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Investigating co-presence and collaboration dynamics in realtime virtual reality user interactions

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As Virtual Reality (VR) technologies advance and gain popularity, their potential as powerful tools for collaboration is increasingly recognized. VR facilitates interaction with the virtual presence of individuals who are not physically co-located. Understanding the dynamics of user interactions and the cognitive perception of virtual presence quality is essential for this technology's progression. This paper introduces CoCoVR, a VR measurement method for measuring the sense of co-presence and collaboration quality among users through real-time data collection and analysis. CoCoVR is evaluated across various scenarios to understand user interactions in VR under different conditions. An extensive analysis of recent literature has been performed that identified avatar realism and communication as two key factors influencing co-presence and collaboration. The experiment includes a custom VR application, the Soma cube puzzle, and real-time sensors. A between-subject experiment was conducted to collect and analyzes real-time data on collaboration and co-presence. This study integrates both objective and subjective measures, offering deeper insights into the immersive experience and its impact on collaborative tasks. The findings show that avatar realism enhances the feeling of co-presence and that communication methods substantially improve collaboration. Additionally, the study found that measuring physiological responses can serve as a novel method for evaluating the quality of user collaborations.

KEYWORDS

VR, virtual reality, collaboration, co-presence, sense of presence, data analysis, collaborative virtual environment, virtual environment

1 Introduction

In the rapidly evolving field of virtual reality (VR) technologies, there is a continuous advancement toward leveraging VR for enhancing the productivity of remote collaborative tasks. VR facilitates collaboration by overcoming physical barriers such as distance and enabling interpersonal interactions that are otherwise challenging to achieve. This capability is particularly valuable for users who are not physically co-located, allowing them to collaborate, discuss, and perform tasks remotely. The recent rise in remote working, exacerbated by the Covid-19 pandemic (Brynjolfsson et al., 2020), has accelerated the adoption of digital communication and collaboration methods across various industries. This trend is evident in emerging technologies, including Meta's Metaverse and Apple's Vision Pro product which enhance video calling experiences with virtual avatars.

Two critical aspects of utilizing VR environments are co-presence and collaboration. Co-presence, defined as the sense of being together with another person in a virtual environment, is essential for designing multi-user VR experiences (Goffman, 2008) (Ijsselsteijn et al., 2001). The perception that a user's avatar accurately represents their intentions and interactions is closely linked to the feeling of immersion and significantly enhances the overall quality of the virtual experience. Previous research indicates that different tasks in VR environments can induce varying levels of co-presence, and the quality of collaboration on these tasks can differ depending on the nature of the task and the virtual elements involved.

Presence and collaboration are critical components in enhancing educational experiences, especially within immersive and interactive environments such as VR. In educational contexts, presence refers to the sense of being there or fully engaged in a learning activity, which significantly contributes to the learners' attention, retention, and emotional connection to the material. This is often categorized into place presence (feeling immersed in the learning environment), social presence (feeling connected to others), and co-presence (being aware of and interacting with others in real time). Co-presence, in particular, has a profound effect on collaborative learning as it fosters communication, problem-solving, and the exchange of ideas in virtual spaces where learners are geographically separated. Collaboration within VR or other immersive environments promotes teamwork and deeper learning. Research shows that collaborative tasks, especially those requiring real-time interaction and problem-solving, benefit from the shared sense of presence. The ability to see, hear, and communicate with peers in a virtual space creates a dynamic that mimics in-person collaboration, driving higher engagement and knowledge sharing (Laine and Lee, 2023). Tools that allow for multimodal communication such as speech, gestures, and even facial expressions—significantly enhance the quality of collaboration. This aligns with findings that realistic avatars and interactive elements in VR contribute to a stronger sense of social presence, further enhancing the collaborative experience (Philipp Freiwald et al., 2021). These immersive features are vital in supporting active learning and group cohesion, leading to better educational outcomes in remote or hybrid learning environments. The sense of presence in virtual environments is crucial for immersive experiences, but it can be affected by factors such as physical discomfort or cybersickness (Mondellini et al., 2018). Mondellini et al. (2018) study on cycling in virtual environments reveals that physical activity can enhance the sense of presence while also contributing to cybersickness, affecting overall user satisfaction. To effectively analyze and understand how different elements influence users' sense of co-presence and their collaboration, it is necessary to effectively discern influence factors that affect these variables. For this purpose the characteristics of Avatar Realism and voice communications were chosen to develop a measurement method capable of assessing these factors within a VR environment.

This paper aims to present a data collection and analysis method to better understand, analyze, and predict the effectiveness of collaboration and co-presence in VR environments. The following research questions guide this study:

RQ1: How do the chosen characteristics of the collaborative virtual environment contribute to the measured user's sense of co-presence and collaboration?

RQ2: How does the effectiveness of physiological sensors compare to self-reported surveys and task outcome analysis in capturing collaboration dynamics?

2 Related work

It is pertinent for the goal of having a precise data collection platform, to understand the basis upon which the data is acquired. Consequently, both collaboration and co-presence metrics need to be clearly defined first. An extensive study of the related work on the aforementioned topics have been conducted, the results of which are going to be discussed in the following sections.

2.1 Co-presence

Co-presence refers to the concept of being with others either physically or through a sense of presence (Ou and Lin, 2023). It encompasses two dimensions: the physical conditions that structure human interaction and the subjective experience of being with others (Almeida et al., 2022). In the context of digital interactions, co-presence can manifest as mediated co-presence, dysco-presence, and disco-presence, reflecting different levels of engagement and resistance online (Hilge, 2022). Additionally, co-presence plays a crucial role in the emergence of collectives, emphasizing feelings of togetherness and shared experiences, especially in online settings where corporeal communication is limited (Chowdhury et al., 2022). Recent advancements in technology, such as telepresence robots and virtual reality platforms, aim to enhance co-presence by creating a sense of presence and closeness in remote interactions (Zhou et al., 2018).

When it comes to virtual presence, among the literature the most well defined terminologies are place presence, social presence and co-presence. The term "presence" refers to the individuals "sense of being" in the virtual environment. It is closely tied to avatar embodiment and sense of presence in the virtual environment. Place presence refers to the sense of being in a virtual environment or place, while "social presence" has been defined in 1968 as the degree of salience of interpersonal communications in the virtual environment (Morton and Mehrabian, 1968). Social presence is heavily affected by the medium's ability to convey language and expressions. Lastly, the term co-presence was first coined in 1963 by Goffman (2008) and was defined as a sense of being together with another person in a virtual environment. Recent research saw co-presence as not only being in the same place, but also a mutual awareness of the individuals and emphasized the sensory properties of the virtual environment. Studies show that in regards to virtual environments specifically, sense of presence, social presence and immersion all affect the sense of co-presence when multiple users are using a technology.

2.2 Collaboration

Collaboration in human-computer interaction and virtual realities involves users working together, either symmetrically or asymmetrically, to perform tasks using shared virtual objects (Huang et al., 2023; Elvezio et al., 2018). Avatars play a crucial role in facilitating social interaction in collaborative virtual environments, especially in corporate settings, where effective collaboration is essential (Hube et al., 2021). Enhancements in collaborative virtual reality applications, such as multiperspective visualizations, can bridge the gap between users' viewpoints, improving communication and efficiency during collaborative tasks (Wang et al., 2020). Virtual reality enables remote collaboration, eliminating logistical challenges and costs associated with physical presence, although physical proximity can enhance performance in certain collaborative tasks (Hatzipanayioti et al., 2019). Overall, collaborative interactions in virtual environments are evolving to support diverse forms of collaboration, offering benefits in terms of equity, adaptability, and cost-effectiveness.

In the context of this research, collaboration refers to the synergy and interactive engagement of individuals within a shared virtual space, fostering joint efforts to achieve common goals, solve problems, or create shared experiences.

2.3 Synthesis of existing literature on co-presence and collaboration in VR

The synthesis and analysis of recent studies on collaboration and co-presence in VR environments offer insights into various experimental designs, influence factors, and measurement methods. The literature reveals significant advancements and gaps in understanding how VR can enhance collaborative efforts and the sense of co-presence. In Table 1 a number of recent papers in this research area were analyzed carefully and summed up in the shown categories. The table includes the area of research, the type of experiment design, the influence factors and the measured dependent variables for understanding collaboration or different types of sense of presence. It also includes information about the equipment used, as technology in this area is rapidly evolving and quality of experience is highly different for different devices.

