normally centered between two people, immersive telepresence systems are designed for multi-user use cases, with a minimum of 2 people but can reach up to N users, normally limited by the technological limitations of the system. As an evolution of remote assistance systems, Giant miniature
collaboration, the system prototype proposed by Piumsomboon et al. (2019), aims to connect visitor and host, while the host carries the 360° camera on his/her hand, allowing this way the user to see the host face.

Show me around, the system proposed by Nassani et al. (2021), has been designed for immersive Virtual Tours. One of the participants in the area of interest holds a Ricoh Theta V 360° camera connected laptop computer with audio headphones and a microphone to capture the whole scene where the guide is also present. This 360 video is integrated into the open source video conferencing platform Jitsi, which allows a large number of users (20 – 30) to access this immersive content through a 2D screen, although without using VR goggles. Likewise remote assistance system, immersive telepresence systems are asymmetric. In the work by Nassani et al. (2021), the reserve side is within the classification of AR host, as the remote user physically co-located with the 360° camera, can see through a screen, 2D videos of every user connected to the session (as in regular 2D videoconferencing), along with hand pointing cues that are overlapped to the also displayed 360° scene.

Exleap, an immersive telepresence system done by Izumihara et al. (2019) allow users the possibility to move around the area of interest through the use of different 360° camera, which are placed at strategic positions, creating the experience of leaping between places. To achieve this, it is only required VR goggles. At the reverse side, the communication is pure audio along with a led string wrapping the camera node to indicate existence of users and respective direction. Owl is also an immersive telepresence system developed by Kachach et al. (2021). It consist on a low cost prototype consisting on either Ricoh Theta V 360° or Vuze XR as omnidirectional cameras along with Raspberry Pi with a touchscreen, a standard hands-free speaker, a 4G/5G modem, and a powerbank, all placed in a custom 3D-printed housing. Then different users joining the session can experience the real space as if they were there using VR googles such as Quest2. Alternatively, Vuze XR can also work in 180° stereo mode, providing the user depth perception. Further, they have the possibility to see avatars of other users joining the session, as well as content such as pdf or images while being immersed. At the reverse side, the system archetype is pure audio communication. In this regard, there are other related works such as Think Fast (Zhang et al., 2020) that represent the visitor depicting his avatar in a tablet attached to the 360 camera, or even by rendering his upper body on top of the robot so that the host can see him/her using AR glasses.

Recent works also offers the possibility of 3D panorama streaming. Bai et al. (2020) developed a 3D panorama sensor cluster that supports instant 3D reconstruction with real-time updating. This is done through a cluster of assembled eight off-the-shelf RGB-Depth cameras into a sensor cluster, which are correctly aligned to create a semi-sphere with no gaps. At the reverse side an AR host system is found. Gaze is depicted as a virtual ray cast line and hand gestures as represented using a 3D mesh of the user’s hand.

Digital Twin archetypes make use of visit and meet element. This is one of the most challenging systems as it implies that two users are feeling at the same time visiting a real place while having the possibilities of seeing each other through avatar representations. The closest related work a is the asymmetric system by Piumsomboon et al. (2018), where a typical remote assistance system is enhanced by the possibility of feeling immersed in a real space with another user on it being represented by a 3D Mesh.

Ideal immersive communication systems should be able to simultaneously provide shared immersion, visual communication and remote presence: the ability for one user to virtually “teleport” to the location of the other, feel immersed in the same location and interact with him/her face to face. This paradigm is defined as Distributed Reality by Villegas et al. (2019). The concept is widely depicted in fiction movies, such as the Jedi Council of Star Wars prequel trilogy, but no practical implementation exists already.
| Work | Archetype | Context | Dialogue | Exploration | Manipulation | Conditions | High Level feature | Low Level Feature |
|------|-----------|---------|----------|-------------|-------------|------------|-------------------|-------------------|
| Kim et al. (2019b) | Face2Face Window | Watch a movie | Comment on the movie | – | – | Big display / small display with following gaze / corner display | Subscale from NMM-SPI for emotions | LIKES/Dislikes of following gaze following |
| Lawrence et al. (2021) | Face2Face Window | Conferencing | Semi-structured conversation with a research confederate | – | – | 3D video conferencing vs. 2D video conferencing system | HOLO for presence, attractiveness, connectedness, reactions, and liking | HG, HN, and EM for non-verbal behaviour |
| Liu and Sidi (2017) | Shared VR | Photo games | – | – | Moving pictures (spaces) | Embodiment types, self-avatar, and facial expression | IT for trust | SocialVR for social presence |
| Lawrence et al. (2017) | Shared VR | Photo sharing | Comment on shared photos | – | – | Face2Face, Moreno, and Facebook Spaces | IT for trust | SocialVR for social presence |
| Otto-Bocchio et al. (2016) | Social XR | Play and collaborate remotely | – | – | Building blocks | VR vs. AR | Semi-structured interview for presence, interaction, and embodiment | Semi-structured interview for visual quality and latency |
| Guadet et al. (2018) | Social XR | Watch a movie and play a game | Comment on the movie or game | – | – | Pong (two-player game) | System performance | RGO: Social presence, interaction, embodiment, and global QoE |
| Prin et al. (2018) | Social XR | Play a game | – | – | Assembly of lego blocks | Audio only, video fixed to HMD, and video fixed to last world | Feedback on presence and overall quality | – |
| Lawrence et al. (2018) | Social XR | Conference | Negotiation | – | – | System performance | – | – |
| Li et al. (2019) | Shared VR | Watch a VR Movie inside the scene | Questions raised by movie characters | – | – | Interact with environment (e.g., click buttons) | HMD vs. screen with game controller | Virtual VR for visual quality |
| Orts-Escolano et al. (2016) | Social XR | Play and collaborate remotely | – | – | Talk to game objects | VR vs. AR | System performance | Feedback on presence and overall quality |
| Gunkel et al. (2018) | Social XR | Watch a movie and play a game | Comment on the movie or game | – | – | Pong (two-player game) | System performance | Feedback on presence and overall quality |
| Prins et al. (2018) | Social XR | Play a game | – | – | Assembly of lego blocks | Audio only, video fixed to HMD, and video fixed to last world | Feedback on presence and overall quality | – |
| Lee et al. (2018) | Remote Assistance | Remote collaboration | – | – | Place the target objects on the desk | Dependent view vs. independent view | MEC for spatial presence | CT for task performance |
| Song et al. (2019) | Remote Assistance | Remote collaboration | – | – | Placing objects on the shelf | No cues, hand gestures, pointer, and hand gestures + pointer | MEC for spatial presence | CT for task performance |
| Tao et al. (2019a) | Remote Assistance | Remote collaboration | – | – | Identify objects | Deco for a bookshelf placing objects | MEC for spatial presence | CT for task performance |
| Tao et al. (2020) | Remote Assistance | Remote collaboration | – | – | Find objects in the task space | Place the target objects in a specific location | MEC for spatial presence | CT for task performance |
| Wang et al. (2022) | Remote Assistance | Remote collaboration on physical tasks | – | – | Locate and follow remote pointers | Assembly of lego blocks | CVE for spatial presence | CT for task performance |
| Bae et al. (2019) | Remote Assistance | Work together remotely | – | – | Search and follow remote indicators and visual cues | Assembly of lego blocks | CVE for spatial presence | CT for task performance |
| Anjos et al. (2019) | A.R. Host | Play games | Subordinates | – | – | System performance | – | – |
| Kasahara et al. (2017) | Immersive Telepresence | Cleaning up a lab room | – | – | Locate objects and clean them | Video stabilization | SSQ for cybersickness | HM for non-verbal behaviours |
| Phumisomboon et al. (2019) | Immersive Telepresence | Remote collaboration | Guess objects of interest | – | – | Types of virtual representations, levels of min-max control, levels of 360-video view dependencies, and 360-camera placement positions | SSQ for cybersickness | SEQ for task performance |
| Zhang et al. (2020) | Immersive Telepresence | Telepresence | – | – | Locate / indicate remote user’s gaze | Distance to avatar and display (AR, tablet) | SSQ for cybersickness | SEQ for task performance |
| Phumisomboon et al. (2018) | Immersive Digital Twin | Remote collaboration | – | – | Locate objects in a specific location | Focused life-size full-body avatar with and without Min-me | NMMS-SPI for social presence | SEQ for task performance |
| Brunström et al. (2020) | No communication | Remote control | – | – | Control a crane to load logs | Literature | BC: Comfort, immersive, and overall quality | WC: Presence, embodiment, and task accomplishment quality |
| Pérez et al. (2021) | No communication | Escape room game | – | – | Manipulate game objects | Real hands vs. VR controllers | – | – |
4 EXISTING QOE METHODOLOGIES FOR IMMERSIVE COMMUNICATIONS