The recent advancements in VR technology have significantly enhanced our understanding of collaboration and co-presence within virtual environments. Before now, the BEAMING project extended the scope of collaborative mixed reality to include the representation of users in multiple modalities, and defined the notion of presence awareness (Oyekoya et al., 2013; Steed et al., 2012). More recently, researchers have explored various factors that contribute to an immersive and collaborative VR experience, providing valuable insights for developing effective VR systems. Gibbs et al. (2022) explored the impact of visual and haptic feedback on users' sense of presence. They used a 3×2 within-subject design where participants interacted with a virtual bouncing ball, and their findings highlighted the importance of multimodal feedback in fostering immersive and collaborative VR environments. This underscores the necessity of integrating multiple sensory inputs to create engaging VR experiences that are crucial for effective collaboration. Similarly, Laine et al. (2023) focused on the significance of sensor fidelity and interface quality in a virtual classroom setting. They found that high-quality sensory inputs are essential for improving immersion and reducing discomfort, thereby enhancing the overall effectiveness of VR collaborations. This research supports the idea that the quality of sensory inputs directly affects the user experience in collaborative VR environments. Yasuoka et al. (2022) examined the role of virtual avatars in influencing social presence and co-presence. Their study indicated that realistic avatars significantly enhance these aspects, suggesting that avatar design is critical for effective collaboration in VR settings. This finding aligns with the notion that the visual representation of users plays a significant role in how they interact and collaborate in virtual spaces. Investigating the effects of different display types, Wolf et al. (2022) found that high-quality visual displays significantly impact perceived presence and embodiment. Their study emphasized the importance of display quality in enhancing immersive experiences and collaboration effectiveness. This highlights the need for advanced visual technologies to improve the sense of presence in VR. Melo et al. (2022) assessed the impact of audiovisual *versus* multisensory VR setups on spatial presence and related factors. Their research demonstrated that multisensory VR setups significantly enhance presence, realism, and enjoyment, suggesting that richer sensory environments can improve collaborative dynamics. This aligns with the broader understanding that multisensory inputs can deepen the immersive experience. Han et al. (2022) explored the effects of different screen types (VR vs. flat) on empathy and presence. They found that VR screens significantly enhance these aspects, supporting their use in creating emotionally engaging and collaborative VR environments. This finding is crucial for designing VR systems that aim to foster strong emotional and cognitive engagement among users. The role of eye and mouth movements in enhancing social and co-presence was investigated by Kimmel et al. (2023). Using advanced facial tracking, they found that these movements are crucial for affective understanding and effective collaboration in VR settings. This underscores the importance of nonverbal cues in virtual interactions, aligning with the findings of other studies that emphasize the role of facial expressions and eye movements. Tea et al. (2021) examined the impact of immersiveness on collaboration during a building inspection activity. Their study found that VR significantly enhances collaboration and task performance, underscoring the value of immersive environments for collaborative tasks. This supports the broader perspective that immersive VR settings can improve collaborative efforts. Archer et al. (2022) investigated the impact of odour on spatial presence and emotional engagement during a VR game. They found that integrating odour enhances presence and emotional responses, suggesting that multisensory inputs can improve collaboration dynamics. This highlights the potential for incorporating diverse sensory inputs to create more engaging VR experiences. Evaluating the sense of presence among healthcare professionals during a mass casualty incident simulation, Paquay et al. (2022) highlighted the effectiveness of VR simulations in enhancing training and preparedness. This study supports the use of VR for realistic and effective collaborative training scenarios, emphasizing its practical applications in professional training environments.

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TABLE 1 Recent literature on collaboration and co-presence.

Author	Year	Research area	Experiment design	Influence factors	Experiment description	Measurement method	Dependant variables	Mixed reality equipment	Refe-rences
Mondellini et al.	2018	Sense of Presence and Cybersickness	Within-subject Design	Physical activity (cycling), VR realism	Investigated the experiences of navigating in the same VEs using a cycle-ergometer and either a projected screen	Questionnaire (Presence, Cybersickness), Task Outcome	Sense of presence and cybersickness	Oculus Rift, VR cycling equipment	Mondellini et al. (2018)
Gibbs et al.	2022	Presence	3 × 2 Within-subject Design	Visual and Haptic Feedback	Virtual bouncing ball on a stick	Questionnaire, 7-Point Likert scale	Sense of presence	Oculus Rift S, Oculus Touch handsets	Gibbs et al. (2022)
Laine et al.	2023	Collaboration, Presence	Within-subject	No Adjusted Factors	Collaborative Virtual Classroom	Questionnaire, 7-Point Likert scale	Involvement, Sensor Fidelity, Immersion, Interface Quality, Presence, Discomfort	Oculus Quest 2	Laine and Lee (2023)
Yasuoka et al.	2022	Social Presence, Co-presence	Within-subject	Virtual Avatar	CommU Conferencing platform	Questionnaire, TPI, Likert Scale	Social Presence, Co-Presence, Immersion, Interaction Quality	Not Specified	Yasuoka et al. (2022)
Wolf et al.	2022	Presence	3 × 1 Between Subject	Display type	interacting with AR holographic mirror	Questionnaire, lgroup presence	Perceived feeling of presence, Embodiment, Body weight misestimation (BWM)	HoloLens 2, Captury body tracker, Original App, OST AR mirror system	Wolf et al. (2022)
Melo et al.	2022	Presence	Cross-sectional with a between-group design	Audiovisual vs. Multisensory VR Setup, Gender	5 min virtual touristic experience	Questionnaire, IPQp	Spatial Presence, Involvement, Realism, Satisfaction, Emotions, Enjoyment, Intention to Visit	HTC VIVE (HMD), Headphones	Melo et al. (2022)
Han et al.	2022	Presence	Mixed design (Between-Subject: Immersion Level, Within-Subject: Perspective)	Type of Screen (VR vs. Flat)	VR Videos	Questionnaire, Igroup (IPQ), 5-likert	Empathy, Presence	Oculus Quest, iPad, Two Laptops	Han et al. (2022)
Kimmel et al.	2023	Co-Presence, Social-Presence	Within-subject	Eye Movement, Mouth Movement, Both	Verbal and graphical explanation of a word to another person	Questionnaire, NMSPI, 7-point likert, Facial Tracking	Co-Presence, Perceived Affective Understanding and Interdependency, Gaze Duration, Gaze Frequency, Mouth Weight Changes, Head Position Changes, Head Rotation Changes	Pico Neo 3 Pro Eye, Tobii VR4 Platform Eye Tracking, VIVE Facial Trackers	Simon et al. (2023)
Tea et al.	2021	Collaboration	Between-subject design	Immersiveness	building inspection activity	Task Performance	Collaborative activities, Task performance	HTC VIVE (HMD), vs. Laptop	Tea et al. (2021)
Archer et al.	2022	Spatial Presence	Within-subject design	Odour	VR Game (Resident Evil 7)	Questionnaire (ITC-SOPI), Heart rate, Body temperature,EDA	Spatial Presence, Emotional State, Smell Recall	Olfactometer for odour, Empatica E4 Wristband, Playstation VR	Archer et al. (2022)
Paquay et al.	2022	Presence	within-subject design	different healthcare professional groups	mass casualty incident (MCI) simulation	Questionnaire	Sense of Presence	VR Laptop, HTC Vive HMD, VR Controllers	Paquay et al. (2022)
Tian et al.	2023	Collaboration, Social Presence	2 × 2 Experiment Design	Type of Spatial Communication (AR vs. VR), Participant Role	Soma Cube Puzzle	Task completion, Logs, Standardized Questionnaires	Social Presence, Sense of Presence, Mental and physical Load, Usability, User Preference	Microsoft HoloLens 2, HTC Vive Pro Eye, Azure Kinect Cameras	Tian et al. (2023)

Tian et al. (2023) explored the effects of spatial communication types (AR vs. VR) and participant roles on collaboration and social presence during a Soma cube puzzle task. Their findings emphasized the superiority of VR over AR for certain collaborative contexts, suggesting that VR settings significantly improve social presence and usability. A systematic review by Huang et al. (2023) on VR and collaborative learning highlighted the potential of VR to support collaborative knowledge building, particularly in educational settings. They found that structured activity design and moderate levels of realism are beneficial for equity, adaptability, and effectiveness in shared VR environments. Additionally, a critical review by Xenakis et al. (2023) on nonverbal communication in VR emphasized the importance of nonverbal cues in enhancing presence and facilitating social interactions. This review highlighted that VR enables the transfer of a broad range of nonverbal cues, essential for effective collaboration. Furthermore, Lui et al. (2023) conducted a systematic literature review on designing collaborative learning environments in immersive VR. They underscored the importance of pedagogical concepts, structured environments, and the affordances of VR in facilitating collaborative learning activities, identifying both the potentials and limitations of VR in educational contexts. The synthesized literature underscores the critical role of multimodal feedback, high-quality sensory inputs, and realistic avatars in enhancing collaboration and co-presence in VR environments. Studies consistently highlight the benefits of immersive and multisensory setups for creating engaging and effective collaborative experiences. However, there are nuanced insights, such as the specific advantages of odour integration and the comparative benefits of VR over AR for certain tasks, suggesting that tailored approaches may be necessary to maximize the benefits of VR for collaboration. The integration of nonverbal communication cues in VR is particularly promising, as it enhances social interactions and presence. This aligns with findings that emphasize the importance of facial expressions, eye movements, and other nonverbal cues in fostering effective collaboration.

Based on the researched literature, the overwhelmingly agreed upon method of measuring presence factors seems to be using questionnaires and gaining user feedback. One of the Standard questionnaire formats most frequently used for measuring sense of presence, is the lgroup presence questionnaire (IPQ), which directly measures the sense of presence, but not co-presence. However the Networked Minds measure of Social Presence (Biocca et al., 2001) has been shown by Kimmel et al. (Simon et al., 2023) to be a valid method for measuring co-presence and social presence.

For measuring collaboration however, while qualitative measurements are a valid approach, the most popular approach seems to be to analyzing the task outcome and deduce the quality of the collaboration based on the user performance of the task, as similarly demonstrated in the paper by Tea et al. (2021) and another research by Tian et al. (2023)

In synthesizing these recent research endeavors, it becomes evident that collaboration and co-presence in VR are multifaceted phenomena. The results of all the experiments, whether from physiological sensors or subjective assessments, all collectively contribute to a comprehensive understanding of the intricacies involved.

The study on recent works collectively underscores the significance of various factors in enhancing collaboration and co-presence in VR environments. Visual and haptic feedback, high-quality sensor input, realistic avatars, and multisensory setups consistently emerge as critical elements that enhance the sense of presence and collaboration. The studies by Gibbs et al. (2022) and Laine and Lee (2023) highlight the importance of multimodal feedback and sensor fidelity, respectively, for an immersive and engaging VR experience. Yasuoka et al. (2022) and Kimmel et al. (Simon et al., 2023) further emphasize the role of avatars and facial expressions in fostering social and co-presence, which are essential for effective collaboration.

Conversely, the research by Wolf et al. (2022) and Melo et al. (2022) illustrates that the type of display and sensory richness significantly impact the immersive experience, thereby influencing collaborative effectiveness. Han et al. (2022) findings on the emotional engagement fostered by VR screens further support this notion. The studies by Tea et al. (2021) and Archer et al. (2022) reinforce the value of immersive environments and multisensory inputs in enhancing collaborative task performance and emotional engagement, respectively.

However, there are also subtle insights, such as the specific benefits of odour integration in VR Archer et al. (2022) and the comparative advantages of VR over AR for spatial communication and social presence Tian et al. (2023). These findings suggest that while VR generally offers substantial benefits for collaboration and co-presence, the specific applications and contexts may require tailored approaches to maximize these benefits.

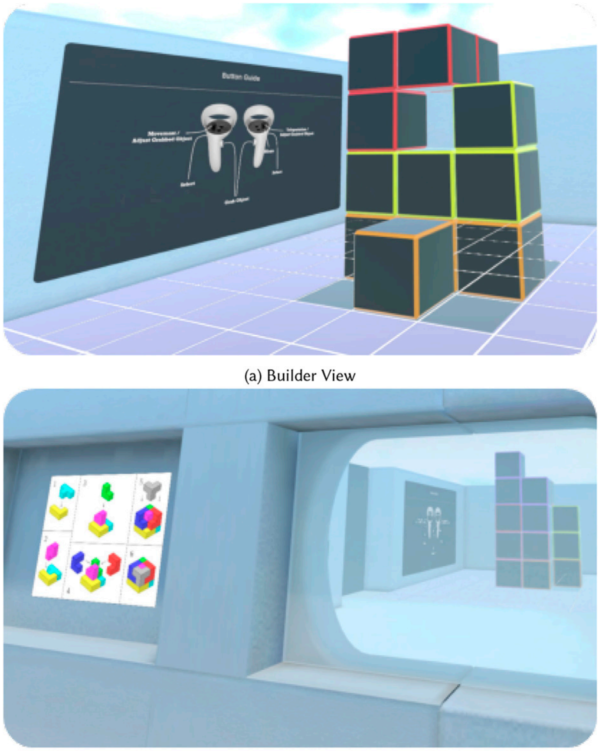
The synthesized literature provides a robust foundation for the focus of this research, aimed at understanding the effects of various factors collaboration and co-presence in VR. By integrating insights from these studies, this study, and future research can further refine VR systems to support more effective and immersive collaborative experiences. This paper is heavily inspired by these studies and builds upon and integrates insights from them to formulate an experiment that measures and addresses important contexts in the evolving landscape of collaborative experiences in virtual reality.

3 Methodology

This study focuses on investigating the influence of specific characteristics within a virtual reality environment. This is achieved by collecting data from users during and after the experiment through sensors and questionnaires, which is then compiled into quantitative, tangible outcomes. Firstly we present the setup of the system, and then present the research protocol.

3.1 System architecture of the VR application environment, CoCoVR

The technical architecture includes a custom built multiplayer collaborative VR environment, which has been developed with the purpose of providing a baseline for the data collection. The collaborative multiplayer application serves as the experimental platform upon which the measurements are taken. This application is developed and publicly available on the Github



(a) Builder View

(b) Instructor View

FIGURE 1
The VR application environment, CoCoVR. **(A)** Builder View. **(B)** Instructor View.

repository for CoCoVR (Ghasempour, 2024). Within the application, the players are tasked with completing a puzzle in collaboration. The puzzle chosen for this purpose is a classic Soma cube puzzle, as inspired by the work of Tian et al. (2023). One of the players, from here on referred to as the "Instructor", will have the solution to the puzzle available to them, but are unable to arrange the pieces themselves. The other player, from here on referred to as the "Builder" cannot see the solution, but can arrange the pieces freely as they wish. Figures 1A, B show the looks of the application from the view of the Instructor and Builder players. The Instructor is able to see the builder through a window and the players can see each other's digital avatars, which enables them to communicate via gestures and body movements, especially when voice communication is disabled in certain scenarios.

The players information from the VR session are captured using physiological sensors to keep track of the players emotional and physical states, and their performance in the game. This means there are two sources of data collection active during the experiment, one being the VR headset itself, more specifically the custom-built application that communicates with the cloud to save collected data, and the second one being the physiological sensors. Figure 2 shows the process diagram setup for the entire data collection that was used for this experiment. As many of the devices and sensors used are interchangeable with other devices and physiological sensors of the same type, so the details of the used devices are not discussed.

For collection of data, Oculus Quest Pro was used running the custom-built experiment environment, which was made using Unity Engine. From within the application the data related to completion of the task is collected, combined with gaze tracking information that measures how many seconds the users spent looking at each other. Simultaneously, Fitbit Charge 6 was used for collection of Physiological data, such as Heartbeat rate and Skin Conductivity Level (SCL). Fitbit Charge 6 needs a mobile phone to sync with to record the data, and for this purpose a Google Pixel 7 Android phone was used. The connection of the data collection devices to the unity dashboard and google cloud was possible using a D-Link DWR-978 5G Router. This router also provides the internet connection necessary for the users multiplayer connection.

3.2 Research protocol

3.2.1 Participants and research contexts

A total of 16 participants, mostly between 18 and 25 years old, from Skellefteå, Sweden volunteered to participate in this study during the period the research was conducted. They were a mixture of students from Luleå University of Technology, Umeå University, Green Flight Academy, Arctic games, and Future games that all exist within Campus Skellefteå. Given that the participants are student volunteers with a keen interest in virtual reality, their perception may exhibit a positive skew.