In this section, we aim to review the related works presented in section 3 and analyze more in detail those who not only describe an immersive communication system, but also assess its subjective Quality of Experience (QoE). Table 3 shows a summary of the QoE evaluation methodologies used in the studied work.

Additionally, there are some few works which are focused more on interaction rather than on communication (Brunnström et al., 2020; Pérez et al., 2021). Still, it is still interesting to understand their related evaluation methodologies for hybrid immersive systems where both communication and interaction are important. For more details regarding the questionnaires reported in Table 3, please refer to Table 4.

Even though there is no common methodology, all the evaluation procedures shared a common basic design: two or more users communicate through the system and perform one or several communication tasks. The same task is performed under two or more different experimental conditions, which are normally related to using different communication systems (e.g., comparing an immersive with a non-immersive one) or different configurations of the same system. Finally, several QoE factors are evaluated, studying whether there exist significant differences between the experimental conditions.

4.1 Tasks

We have classified the communication tasks in three categories:

- **Deliberation**: conversations between peers, normally oriented to achieve a common goal.
- **Exploration**: exploration of the environment and identification of objects following indications.
- **Manipulation**: interaction with system elements and manipulation of physical objects (e.g., lego blocks).

It is worth noting that all the tasks are communication tasks, and therefore they require a conversation between the users. The main difference is the nature of the conversation: in deliberation tasks the conversation is the task, in exploration tasks the conversation is used to discuss about the immersive environment, and in manipulation tasks the conversation is used to cooperate (or compete) in the execution of the task (e.g. provide instructions), which usually involves object interaction.

Various tasks related to deliberation are used in several studies to test the communication capabilities of almost all the system archetypes, especially those involving the Face element (see Table 1). For instance, in Social XR/VR environments where shared experiences are provided to the users, such as watching movies together (Li et al., 2021), sharing photos (Li et al., 2019), and playing games (Gunkel et al., 2018), the deliberation task focused on commenting on the shared content. This was also studied in face-to-face window systems as in Kim et al. (2019b). Other studies that do not use shared contents emphasize the deliberation proposing tasks such as negotiation (Lawrence et al., 2018), playing games (e.g., riddles in Anjos et al. (2019), tell a lie in Orts-Escalano et al. (2016), etc.) or using semi-structured interviews (Lawrence et al., 2021). Finally, in remote assistance and telepresence systems, which entail remote collaboration, identifying objects of interest can serve to test the communication capabilities in scenarios (Piumsomboon et al., 2019).

Exploration tasks are used in several user studies to test systems involving the Visit element, in which the visitor sees the environment of the host. For instance, identifying and locating objects (e.g., Lego blocks) in the task space is a widely used task in remote assistance scenarios (Kasahara et al., 2017, Lee et al.
Table 4. Description of common questionnaires used in immersive communication experiments.