3.2.2 Influence factors for Co-presence and collaboration in VR environment

Factors influencing co-presence in virtual reality include technical aspects like visual realism and field of view, emotional factors such as fear, physical feedback like applied force, haptic feedback, or even odour (Archer et al., 2022), as well as social dynamics during collaborative tasks (Simon et al., 2023). Technical factors like visual realism and field of view interact with human factors like emotions and agency to shape presence formation (Jicol et al., 2023b). Physical coherence factors, particularly force, occlusion, and lighting, significantly impact presence during user-object interactions in XR environments (Lim and Ji, 2023). Additionally, social presence during dynamic remote collaboration in Mixed Reality settings is influenced by spatial layouts and the level of affordance, with VR facilitating higher co-presence than AR through HMDs (Shin et al., 2022). Emotions, arousal levels, and personality traits also play a role in shaping presence, with high-arousal emotions showing a stronger effect on presence formation (Jicol et al., 2023a). Incorporating credible multisensory stimuli like wind, passive haptics, vibration, and scent can enhance the sense of presence in virtual environments as well (Archer et al., 2022; Gonçalves et al., 2020).

Influencing factors that affect Collaboration, include facial expressions, such as eye and mouth movements, significantly influence Social Presence in Virtual Reality (VR) collaboration, enhancing the feeling of co-presence and connection (Simon et al., 2023). Mutual awareness of visual attention, facilitated by Field-of-View (FoV) frustum visualizations, supports collaboration by improving visual attention coupling and reducing distractions (Bovo et al., 2022). Avatar appearance, particularly gender, impacts collaboration quality in VR environments, with same-gender pairs perceived as more productive and supportive during collaborative tasks (Yassien et al., 2021). Effective collaboration in VR is also

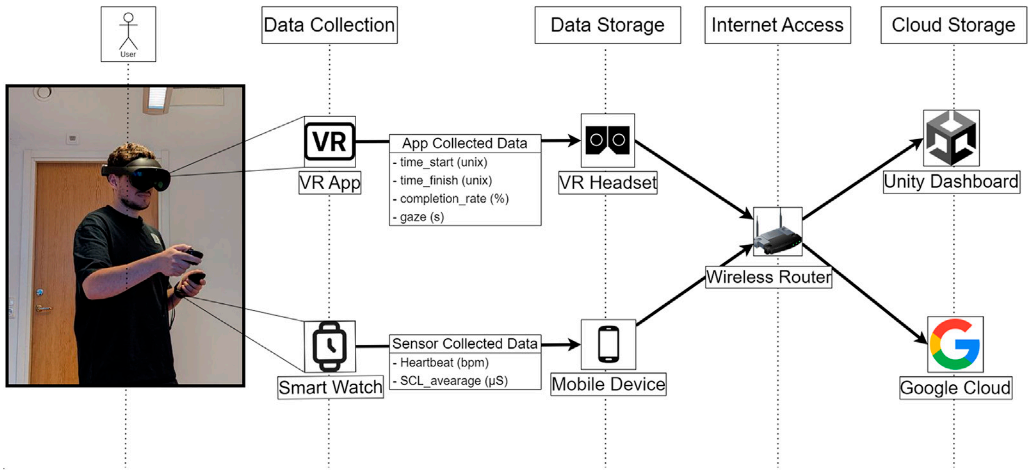


FIGURE 2
Experiment process diagram for data collection.

TABLE 2 Influence factors.

	Low collaboration	High collaboration
Low	Abstract Avatar	Abstract Avatar
Co-presence	Voice Communication	Voice Communication
	Disabled	Enabled
High	Realistic Avatar	Realistic Avatar
Co-presence	Voice Communication	Voice Communication
Co-presence	Disabled	Enabled

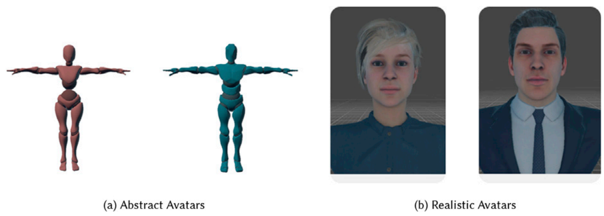


FIGURE 3
VR avatars. **(A)** Abstract Avatars. **(B)** Realistic Avatars.

influenced by the fidelity of partner avatars, where higher kinematic fidelity, such as in a streamed point-cloud avatar, enhances collaborative performance in spatial tasks (Nils, 2023). These factors collectively contribute to shaping the dynamics of collaboration in virtual reality environments.

For this research to carefully choose the influencing factors for this experiment, influencing factors from previous literature has been taken into account. The literature shows that numerous physical and psychological factors can affect the level of co-presence and collaboration experienced by users in a virtual reality environment. Namely, digital avatars and their appearance in the virtual reality environment influence collaboration and co-presence (Yasuoka et al., 2022). Realistic digital avatars help the feeling of being there with another person while also providing better measures of communication (gestures, facial details) for collaborating (Simon et al., 2023). As mentioned, communication is an important part of effective collaboration, (Tea et al., 2021; Tian et al., 2023), and so one of the influence factors in this study will be the level of communication the players are able to carry. Voice explanations tend to have a more pronounced effect on co-presence than graphical explanations (Simon et al., 2023). Besides, voice type, traits, emotion and social presence have been studied to influence communication in VR (Higgins et al., 2022). Other possible influence factors also include multi-sensory stimuli to increase the level of co-presence by stimulating user's senses. This could be through introducing odour (Archer et al., 2022) or replicating pain or applying force to the user based on the VR scenario.

According to our synthesis of existing literature, Table 2 shows the different scenarios on how the chosen influence factors should affect collaboration and co-presence. Based on these chosen influence factors, an appropriate task and experiment was designed for the experiment, which is discussed in the next section.

3.2.3 Experiment setup

This study employs a between-subject experiment design to manipulate collaboration and co-presence metrics in VR and effectively measure them in an objective and subjective manner.

As shown in Table 2 within the experiment setup, two influence factors are manipulated: Digital avatar and voice communication which are expected to respectively affect co-presence and collaboration. For comparison of digital avatar scenarios, two pairs of realistic and abstract avatars were prepared, as shown in Figures 3A, B. Regarding communication, voice communication was enabled and disabled between different pairs of participants, to realize the differences in collaboration levels.

With a clear goal of which influence factors need to be adjusted in the game, a collaborative virtual reality environment was developed for the purposes of engaging players and capturing their collaboration and co-presence metrics within the game.

Participants wears the VR headsets and controllers, along with the physiological sensors for data collection. They were randomly assigned one of the following between-subject scenarios.

- Scenario 1: Abstract Avatar, Voice Communication Enabled
- Scenario 2: Realistic Avatar, Voice Communication Disabled
- Scenario 3: Realistic Avatar, Voice Communication Enabled
- Scenario 4: Abstract Avatar, Voice Communication Disabled

3.2.4 Experiment procedure

The participants, which are a group of adult volunteers arrived to the lab building and were randomly split into two physically separate rooms where they could not see or hear each other. They were briefed on what the experiment and the application entails, and additional instructions regarding VR controller usage and how to play the puzzle game to the end were available both within the VR application and outside the virtual environment. The participants were prompted to put on the Fitbit Charge 6 device on one of their wrists. These devices have been synchronised beforehand with phones available to the researchers, and are responsible for gathering heartbeat per minute data from the participants while they are performing the task.

Afterwards the participants are prompted to put on the VR headset, which is already pre-loaded with a version of the CoCoVR application based on the scenario the participants are assigned to. The application handles the data collection smoothly and updates the data in Unity Dashboard. The participants were granted as much time as needed to finish the puzzle, and they also had the choice to leave the puzzle unfinished if they wanted to. Regardless of that fact, the time to finish the puzzle were always less than 30 min across all participants.

Afterwards, the participants took off their VR headsets and performed an EDA (Mindfulness) test on the Fitbit Charge 6 for the duration of 3 min, which would also be synchronized with the phones and sent to Google cloud. After the EDA test, the participants were asked to answer the questionnaire, which does not collect any personal information and only focuses on the research variables.

During and after the experiment, the participants were not informed about their performance metrics in comparison to other participants.

3.2.5 Ethical considerations

This study was conducted in accordance with the Declaration of Helsinki. Informed consent was obtained from all participants, who were adult volunteers. Before participating, a researcher briefed them on the experiment's details, including how the collected data would be used and potential VR side effects (e.g., Dizziness, Eye strain). The consent of participants were sorted before the experiment was conducted.

3.2.6 Data collection methods

To measure collaboration on both objective and subjective levels, a combination of real-time sensor data and participant feedback will be collected. In order to do this, the following methods were employed.

- Task Outcome Analysis: The quality and success of collaborative tasks within the VR application will be continuously collected in real time. This analysis provides measurement methods such as:

  - Completion time of the puzzle (if completed).
  - Completion Percentage of the puzzle.

These metrics will provide an immediate insights into the effectiveness of collaboration.

- EDA readings: Electrodermal Activity (EDA) sensors will be used to monitor the electrical conductance of the skin, which varies with its moisture level. The skin conductance level collected by the EDA sensors reflects the general state of arousal or activation of the sympathetic nervous system, which can be valuable for measuring the sense of collaboration among participants. After the experiment, the participants are asked to perform a “mindfullness” test on the fitbit charge 6 devices. This collects EDA readings from the participants over the duration of 3 min after the experiment, to highlight their emotional state.
- Heartbeat readings: During the experiment, the fitbit heartbeat sensors on the participants would be passively collecting heartbeat information. This data is later used to measure whether or not participants have a sense of synchronicity in their bodily responses to in-game events. This inter-body synchronicity is used as a measure of collaboration between the two participants.
- Gaze Tracking: Various sensors from the VR hardware provide valuable insight into user behaviour. The real-time data collected from these sensors, as proposed by the ManySense VR framework (Moon et al., 2022), will contribute to an ongoing and dynamic understanding of co-presence beyond traditional measures. For the purposes of this experiment, to understand the essence of co-presence, the gaze of the players during the experiment was analysed, which is to say, where the players were looking during the experiment, and how long.
- Questionnaires: Following the completion of the session, participants will be prompted to provide information about themselves and provide insight to their experience through questionnaires. The questionnaire contains to 3 separate sections, followed by fourth non-mandatory open-question section. Full details of the questionnaire are further elaborated in the following section.

The subjective and objective data are analysed to form an understanding of collaboration and co-presence in the VR environment. The idea is to observe real-time patterns and trends in the data and assist in developing a better understanding of intricacies of co-presence and collaboration in VR environment.

3.2.7 Questionnaire design

The questionnaire given to participants consisted of 4 sections, with the fourth section being non-mandatory and only containing open-ended questions. The sections are as following:

a) Initial questions, 5 items including gender, participant's respective role in the experiment, and their level of familiarity with VR devices, the Soma cube puzzle and their partner in the experiment. This data only acted as a basis for the researchers to differentiate the results based on the participants. b) Co-presence questionnaire, 38 questions adapted from the study of Networked Minds measure of Social Presence (Biocca et al., 2001), modified to fit a 5-point Likert scale type question. Only two variables from that study, regarding mutual awareness to others in the room were omitted, due to them not

TABLE 3 Summary of all combined data.

	Gaze	Gaze_ percent	Rate	Finish finish	Hb_ avg	Hb correlation	Scl_ avg	Social_presence_ score	co_presence_ score	collaboration_ score
count	12.00	10	16.00	14.00	16.00	16.00	16.00	16.00	16.00	16.00
mean	1060.40	0.73	94.91	1003.41	87.90	0.13	36.82	3.29	2.92	3.65
std	462.47	0.15	13.92	467.84	12.30	0.12	5.35	0.15	0.24	0.17
min	550.46	0.54	59.26	358.15	70.94	0.00	23.42	3.08	2.50	3.44
25%	741.60	0.60	100.00	570.88	80.15	0.04	34.64	3.17	2.75	3.56
50%	983.05	0.70	100.00	1010.98	88.20	0.10	36.52	3.32	3.00	3.61
75%	1143.40	0.86	100.00	1292.91	90.83	0.23	40.43	3.37	3.00	3.69
max	2210.14	0.97	100.00	1741.50	117.27	0.35	44.69	3.61	3.25	4.11

being applicable for this experiment. c) Collaboration questionnaire, 9 questions which is directly respective to three categories of the Collaboration Assessment Tool (CAT) from the work of Marek et al. (2015). This corresponds to the categories of clarity of mission, communication, and collaborative environment. The rest of the categories were omitted for not being applicable to this experiment. d) 3 non-mandatory open ended questions that provided a chance to give more feedback to researchers. These questions asked of 1) The participants experience with another person in VR, 2) The participants perceived quality of collaboration with the other person 3) Open text field for feedback and extra thoughts.

3.2.8 Measures

To begin analysing the data collected from the experiment, the first step was to synchronize the data gathered from the sensors to the data connected by the VR application. Both of these sources have varying information that are important for this study. The body sensors gather the following data: a) Heartbeat data (Bpm) throughout the experiment, divided into two values of *Average Heartbeat* and *Heartbeat Correlation* (Pearson Coefficient) between users; b) Skin Conductivity Level (μ S). Both measurements are tagged with timestamps for the duration they have been taken. This helps us pair them up with the data collected from the VR application, since it includes a timestamp as well. The following are the data from the VR application.

- Session Start Time (Unix Timestamp): The Unix timestamp of when the users start the experiment via the CoCoVR app.
- Task Completion Time (Seconds): The time it takes the users to accomplish the task and fully assemble the Soma cube (Null if not finished).
- Task Completion Rate (%): The percentage of the puzzle the users were able to finish, calculated by dividing the number of cubes in the right place divided by the total number of cubes. In case users finish the puzzle this percentage is 100, and if no cubes are in a satisfactory position the percentage is zero.
- Gaze-Tracking (Seconds): This is the time the player spends with the other player in their field of vision, which more often than not, is the times they are looking at the other player.
- Gaze Percentage (%): Gaze-tracking data, divided by the total session time, to show what percentage of time the user spent looking at the other user.

Following the objective data, there is the subjective questionnaire data collected in 5-point Likert-scale (strongly disagree to strongly agree) that each participant submits after the experiment, containing, 38 co-presence variables, and 9 collaboration effectiveness variables.

3.2.9 Statistical analysis

This paper analyse subjective and objective data to provide a clear understanding of how collaboration and co-presence metrics were affected in a virtual reality environment. Descriptive statistics was used to present the sensor data, collaborative virtual environment data, and questionnaire data. Simple correlations were run to measure how much the experiment variables affect each other. Boxplots were used as a comprehensive data visualization method to showcase the differences between the four scenarios. The collected and analysed data for this experiment is publicly available for further research (n.d].). The "NaN" values were missing data in the experiment. The ones on finish_time essentially mean that the participants did not complete the task. The ones on gaze_duration happened during data transfer from the app to the web dashboard.

4 Results

In this section, the findings from the experiment are presented without interpretation or analysis. The focus is on reporting the outcomes of the data collected from various methods, including task completion times, gaze tracking, physiological sensors (heart rate, EDA), and questionnaire responses. The results are organized based on key variables such as co-presence, collaboration, and physiological synchrony.

4.1 Descriptive statistics of sensor, CoCoVR, and questionnaire data

In order to understand the questionnaire data, the average value of the second section of the questionnaire amounts to an overall co-presence score, and the average value of the third section amounts to an overall collaboration score. A co-presence score shall also be calculated using the three questions relating to mutual awareness,