| Questionnaire | Measure, N. items, Scale, Subscales, Factors |
|---------------|---------------------------------------------|
| Interpersonal Trust (IT) | Interpersonal trust in social situations. 21 items for male version, 13 items for female version. 9-point Likert scale. Subscales: reliability (male & women), emotional trust (male & women), and general trust (male). |
| Nasa Task Load Index (NASA-TLX) | Workload of task. 6 items. 21-point Likert scale. Measuring mental, physical and temporal demand, performance, effort and frustration. |
| Simulator Sickness Questionnaire (SSQ) | Users’ levels of cybersickness symptoms. 16 items. 4-point scale. 3 subscales: Nausea (N), Oculomotor (O), and Disorientation (D). |
| Subjective Mental Effort Question (SMEQ) | One question that measures the mental effort. 1 item. 9 labels scale (from “Not at all hard to do” to “Tremendously hard to do”). |
| Witmer and Singer (WS) | Sense of presence. 32 items. 7-point Likert scale. Subscales: Involvement/Control, Natural, Auditory, Haptic, Resolution, Interface Quality. Factors: Involvement/Control, Natural, Auditory, Haptic, Resolution. |
| System Usability Scale (SUS) | Usability. 10 items. 5-point Likert scale. |
| Networked Minds Measure Social Presence Inventory (NMM-SPI) | Social presence and emotions. 3 items. 9-point Likert scale. Subscales: presence, involvement, experienced realism. |
| MEC Spatial Presence Questionnaire (MEC-SPQ) | Spatial presence. 32, 45, 64, (items 1, 6 and 8 items per each of the 8 subscales), 5-point Likert scale. Subscales: attention allocation, higher cognitive involvement, suspension of disbelief, spatial situation model, spatial presence self location, spatial presence possible actions, domain specific interest, visual spatial imagery. |
| Single Ease Question (SEQ) | Assessment of how difficult users find a task. 1 item. 7-point Likert scale. |
| Pictorial Mood Reporting Instrument (PMRI) | Emotions. 9 items. 5-point scale. Nine moods: excited, cheerful, relaxed, calm, bored, sad, irritated, tense and neutral. |
| Embodiment | User embodiment on immersive experiences. 25 items. 7-point Likert scale. Subscales: body ownership, tactile sensations, location of the body, external appearance, and response to external stimuli. |
| Feedback | Requirements gathering to understand user expectations for social VR. 6 items. 7-point Likert scale. Subscales: Social presence, interaction, explorability, visual quality, audio quality, and overall quality. |
| Requirements Gathering Questionnaire (RGQ) | Short questionnaire to gather feedback form users’ immersive experiences. 2 items. 5-point Likert scale. Subscales: Presence and overall quality. |
| SocialVR Questionnaire (S-VQ) | Social and interactive experiences in immersive media. 24 items. 5-point Likert scale. Subscales: Presence / Immersion (PI), Social Meaning (SM), and Quality of Interaction (QI). |
| Distributed Reality Experience Questionnaire (DREQ) | Presence and quality aspects. 10 items. 5-point scale. Subscales: presence, video quality, cybersickness and quality of experience. |
| Remote Control (RC) | QoE aspects. 6 items. 5-point Likert scale. Subscales: picture quality, comfort quality, immersive quality, overall quality, responsiveness quality, and task accomplishment quality. |
| Tele-collaboration Quality (TQ) | Social presence (slightly modified from Gupta et al. 2019) and Harms and Biocca 2004 to better reflect the experiment. 7 items. 7-point Likert scale. Subscales: co-presence, interactivity, explorability, visual quality, audio quality, fatigue. |
| Visual Quality of Experience (VQoE) | Visual quality of self and others’ volumetric representations. 2 items. 5-point Likert scale. |

2018 Teo et al., 2019a, 2020 Wang et al., 2020 Bai et al., 2020. In this type of systems, as well as in immersive telepresence and digital twin systems, the proposed tasks can also involve the exploration of the remote environment (Young et al., 2019; Piumsomboon et al., 2018, 2019). Also, the usefulness of visual cues, such as pointers (Wang et al., 2020; Bai et al., 2020) and eye-gaze (Zhang et al., 2020) on the remote
collaboration can be assessed with exploration tasks. In this sense, Social XR systems can also include tasks related to the exploration of the shared environment as studied by Li et al. (2021), where the users were asked to follow the characters of the VR movie through the scene.

Finally, a variety of manipulation tasks have been used in different studies involving the Meet and Move elements. Several user studies test the capabilities of remote assistance and immersive telepresence systems proposing tasks where the host manipulates physical objects (e.g., Lego blocks in Wang et al. (2020); Bai et al. (2020)) or places them in the task environment (Lee et al. 2018; Teo et al. 2019a; Piumsomboon et al. 2018, 2019) following the indications of the visitor. These tasks have been also exploited in Social XR systems, such as in Lawrence et al. (2018) and Orts-Escolano et al. (2016). Nevertheless, Social XR/VR systems offer the possibility to test the interact with the environment, such as in Li et al. (2021), where the users could press buttons, or with virtual objects, such as in Pan and Steed (2017) and Prins et al. (2018), where the users played together puzzles and pong games, respectively. In this sense, it is also worth mentioning the insights that can provide user studies focused on analyzing the interaction of the users with the systems without accounting for communication, such as the one carried out by Brunnström et al. (2020) with a crane-control system and by Pérez et al. (2021) considering a scape room scenario.

4.2 Conditions

While few user studies are limited to the evaluation of the overall system performance, such as Prins et al. (2018); Gunkel et al. (2018); Anjos et al. (2019), most of them establish different conditions for its validation. For example, some studies compare the performance of the analyzed system with previous technologies (e.g., traditional videoconferencing systems in Lawrence et al. (2021)) or with alternative immersive technologies and/or the face-to-face scenario in Li et al. (2019). Other works test different conditions based on certain technical aspects of the systems under study. For example, testing different displays has been used to evaluate the performance of different system archetypes, such as Social XR (e.g., HMD vs. 2D screen with game controller in Li et al. (2021), or VR vs. AR HMD in Orts-Escolano et al. (2016)), immersive telepresence (e.g., HMD vs. tablet (Zhang et al. 2020), and face-to-face window (e.g., big vs. small displays in Lawrence et al. (2021)). For remote assistance systems, user studies typically address the comparison of different visualization techniques of pointers and cues (e.g., cursors, head pointers, eye pointers, hand gestures, etc.) to support the indications from the remote user (Teo et al. 2019a, Wang et al. 2020; Bai et al. 2020), as well as different ways of interaction between the host and the visitor (Young et al. 2019). Also, the assessment of technical aspects related to the acquisition of the video from the host and the rendering for the visitor is relevant in these environments, such as the host’s video stabilization in Kasahara et al. (2017) and visitor’s view dependency on the host movements in Lee et al. (2018); Teo et al. (2020); Piumsomboon et al. (2019). Other conditions that influence higher-level features of the of the user experience can provide also insights of the performance of the systems, such as the use of different types of embodiment in Shared VR (e.g., with or without self-avatar in Pan and Steed (2017)) or the positioning of the visitor representation (e.g., video, volumetric representation, etc.) in immersive telepresence and Social XR systems (Lawrence et al. 2018; Zhang et al. 2020; Piumsomboon et al. 2018, 2019). Finally, systems that do not consider communication also study technical aspects related to the interaction of the users with the systems, such as latency (Brunnström et al. 2020) or the use of controllers (Pérez et al. 2021).

4.3 Features

Several high-level factors are involved in the user experience that are evaluated in immersive communication systems. We have identified two broad categories of QoE factors. High-level features
focus on the user, addressing cognitive or psychological constructs such as presence, empathy or workload. **Low-level** features directly evaluate technical aspects of the system: audio-visual quality, responsiveness, usability, etc.

The most common feature evaluated in several studies is presence, which sometimes is evaluated in terms of spatial, social, and co-presence. As shown in Table 3, presence was considered in user studies involving almost all system archetypes, such as Social XR (Orts-Escolano et al., 2016; Prins et al., 2018; Lawrence et al., 2018; Gunkel et al., 2018; Li et al., 2021), Shared VR (Li et al., 2019), face-to-face window (Lawrence et al., 2021), remote assistance (Young et al., 2019; Lee et al., 2018; Teo et al., 2019a, 2020; Wang et al., 2020; Bai et al., 2020), immersive telepresence (Piumsomboon et al., 2019), and digital twin systems (Piumsomboon et al., 2018). As reflected in Table 4, different questionnaires have been used to evaluate presence in its different forms, although some traditional ones are used in several different studies, such as the one proposed by Witmer and Singer (WS) (Witmer and Singer, 1998) and the MEC Spatial Presence Questionnaire (MEC-SPQ) from Vorderer et al. (2004) for spatial presence, and the Networked Minds Measure Social Presence Inventory (NMM-SPI) from Harms and Biocca (2004) for social and co-presence. While some other studies used variations of these questionnaires (e.g., Young et al., 2019 used modified versions of NMM-SPI for co-presence and of the Igroup presence questionnaire (IPQ) from Schubert et al. (2001) for spatial presence, others proposed their own questionnaires. For instance, to assess spatial presence, Li et al. (2019) proposed the SocialVR questionnaire, Lawrence et al. (2021) the Holoportation questionnaire (HOLO), and Wang et al. (2020) the Telle-collaboration Quality (TQ), Gunkel et al. (2018) the VR experience questionnaire (with a 7-point scale question among 4 questions related to the VR experience), and Prins et al. (2018) (with a single 5-point scale question) for social presence.

After presence, workload and simulator/cyber sickness are factors commonly evaluated in the considered systems, mainly using well-established questionnaires, such as the Nasa Task Load Index (NASA-TLX) (Hart and Staveland, 1988) and Subjective Mental Effort Question (SMEQ) (Zijlstra, 1993) questionnaires for workload, and the Simulator Sickness Questionnaire (SSQ) (Kennedy et al., 1993). As mental stress conditions have an effect in the Central Nervous System (CNS) or the Autonomic Nervous System (ANS), it is also possible to monitor them using psychophysiological measures (Engelke et al., 2016), even though none of the works reported in Table 3 uses this approach. In other contexts, for instance, Electroencephalography (EEG) has been used to detect mental load (Jiao et al., 2018) or cybersickness (Kim et al., 2019a) in VR users.

The SocialVR questionnaire proposed by Li et al. (2019) included 10 items to evaluate quality of interaction in Li et al. (2021) and 11 items covering social connectedness. Similarly, these two factors were also evaluated by Wang et al. (2020) using two of the subscales included in their TQ questionnaire. In addition, Gunkel et al. (2018) included one item in their VR experience questionnaire to evaluate interactivity and Lawrence et al. (2021) evaluated social connectedness with one subscale of their HOLO questionnaire.

Other factors were evaluated in a few studies. For example, Kim et al. (2019b) used questions adopted from the NMM-SPI questionnaire Harms and Biocca (2004) to evaluate sharing emotions with their face-to-face window system, while Li et al. (2019) used a self-report emotion rating questionnaire proposed by Vastenburg et al. (2011). Also, explorability and the global QoE was evaluated with two items of the VR experience questionnaire of Gunkel et al. (2018), attentiveness and reaction/gauging were evaluated by Lawrence et al. (2021) with two subscales of their HOLO questionnaire, Pan and Steed (2017) evaluated trust using the questionnaire proposed by Johnson-George and Swap (1982), Brunnström et al. (2020)
analyzed immersion and comfort (among other factors) with their RC questionnaire, and Pérez et al. (2021) studied embodiment with the questionnaire proposed by Gonzalez-Franco and Peck (2018).

Regarding lower level features more related to technical factors of the immersive communication systems, task performance is the most commonly evaluated in user studies, both through objective measurements and questionnaires. For example, completion time seem to be one of the most relevant measurements (Pan and Steed, 2017; Lee et al., 2018; Bai et al., 2020; Teo et al., 2020) to assess task performance, while other technical measurements more specific to the task under study can also be used (e.g., angular error in the estimation of the location of the remote user’s gaze in Zhang et al. (2020)). An example of useful questionnaires to evaluate task performance is the Single Easement Question (SEQ) (Sauro and Dumas, 2009) used by Piumsomboon et al. (2018, 2019); Teo et al. (2020). Finally, semi-structured interviews can also be considered, as well as preference rankings to compare the performance among the considered conditions in Kim et al. (2019b). Visual quality is another factor commonly evaluated in related user studies, mainly using questionnaires. For example, Li et al. (2021) proposed the Visual QoE (VQoE) questionnaire to rate the visual quality of the volumetric representations using a 5-point Likert scale, while Prins et al. (2018) used a similar scale to evaluate the overall visual quality. Similarly, Gunkel et al. (2018) asked the participants of their study to rate the visual and audio quality using a 7-point Likert scale. As shown in Table 3, other low-level features have been also addressed in user studies, such as usability (typically evaluated with the System Usability Scale (SUS) by Brooke (1996) as in Bai et al. (2020); Teo et al. (2020)), exploration (e.g., using objective measurements of the head movements of the users while performing the tasks, as in Kasahara et al. (2017)), and responsiveness (Brunnström et al., 2020).

Finally, semi-structured interviews have been also used to evaluate diverse high and low-level factors, as done by Orts-Escolano et al. (2016) to assess presence, interactivity, explorability, believability, visual quality, and latency, and by Anjos et al. (2019) to assess task performance.

5 DISCUSSION

There have been numerous attempts of designing, building, and testing immersive communication systems. Even though the technology has experimented a profound evolution over the last two decades, there is still no standard way to approach the problem, not even a de-facto one. As a consequence, a diversity of systems have been designed and proposed in the literature, each one typically proposing its own evaluation methodology. At a first glance, this makes it difficult to propose a common analysis or evaluation framework for this variety.

However, our analysis shows that this apparent diversity can be structured around a few categories:

- There are not many different types of systems. Most of the systems can be classified according to whether and how they implement four basic communication features: Face (visual communication), Visit (remote presence), Meet (shared immersion), and Move (embodied interaction). As a result, most systems map into one of the models or archetypes identified in Figure 3.
- Most evaluation protocols are similar: they compare two similar systems, or a few configurations of the same system, using a few communication tasks.
- There are not many types of tasks used for this evaluation. Most of them can be described as deliberation, exploration, or manipulation.

The design of the tasks is normally related to the fundamental communication elements which are provided by the system. Even though any system (including audioconference!) can, in principle, be used...
for deliberation, exploration and manipulation tasks, some tasks which are more appropriate for each type of system.

High-level and low-level QoE factors, on the other hand, are less dependent on the type of system. All the systems are able to provide high-level QoE features: elicit sense of presence, enhance immersion, or improve interpersonal communication and empathy. They all suffer from mental load issues too. And in all of them it is possible to evaluate similar low-level features, such as task performance, audiovisual quality, or interactivity. However, the specific details of which questionnaires are more suitable, which presence factors are more relevant, or which system factors are more critical will depend on the specific system and on the designed task.