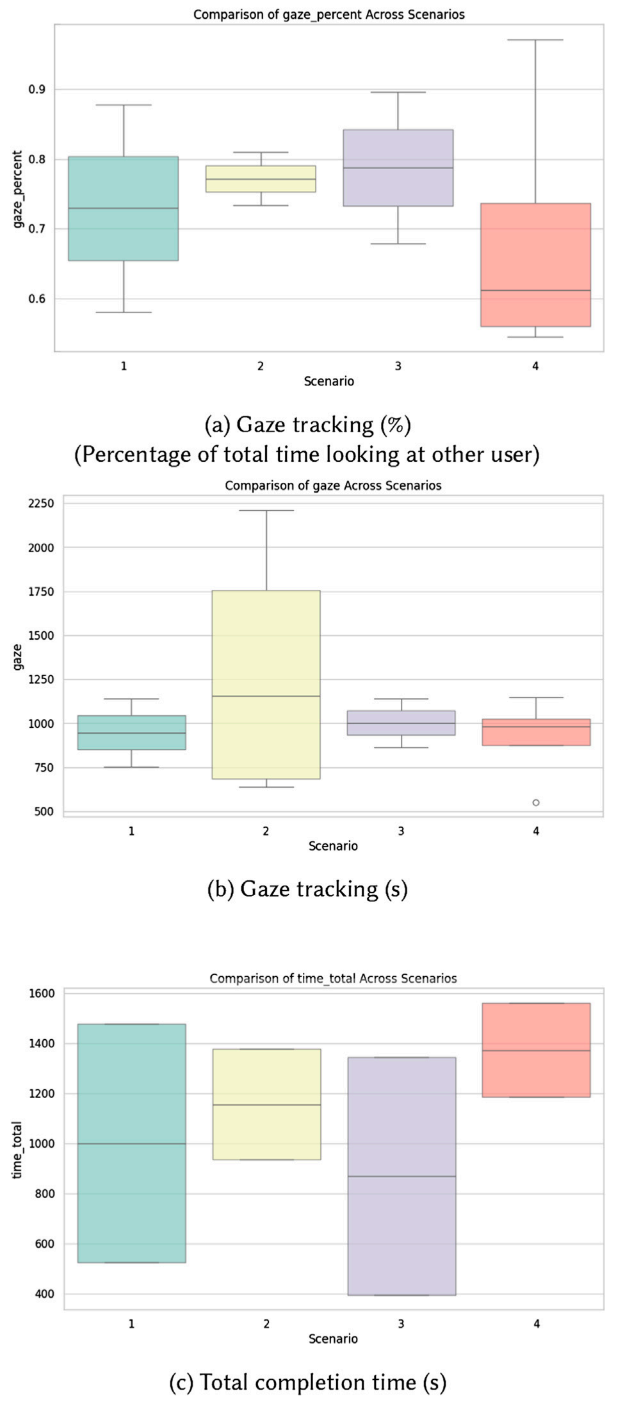


FIGURE 4
Boxplots for Application data. **(A)** Gaze tracking (%) (Percentage of total time looking at other user) **(B)** Gaze tracking (s) **(C)** Total completion time (s).

which are part of the social presence questionnaire. The overall shape of the data after preparations is shown in Table 3.

However, as we want to know the difference between the 4 between-subject scenarios, it is important we divide the data into each scenario as well. After doing so and plotting, the overall data was plotted into boxplots as shown in Figure 4.

4.2 Comparison of scenarios

In order to effectively compare the data across scenarios, they have been split up and presented as Tables 4–7. In scenario 2, the only scenario where users gave up on finishing the task, instead of having a finish time, we see that the users had a completion rate of 59.26 percent, meaning they had a little bit more than half of the pieces of the puzzle in the correct place.

The best way to visualize this data for comparison, is to use box plots that can easily depict the median, first (25%) and third (75%) quartile of the data. The box plots also contain whiskers that depict the highest and lowest data point as for that scenario. These boxplots are shown in Figures 4–6.

4.3 Correlation analysis

In this section, the correlation analysis conducted on the experiment data is presented. The spearman correlation matrix helps to understand the relationships between various metrics collected during the study. Correlation analysis helps in identifying the strength and direction of relationships between pairs of variables, which can provide insights into how different aspects of the virtual reality experience influence each other. This is crucial for evaluating the performance of the participants, since it can show the correlation between the objectively measured data and the subjective values of collaboration and co-presence gathered by the questionnaire. The overall correlation matrix for the collected data and the averaged out collaboration, co-presence and social presence scores are visible in Figure 7. As the data from the experiment suggests, there are indeed some visible correlations between the 4 between-subject scenarios that are introduced to better highlight these correlations on a per scenario basis, the correlation matrices have been split up by the scenarios. These are depicted in Figure 8.

4.4 Contributions of collaborative environment features to Co-Presence and collaboration

To investigate how features of the collaborative environment contribute to the user's sense of co-presence and collaboration, we analyzed the different scenarios and their applied conditions. Among the four scenarios, the two without voice communication (Scenarios 2 and 4) demonstrated lower co-presence scores compared to Scenarios 1 and 3, which included voice communication, as illustrated in Figure 5A. This finding aligns with previous literature, such as the study by Shuva et al. (Chowdhury et al., 2022).

Scenario 4, hypothesized to emulate a low collaboration and low co-presence environment, yielded the lowest collaboration score and a low social presence score. However, it did not necessarily result in the lowest co-presence score. Due to the limited data collected, it cannot be conclusively stated that Scenario 4 leads to a lower sense of co-presence between users compared to Scenarios 1 and 2, which lack realistic avatars and voice communication, respectively. Nevertheless, Scenario 4 did result in a lower average social presence score compared to Scenarios 1 and 3.

TABLE 4 Data for Scenario 1.

user_id	Gaze	gaze_percent	Rate	time_finish	Hb_avg	Hb_correlation	Scl_avg	social_presence	co_presence	collaboration
0	NaN	NaN	100.0	471.56	96.25	0.010	44.31	3.18	2.75	3.67
1	NaN	NaN	100.0	471.56	81.91	0.010	37.71	3.47	3.00	4.11
8	754.32	0.58	100.0	1299.40	92.20	0.081	44.69	3.13	3.00	3.78
9	1141.08	0.88	100.0	1299.40	89.16	0.081	36.28	3.37	3.00	3.56

TABLE 5 Data for Scenario 2.

user_id	Gaze	gaze_percent	Rate	time_finish	Hb_avg	Hb_correlation	Scl_avg	social_presence	co_presence	collaboration
2	637.49	0.73	100.0	868.84	70.94	0.261	41.16	3.21	2.75	3.78
3	703.45	0.81	100.0	868.84	87.74	0.261	36.75	3.13	2.50	3.56
10	1607.63	NaN	59.26	NaN	90.38	0.356	23.42	3.32	3.00	3.56
11	2210.14	NaN	59.26	NaN	71.48	0.356	35.72	3.37	3.25	3.67

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TABLE 6 Data for Scenario 3.

user_id	Gaze	gaze_percent	Rate	time_finish	Hb_avg	Hb_correlation	Scl_avg	social_presence	co_presence	collaboration
4	864.18	0.68	100.0	1273.43	74.55	0.055	32.36	3.61	2.50	3.67
5	1141.84	0.90	100.0	1273.43	86.66	0.055	37.98	3.11	3.00	3.67
12	NaN	NaN	100.0	358.15	88.31	0.000	35.43	3.37	3.00	3.89
13	NaN	NaN	100.0	358.15	88.09	0.000	34.48	3.34	2.75	3.56

TABLE 7 Data for Scenario 4.

user_id	Gaze	gaze_percent	Rate	time_finish	Hb_avg	Hb_correlation	Scl_avg	social_presence	co_presence	collaboration
6	550.46	0.54	100.0	1010.98	89.57	0.220	31.20	3.24	3.00	3.44
7	981.86	0.97	100.0	1010.98	117.27	0.220	34.69	3.08	3.25	3.56
14	1148.08	0.66	100.0	1741.50	74.88	0.121	40.19	3.32	2.75	3.56
15	984.25	0.57	100.0	1741.50	107.07	0.121	42.68	3.39	3.25	3.44