5.1 Selection of tasks for the evaluation of immersive communication systems

Face-enabled systems are usually evaluated using deliberation tasks, since face-to-face contact is supposed to enhance a conversation compared to less immersive setups, including audioconference. Visit-enabled systems allow the visitor to explore the environment of the host, and therefore exploration tasks are suitable for them. Both Face and Visit-enabled systems support manipulation tasks, normally in the form where one user (the host in the case of Visit systems) performs the task and the other provides support or instructions.

Meet-enabled systems rely mostly on cooperative (or competitive) manipulation tasks, where all the users manipulate the same (virtual) objects. Conversation and (virtual) exploration tasks are also useful. Finally, Move features are also tested with manipulation tasks, normally jointly with the appropriate communication function.

5.2 Relationship between high-level features

As seen in section 4.3, different works address different high-level QoE features. In particular, different experimental works measure different aspects of presence or related constructs. Without the explicit intention of being exhaustive, in this section we identify and classify the most relevant presence factors used in the studies presented before. Figure 6 shows a graphic representation of them, together with other high-level QoE features.

Presence can be defined as “the subjective experience of being in one place or environment, even when one is physically situated in another” (Witmer and Singer, 1998). The phenomenon of presence is complex and multi-factorial, and it has been subject of study for the last decades. For a thorough discussion on presence, the reader can refer to Skarbez et al. (2017) or Lombard and Jones (2015), among others.

Our starting point is the analysis in Biocca (1997), which identifies 3 forms in which users can feel present in a virtual environment: Spatial Presence (the sense of “being physically there”), Social Presence (“being with another body”), and Self Presence (“this body is really me”).

Spatial Presence is frequently analyzed in two dimensions (Hartmann et al., 2015):

- **Self-location**: the feelings that the user has departed from their real environment and feel they are in another place. Also defined as Place illusion by Slater (2009). It is mostly achieved through “perceptual immersion” (Lombard et al., 2000): the ability of the XR system to immerse the user into a different environment.
Social Presence has two dimensions or perspectives (Lee [2004]; Skarbez et al. [2017]):

- **Co-presence**, or the sense of being together with another or others, the “a condition in which instant two-way human interactions can take place” Zhao (2003). It is a perceptual feature: co-presence exists whenever a person senses that there is another person in the environment.

- **Social connectedness**, “social presence illusion” or simply “social presence”, the engagement with others (which requires interaction), defined in Van der Land et al. (2011) as “the awareness of being present with others in a mediated environment combined with a certain degree of attention to the other’s intentional, cognitive, or affective states”.

Self-presence implies the self-perception of one’s body, emotions and/or identity (Ratan [2013]). The perception of one’s body, or embodiment, has some dimensions on its own, as described by Kilteni et al. (2012): self-location (being inside a body), agency (having global motor control of the body), and body ownership (self-attribution of a body).

There are other aspects of presence which are not totally included in our previous classification, and somehow overlap among them (Lombard and Jones [2015]; Skarbez et al. [2017]):

- **Realism, plausibility, coherence, cultural presence.** Those concepts describe different ways in which the experience feels “real” or “realistic”, shows internal coherence, matches with the users’ expectations.
and cultural background, etc. Most authors agree that these factors form an integral part of the concept of presence.

- **Psychological immersion, engagement, attention, flow.** Those concepts describe the situation when the user feels absorbed, engaged or involved with the environment. Although they are closely related to presence, a majority of authors agree that these factors describe a different psychological construct.

- **Empathy, emotion conveyance, trust, etc.** Although a relation with social presence exist, those concepts describe a different phenomenon, more related to the area of empathic communication.

As described in section 4.3 there are other high-level factors addressed in the studies. Some are related with mental stress: cybersickness (or simulator sickness), workload, comfort, etc. Others address independent concepts such as the overall Quality of Experience.

### 5.3 Evaluation of low-level features

The experiments described before have been designed in a way which is possible to assess the difference of some high-level QoE factors (response variables) when executing a task under different system conditions. Table 3 shows the different tasks that have been proposed and the conditions that have been tested. An important implication is that, to elicit high-level features such as presence or mental load, each task needs to be several minutes long. This reduces the number of possible conditions that can be tested in each experiment.

Besides, it is expected that high-level features only experiment significant differences where the test conditions are sufficiently different among them. Consequently, in the described experiments, only a few conditions are tested, and they are one of this two cases:

- Comparison of different communication systems. E.g. comparing the immersive system under study with conventional videoconference.

- Comparison between distinct options of key system features shown in Figure 2. E.g. comparing a screen with an HMD, or different modes of interaction.

A drawback of this approach is that the same restrictions on the assessment methodology are applied to low-level features, which are known to respond to finer-grain variations of the system conditions, and which can be evaluated with much shorter stimuli. For instance, ITU-T P.919 recommends 10-second sequences to assess visual quality of 360° video.

The conventional solution for this problem is conducting targeted experiments to only assess low-level features with shorter stimuli. For instance, to evaluate the visual quality of 360° (Gutierrez et al., 2021) or point clouds (Viola et al., 2022), or the effect of delay in task performance (Brunnström et al., 2020). As an alternative approach, Orduna et al. (2022) propose a methodology to combine frequent assessment of low-level features during the execution of the test with the evaluation of high-level features using post-experience questionnaires. In particular, visual quality is evaluated each 25 seconds using Single-Stimulus Discrete Quality Evaluation (SSDQE) (Gutiérrez et al., 2011), while a set of high-level features (spatial and social presence, empathy, memory) is evaluated after each 5-minute sequence.

The evaluation of low-level features has been widely covered by ITU-T Recommendations. ITU-T P.919 proposes scales for video quality evaluation (e.g. ACR, Absolute Category Rating) and simulator sickness, as well as a method for the analysis of head and eye tracking data based on the works of David et al. (2018) and Fremerey et al. (2018). ITU-T P.1305 proposes techniques to analyze the conversation structure, which
is useful to assess the effect of latency in the communication. ITU-T P.1312 proposes a framework for task performance analysis.

5.4 Good Practises

As it has been seen, there are significant similarities between immersive communication systems, as well as between the evaluation methodologies proposed to assess their QoE. Based on them it is possible to propose a set of best practises for the QoE assessment of immersive communication systems, even though a standardized methodology does not exist yet.

1. **Characterize the system under test** according to the taxonomy defined in section 2: which of the fundamental elements (Face, Visit, Meet, Move) are implemented in the system and which archetype can be applied to it.

2. **Determine the system factors** that are going to be tested: whether the system is being compared with others or different configurations / conditions of the same system are being tested. In the former case, verify whether all the systems under consideration share the same fundamental elements or not.

3. **Identity a set of tasks** which can react to the variation of the experimental condition. As a minimum, consider using the tasks appropriate for the fundamental elements: deliberation (Face), exploration (Visit), manipulation of a shared object (Meet), manipulation of an interactive element (Move). Pay special care in the design of the tasks if the systems under test do not share the same fundamental elements, as there is a high risk that the task definition biases the results towards one specific system.

4. **Identify the relevant QoE factors** to measure. High-level factors should reflect the expectation of the use case foreseen for the system (what it is going to be used for), while low-level factors should address the most relevant technical variables of the system itself.

5. **Refine the tasks** so that they cover the QoE factors in a relevant way. Adjust the duration of the tasks to find the proper trade-off between having a sufficiently stable environment to allow for high-level QoE features to arise, and allocating the maximum number of test conditions. Define the steps of the experiment and their timing, how the different tasks or subtask are executed, and how the different conditions are tested.

6. **Select the right assessment tool** for each QoE factor. Select high-level evaluation questionnaires according to the nature of the system and the task. For low-level measures, consider using performance evaluation and other non-intrusive strategies as much as possible.

6 CONCLUSION

Users of immersive communication technologies, such as extended reality (XR), can explore and experience the stimuli in a more interactive and personalized way than previous technologies (e.g., 2D video). Thus, considering the new technological challenges related to these systems and the new perceptual dimensions and interaction behaviors involved, a deep understanding of the users’ Quality of Experience (QoE) is required to satisfy their demands and expectations, especially in what regards the quality of communication and interaction between people. It is therefore needed to establish some common metrics and methodologies that can be used to assess such QoE.
In the paper, we provide an overview of existing immersive communication systems and related user studies. Our analysis shows that the apparent diversity of systems and methodologies can be grouped around a few categories.

We have identified 4 fundamental elements of immersive communication systems: Face, Visit, Meet, and Move. We have shown that no existing system fulfills all of them and the same time, and therefore we have created a taxonomy of systems according to which of them they focus on. Particularly with Face, Visit, and Meet elements, systems typically address only one or two of them. We have also found that the systems which address the same combination of these elements tend to be based on the same set of technological components, which has allowed us to define a set of immersive communication system archetypes.

We have also identified the commonalities of the assessment methodologies used in the literature when testing this type of systems. Most evaluation protocols are similar: the compare two similar systems, or a few configurations of the same system, using a few communication tasks: deliberation, exploration, or manipulation. We have also identified the most relevant QoE factors addressed in the literature, both high-level user experience traits and low-level system features.

With this analysis, we have provided a set of simple good practices for the QoE evaluation of immersive communication systems. We expect our contribution to be relevant to the community of immersive communication as well as VR, AR, MR, and XR, so that other researchers can build upon our proposed analysis framework. We also intend to feed this contribution into relevant standardization communities, such as the Video Quality Experts Group (VQEG) or the ITU-T, to help in the design of the next generation of subjective assessment methodologies for immersive communication systems.

CONFLICT OF INTEREST STATEMENT

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

AUTHOR CONTRIBUTIONS

P.P. was the main contributor to the conceptualization of the work, with the support from the rest of the authors. P.P., E.G., and J.G. worked on the investigation process and writing of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

FUNDING

This work has been partially supported by project PID2020-115132RB (SARAOS) funded by MCIN/AEI/10.13039/501100011033 of the Spanish Government. The work of J. Gutiérrez was partially supported by a Juan de la Cierva fellowship (IJC2018-037816) of the Ministerio de Ciencia, Innovación y Universidades of the Spanish Government.

REFERENCES

Anjos, R. K. d., Sousa, M., Mendes, D., Medeiros, D.,Billinghurst, M., Anslow, C., et al. (2019). Adventures in hologram space: exploring the design space of eye-to-eye volumetric telepresence. In 25th ACM Symposium on Virtual Reality Software and Technology. 1–5
Bai, H., Sasikumar, P., Yang, J., and Billinghurst, M. (2020). A user study on mixed reality remote collaboration with eye gaze and hand gesture sharing. In Proceedings of the 2020 CHI conference on human factors in computing systems. 1–13

Billinghurst, M., Clark, A., and Lee, G. (2014). A survey of augmented reality. Foundations and Trends in Human-Computer Interaction 8, 73–272

Biocca, F. (1997). The cyborg’s dilemma: Progressive embodiment in virtual environments. Journal of computer mediated communication 3, JCMC324

Brooke, J. (1996). Sus: a “quick and dirty’usability. Usability evaluation in industry 189

Brunnström, K., Dima, E., Qureshi, T., Johanson, M., Andersson, M., and Sjöström, M. (2020). Latency impact on quality of experience in a virtual reality simulator for remote control of machines. Signal Processing: Image Communication 89, 116005

Carballeira, P., Carmona, C., Díaz, C., Berjón, D., Quesada, J. C., Moran, F., et al. (2021). Fvv live: A real-time free-viewpoint video system with consumer electronics hardware. IEEE Transactions on Multimedia

David, E. J., Gutiérrez, J., Coutrot, A., Da Silva, M. P., and Callet, P. L. (2018). A dataset of head and eye movements for 360 videos. In Proceedings of the 9th ACM Multimedia Systems Conference. 432–437

Durlach, N. and Slater, M. (2000). Presence in shared virtual environments and virtual togetherness. Presence: Teleoperators & Virtual Environments 9, 214–217

Engelke, U., Darcy, D. P., Mulliken, G. H., Bosse, S., Martini, M. G., Arndt, S., et al. (2016). Psychophysiology-based qoe assessment: A survey. IEEE Journal of Selected Topics in Signal Processing 11, 6–21

Fremerey, S., Singla, A., Meseberg, K., and Raake, A. (2018). Avtrack360: an open dataset and software recording people’s head rotations watching 360° videos on an hmd. In Proceedings of the 9th ACM Multimedia Systems Conference. 403–408

Gao, L., Bai, H., Billinghurst, M., and Lindeman, R. W. (2020). User behaviour analysis of mixed reality remote collaboration with a hybrid view interface. In 32nd Australian Conference on Human-Computer Interaction. 629–638

Gao, L., Bai, H., He, W., Billinghurst, M., and Lindeman, R. W. (2018). Real-time visual representations for mobile mixed reality collaboration. In Proceedings of SA’18 Virtual and Augmented Reality. 1–2

Gonzalez-Franco, M. and Peck, T. C. (2018). Avatar embodiment. towards a standardized questionnaire. Frontiers in Robotics and AI 5, 74

Gunkel, S., Stokking, H., Prins, M., Niamut, O., Siahaan, E., and Cesar, P. (2018). Experiencing virtual reality together: Social vr use case study. In Proceedings of the 2018 ACM International Conference on Interactive Experiences for TV and Online Video. 233–238