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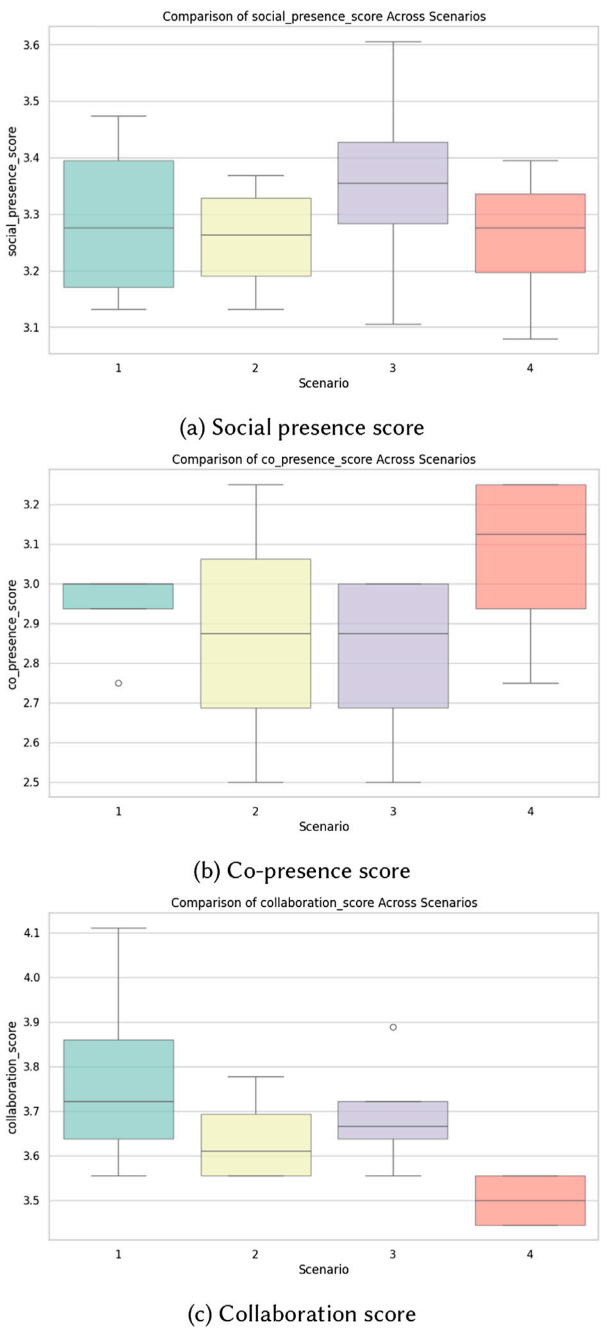


FIGURE 5
Boxplot of the questionnaire score results. **(A)** Social presence score **(B)** Co-presence score **(C)** Collaboration score.

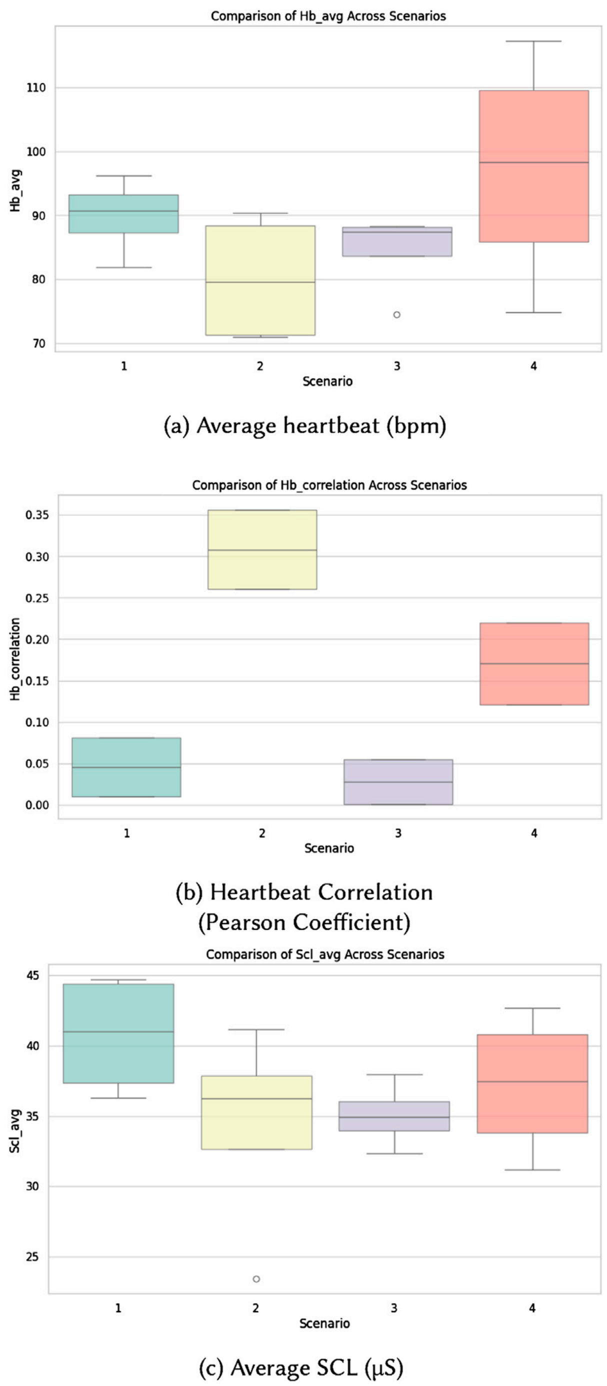


FIGURE 6
Box plots for Sensor data. **(A)** Average heartbeat (bpm) **(B)** Heartbeat Correlation (Pearson Coefficient) **(C)** Average SCL (μ S).

4.5 Comparing the effectiveness of physiological sensors, self-reported surveys, and task outcome analyses in capturing collaboration dynamics

An interesting aspect of this study is the relationship between physiological sensor data and subjective questionnaire results. As shown in Figure 6C, scenarios 1 and 4, where users are represented by abstract avatars, recorded higher levels of skin conductivity. This suggests a heightened emotional reaction, indicating that EDA sensors can be a viable method for measuring co-presence. Higher EDA values may correlate with a lower presence score for users, aligning with findings by Archer et al. (Archer et al., 2022), who showed that introducing odors in a virtual environment resulted in lower EDA measurements and an increased sense of presence.

The relationship between digital avatar representation and co-presence has been extensively studied in existing literature (Philipp

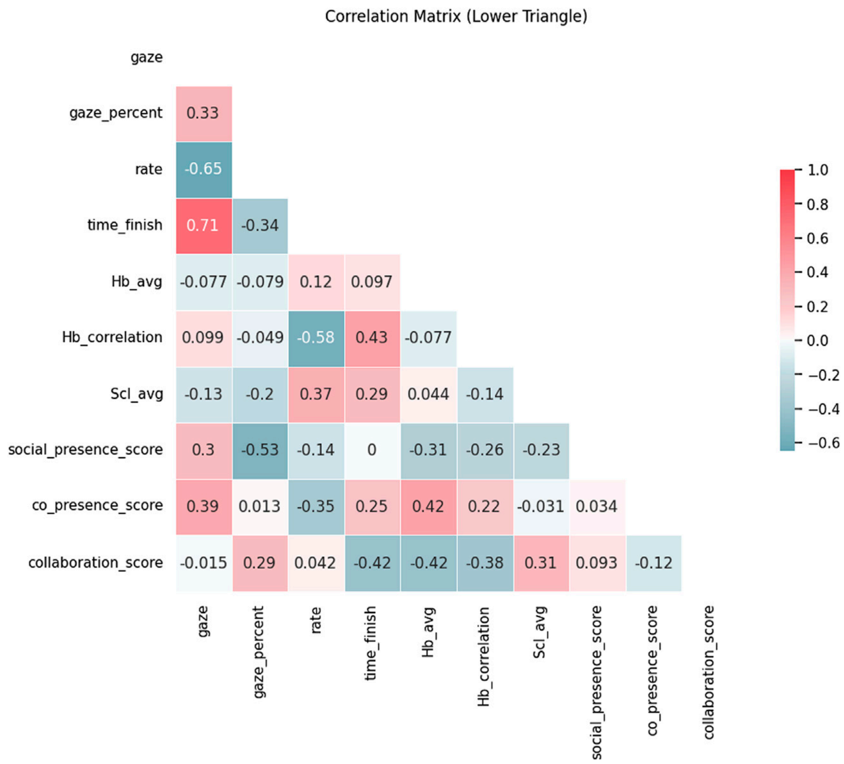


FIGURE 7
Overall correlation matrix.

Freiwald et al., 2021; Yasuoka et al., 2022; Simon et al., 2023; Ulrike, 2010). The positive correlation between presence and virtual avatar representation is evident in the social presence scores (Figure 5A), with scenarios 2 and 3 showing more promising results.

Scenarios 2 and 4, both lacking voice communication and relying on gestures, generated higher feelings of co-presence, as shown in Figure 5B. This is likely due to users' increased dependency on perceiving the other user. However, these scenarios also resulted in lower collaboration scores, highlighting the difficulty of collaboration without verbal communication. This suggests a more intricate relationship between co-presence and social presence than initially assumed, as supported by Bulu (2012). Communication clearly affects both social presence and co-presence, suggesting the need to explore scenarios that isolate these variables for independent measurement.