Gupta, K., Lee, G. A., and Billinghurst, M. (2016). Do you see what i see? the effect of gaze tracking on task space remote collaboration. IEEE transactions on visualization and computer graphics 22, 2413–2422

Gutiérrez, J., Pérez, P., Jaureguizar, F., Cabrera, J., and García, N. (2011). Subjective assessment of the impact of transmission errors in 3dtv compared to hdtv. In 2011 3DTV Conference: The True Vision-Capture, Transmission and Display of 3D Video (3DTV-CON) (IEEE), 1–4

Gutierrez, J., Perez, P., Orduna, M., Singla, A., Cortes, C., Mazumdar, P., et al. (2021). Subjective evaluation of visual quality and simulator sickness of short 360 videos: Itu-t rec. p.919. IEEE Transactions on Multimedia, 1–1doi:10.1109/TMM.2021.3093717
Harms, C. and Biocca, F. (2004). Internal consistency and reliability of the networked minds measure of social presence. In 7th Annual International Workshop: Presence

Hart, S. G. and Staveland, L. E. (1988). Development of nasa-tlx (task load index): Results of empirical and theoretical research. In Advances in psychology (Elsevier), vol. 52. 139–183

Hartmann, T., Wirth, W., Schramm, H., Klimmt, C., Vorderer, P., Gysbers, A., et al. (2015). The spatial presence experience scale (spes). Journal of Media Psychology

Izumihara, A., Uriu, D., Hiyama, A., and Inami, M. (2019). Exleap: Minimal and highly available telepresence system creating leaping experience. In 2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR) (IEEE), 1321–1322

Jiao, Z., Gao, X., Wang, Y., Li, J., and Xu, H. (2018). Deep convolutional neural networks for mental load classification based on eeg data. Pattern Recognition 76, 582–595

Johnson-George, C. and Swap, W. C. (1982). Measurement of specific interpersonal trust: Construction and validation of a scale to assess trust in a specific other. Journal of personality and social psychology 43, 1306

Kachach, R., Morcuende, S., Gonzalez-Morin, D., Perez-Garcia, P., Gonzalez-Sosa, E., Pereira, F., et al. (2021). The owl: Immersive telepresence communication for hybrid conferences. In 2021 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct) (IEEE), 451–452

Kasahara, S., Nagai, S., and Rekimoto, J. (2017). Jackin head: Immersive visual telepresence system with omnidirectional wearable camera. IEEE Transactions on Visualization and Computer Graphics 23, 1222–1234

Kauff, P. and Schreer, O. (2002). An immersive 3d video-conferencing system using shared virtual team user environments. In Proceedings of the 4th international conference on Collaborative virtual environments. 105–112

Kennedy, R. S., Lane, N. E., Berbaum, K. S., and Lilienthal, M. G. (1993). Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. The international journal of aviation psychology 3, 203–220

Kilteni, K., Groten, R., and Slater, M. (2012). The sense of embodiment in virtual reality. Presence: Teleoperators and Virtual Environments 21, 373–387

Kim, J., Kim, W., Oh, H., Lee, S., and Lee, S. (2019a). A deep cybersickness predictor based on brain signal analysis for virtual reality contents. In Proceedings of the IEEE/CVF International Conference on Computer Vision. 10580–10589

Kim, K., Billinghamurst, M., Bruder, G., Duh, H. B.-L., and Welch, G. F. (2018). Revisiting trends in augmented reality research: A review of the 2nd decade of ismar (2008–2017). IEEE transactions on visualization and computer graphics 24, 2947–2962

Kim, S., Billinghamurst, M., Lee, G., Norman, M., Huang, W., and He, J. (2019b). Sharing emotion by displaying a partner near the gaze point in a telepresence system. In International Conference in Information Visualization – Part II. 86–91

Kim, S., Jing, A., Park, H., Kim, S.-h., Lee, G., and Billinghamurst, M. (2020). Use of gaze and hand pointers in mixed reality remote collaboration. In The 9th International Conference on Smart Media and Applications. SMA, Jeju, Republic of Korea. 1–6

Lawrence, J., Goldman, D. B., Achar, S., Blascovich, G. M., Desloge, J. G., Fortes, T., et al. (2021). Project starline: A high-fidelity telepresence system. ACM Transactions on Graphics (Proc. SIGGRAPH Asia) 40(6)
Lawrence, L., Dey, A., and Billinghurst, M. (2018). The effect of video placement in AR conferencing applications. In Proceedings of the 30th Australian Conference on Computer-Human Interaction. 453–457

Lee, G. A., Teo, T., Kim, S., and Billinghurst, M. (2018). A user study on MR remote collaboration using live 360 video. In 2018 IEEE International Symposium on Mixed and Augmented Reality (ISMAR) (IEEE), 153–164

Lee, K. M. (2004). Presence, explicated. Communication theory 14, 27–50

Li, J., Kong, Y., Röggl, T., De Simone, F., Ananthanarayan, S., De Ridder, H., et al. (2019). Measuring and understanding photo sharing experiences in social virtual reality. In Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems. 1–14

Li, J., Subramanyam, S., Jansen, J., Mei, Y., Reimat, I., Ławicka, K., et al. (2021). Evaluating the user experience of a photorealistic social VR movie. In 2021 IEEE International Symposium on Mixed and Augmented Reality (ISMAR) (IEEE), 284–293

Lombard, M., Ditton, T. B., Crane, D., Davis, B., Gil-Egui, G., Horvath, K., et al. (2000). Measuring presence: A literature-based approach to the development of a standardized paper-and-pencil instrument. In Third international workshop on presence, Delft, the Netherlands. vol. 240, 2–4

Lombard, M. and Jones, M. T. (2015). Defining presence. In Immersed in media (Springer). 13–34

McVeigh-Schultz, J., Kolesnichenko, A., and Isbister, K. (2019). Shaping pro-social interaction in VR: an emerging design framework. In Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems. 1–12

[Dataset] Microsoft (2021). Microsoft Mesh

Nassani, A., Zhang, L., Bai, H., and Billinghurst, M. (2021). Showmearound: Giving virtual tours using live 360 video. In Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems. 1–4

Orduna, M., Perez, P., Gutierrez, J., and Garcia, N. (2022). Methodology to assess quality, presence, empathy, attitude, and attention in 360-degree videos for immersive communications. IEEE Transactions on Affective Computing, 1–11 doi:10.1109/TAFFC.2022.3149162

Orts-Escolano, S., Rhemann, C., Fanello, S., Chang, W., Kowdle, A., Degtyarev, Y., et al. (2016). Holoportation: Virtual 3D teleportation in real-time. In Proceedings of the 29th annual symposium on user interface software and technology. 741–754

Pan, Y. and Steed, A. (2017). The impact of self-avatars on trust and collaboration in shared virtual environments. PloS one 12, e0189078

Park, S.-M. and Kim, Y.-G. (2022). A metaverse: taxonomy, components, applications, and open challenges. IEEE Access

Pérez, P., González-Sosa, E., Kachach, R., Pereira, F., and Villegas, A. (2021). Ecological validity through gamification: an experiment with a mixed reality escape room. In 2021 IEEE International Conference on Artificial Intelligence and Virtual Reality (AIVR). 179–183

Perez, P., Gonzalez-Sosa, E., Kachach, R., Ruiz, J., Benito, I., Pereira, F., et al. (2019). Immersive gastronomic experience with distributed reality. In 2019 IEEE 5th Workshop on Everyday Virtual Reality (WEVR) (IEEE), 1–6

Pérez, P., Oyaga, N., Ruiz, J. J., and Villegas, A. (2018). Towards systematic analysis of cybersickness in high motion omnidirectional video. In 2018 Tenth International Conference on Quality of Multimedia Experience (QoMEX) (IEEE), 1–3
Piumsomboon, T., Lee, G. A., Hart, J. D., Ens, B., Lindeman, R. W., Thomas, B. H., et al. (2018). Mini-me: An adaptive avatar for mixed reality remote collaboration. In Proceedings of the 2018 CHI conference on human factors in computing systems. 1–13

Piumsomboon, T., Lee, G. A., Irlitti, A., Ens, B., Thomas, B. H., and Billinghurst, M. (2019). On the shoulder of the giant: A multi-scale mixed reality collaboration with 360 video sharing and tangible interaction. In Proceedings of the 2019 CHI conference on human factors in computing systems. 1–17

Prins, M. J., Gunkel, S. N., Stokking, H. M., and Niamut, O. A. (2018). Togethervr: A framework for photorealistic shared media experiences in 360-degree vr. SMPTE Motion Imaging Journal 127, 39–44

Ratan, R. (2013). Self-preservation, explicated: Body, emotion, and identity extension into the virtual self. In Handbook of research on technoself: Identity in a technological society (IGI Global). 322–336

Sanchez-Vives, M. V. and Slater, M. (2005). From presence to consciousness through virtual reality. Nature Reviews Neuroscience 6, 332–339

Sasikumar, P., Gao, L., Bai, H., and Billinghurst, M. (2019). Wearable remotefusion: A mixed reality remote collaboration system with local eye gaze and remote hand gesture sharing. In 2019 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct) (IEEE), 393–394

Sauro, J. and Dumas, J. S. (2009). Comparison of three one-question, post-task usability questionnaires. In Proceedings of the SIGCHI conference on human factors in computing systems. 1599–1608

Schubert, T., Friedmann, F., and Regenbrecht, H. (2001). The experience of presence: Factor analytic insights. Presence: Teleoperators & Virtual Environments 10, 266–281

Singla, A., Fremerey, S., Robitza, W., and Raake, A. (2017). Measuring and comparing qoe and simulator sickness of omnidirectional videos in different head mounted displays. In 2017 Ninth international conference on quality of multimedia experience (QoMEX) (IEEE), 1–6

Skarbez, R., Brooks, F. P., Jr, and Whitton, M. C. (2017). A survey of presence and related concepts. ACM Computing Surveys (CSUR) 50, 1–39

Slater, M. (2009). Place illusion and plausibility can lead to realistic behaviour in immersive virtual environments. Philosophical Transactions of the Royal Society B: Biological Sciences 364, 3549–3557

Steed, A. (2021). What we measure in mixed reality experiments. arXiv preprint arXiv:2104.05356

Szigeti, T., McMenamy, K., Saville, R., and Glowacki, A. (2009). Cisco telepresence fundamentals (Cisco Press)

Teo, T., Lee, G. A., Billinghurst, M., and Adcock, M. (2019a). Investigating the use of different visual cues to improve social presence within a 360 mixed reality remote collaboration. In The 17th International Conference on Virtual-Reality Continuum and its Applications in Industry. 1–9

Teo, T., Lee, G. A., Billinghurst, M., and Adcock, M. (2019b). Merging live and static 360 panoramas inside a 3d scene for mixed reality remote collaboration. In 2019 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct). 22–25

Teo, T., Norman, M., Lee, G. A., Billinghurst, M., and Adcock, M. (2020). Exploring interaction techniques for 360 panoramas inside a 3d reconstructed scene for mixed reality remote collaboration. Journal on Multimodal User Interfaces 14, 373–385

Van der Land, S., Schouten, A., and Feldberg, F. (2011). Modeling the metaverse: a theoretical model of effective team collaboration in 3d virtual environments. Journal of Virtual Worlds Research 4

Vastenburg, M., Romero Herrera, N., Van Bel, D., and Desmet, P. (2011). Pmri: development of a pictorial mood reporting instrument. In CHI’11 Extended Abstracts on Human Factors in Computing Systems. 2155–2160

This is a provisional file, not the final typeset article
Villegas, A., Pérez, P., and González-Sosa, E. (2019). Towards a distributed reality: a multi-video approach to xr. In Proceedings of the 11th ACM Workshop on Immersive Mixed and Virtual Environment Systems. 34–36

Viola, I., Subramanyam, S., Li, J., and Cesar, P. (2022). On the impact of vr assessment on the quality of experience of highly realistic digital humans. arXiv preprint arXiv:2201.07701

Vorderer, P., Wirth, W., Gouveia, F. R., Biocca, F., Saari, T., Jäncke, L., et al. (2004). Mec spatial presence questionnaire. Retrieved Sept 18, 2015

Wang, P., Bai, X., Billinghurst, M., Zhang, S., He, W., Han, D., et al. (2020). Using a head pointer or eye gaze: The effect of gaze on spatial ar remote collaboration for physical tasks. Interacting with Computers 32, 153–169

Witmer, B. G. and Singer, M. J. (1998). Measuring presence in virtual environments: A presence questionnaire. Presence 7, 225–240

Young, J., Langlotz, T., Cook, M., Mills, S., and Regenbrecht, H. (2019). Immersive telepresence and remote collaboration using mobile and wearable devices. IEEE transactions on visualization and computer graphics 25, 1908–1918

Zhang, J., Katzakis, N., Mostajeran, F., Lubos, P., and Steinicke, F. (2020). Think fast: Rapid localization of teleoperator gaze in 360° hosted telepresence. International Journal of Humanoid Robotics 17, 1950038

Zhao, S. (2003). Toward a taxonomy of copresence. Presence 12, 445–455

Zijlstra, F. (1993). Efficiency in Work Behaviour: A Design Approach for Modern Tools (Delft University Press)