Figure 6B reveals a higher correlation coefficient between the continuously collected heart rate data of participants in scenarios 2 and 4. These scenarios, characterized by high co-presence and low collaboration, showed higher synchronicity in participants' heart rates. The highest synchronicity was observed in scenario 2, where users had realistic avatars but no verbal communication, suggesting that physiological synchrony is influenced by the interplay between avatar realism and communication modality.

Another natural and expected outcome of the experiment was the amount of time it took for users to finish the task, and it is worth mentioning that the quickest users to finish the task, naturally had access to voice communication (scenario 1 and 3) as shown in Figure 4C. The gaze tracking metric however, as shown in Figures 4A,B, did not yield any obvious visible results, perhaps given the low amount of participants. However, in a larger sample size, the significance of this metric might prove itself.

4.6 Results of open-ended questions from the survey

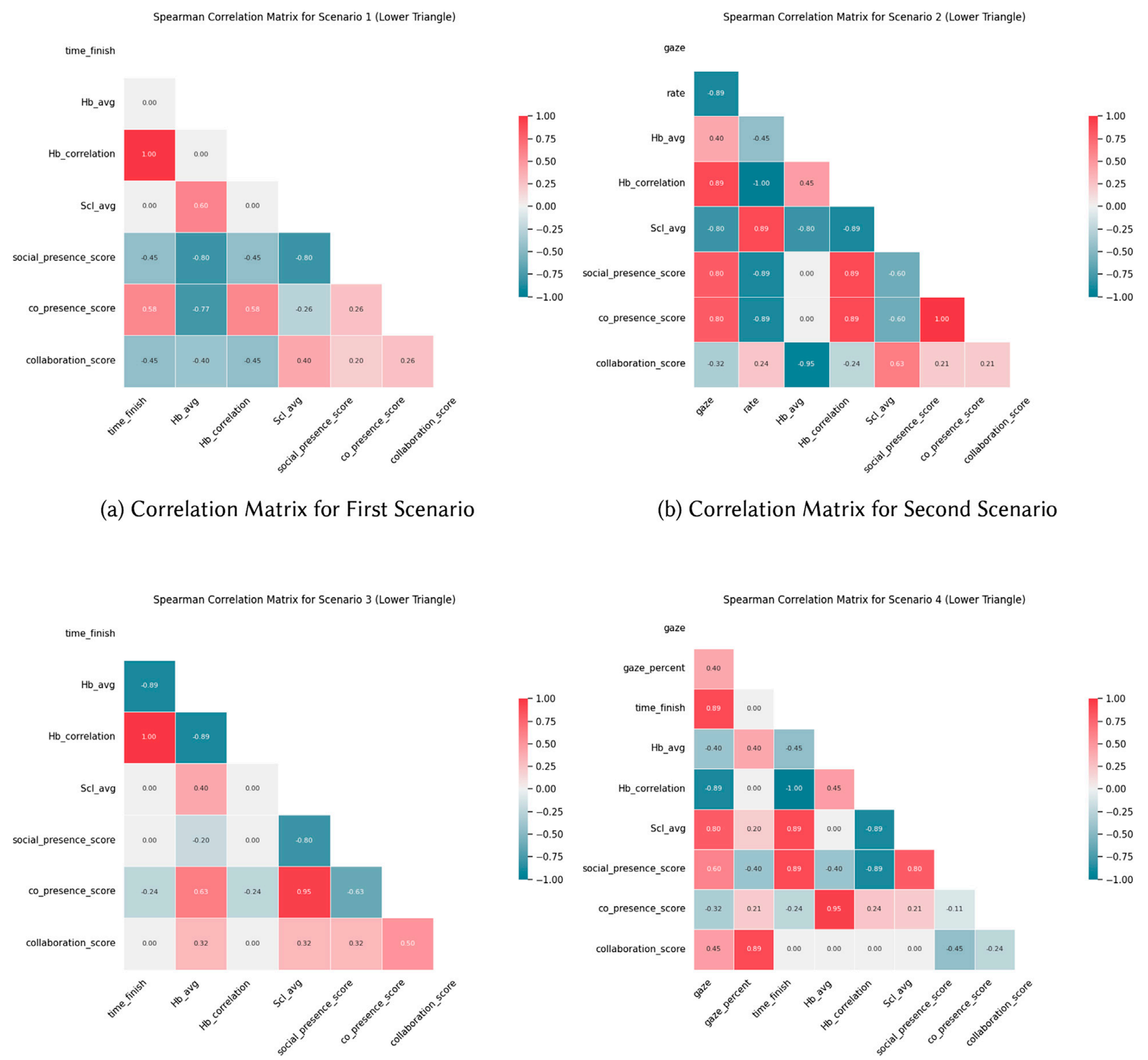
We observed five themes from the qualitative analysis of the responses from the open-ended survey.

4.6.1 General sentiment

The majority of respondents describe their experience as "fun," "enjoyable," and "engaging," indicating a generally positive reception of the collaborative VR experience. Words like "efficient," "good," "interesting," and "positive" were frequently used, suggesting that participants were not only entertained but also found value in the collaboration.

4.6.2 And collaboration dynamics

Respondents who had audio communication highlighted the ease and effectiveness of collaboration, with mentions of being able to "take the other person's advice" and "cross-check" actions. This indicates that audio communication facilitated smoother interactions and more straightforward task completion. Those without audio faced challenges, often finding creative ways to communicate, like using "physical signage," "gestures," or relying on the "arms and head" for communication. Some described this limitation as



(a) Correlation Matrix for First Scenario

(b) Correlation Matrix for Second Scenario

(c) Correlation Matrix for Third Scenario

(d) Correlation Matrix for Fourth Scenario

FIGURE 8
Correlation matrices for all scenarios. **(A)** Correlation matrix for first Scenario **(B)** Correlation matrix for Second Scenario **(C)** Correlation matrix for third Scenario **(D)** Correlation matrix for fourth Scenario.

"challenging but interesting," showcasing resilience and adaptability in problem-solving. A few responses point out difficulties, with one noting that "gestures could be misunderstood due to lag," emphasizing the technical constraints that sometimes hindered smooth communication.

4.6.3 Engagement and task interaction

Many participants mentioned enjoying the collaborative aspect, appreciating the teamwork required to complete the task. For example, statements like "It was good to work in a team and crucial to complete the objective" reflect the immersive and cooperative nature of the VR setup. Several comments addressed technical aspects of the interaction, such as "the color of the location to which the object will snap could be darker" and a desire for "objects [to] remain placed after assembling." These observations suggest an interest in refining the environment to improve task performance and reduce friction in gameplay.

4.6.4 Novelty and immersion

For some, this was their first time experiencing collaborative VR, with one respondent noting, "as my first experience playing a collaborative game in VR, it was very fun." The newness and immersive nature of VR seem to add a layer of engagement, with participants frequently describing the concept as "interesting" and the physics as making "the game more fun."

4.6.5 Challenges and suggestions

A few respondents highlighted specific challenges, including visual and interaction difficulties. Issues like "wonky physics," difficulty seeing certain snap points, and limits of non-verbal communication suggest areas for enhancement in realism and ease of use. Several participants offered constructive suggestions to improve usability, such as adding "darker" snap-point indicators or ensuring that "objects remain placed after assembling."

5 Discussion

This study investigated the dynamics of co-presence and collaboration in a VR environment through a custom-built multiplayer VR application called CoCoVR. By manipulating key variables such as avatar realism and communication modalities (i.e., voice communication enabled or disabled), we aimed to better understand how these factors influence both the objective outcomes of collaboration (such as task completion times) and subjective user experiences (as captured through questionnaires and physiological measurements). This discussion will focus on addressing the research questions posed at the outset, reflecting on the objective and subjective data collected, and situating the findings within the broader context of existing research.

5.1 Contributions of VR characteristics to co-presence and collaboration (RQ1)

5.1.1 Avatar realism and co-presence

One of the central findings from this study is that the realism of digital avatars had a measurable effect on participants' sense of co-presence. The results from the questionnaire data showed that participants reported a higher sense of co-presence when using realistic avatars compared to abstract ones. This supports the broader literature, which consistently demonstrates that avatar fidelity contributes significantly to the feeling of "being there" with another person in a virtual space (Yasuoka et al., 2022; Simon et al., 2023). Realistic avatars provide richer visual cues, allowing participants to interpret the actions and intentions of their partners more easily. These findings align with Gibbs et al., (2022), who showed that enhanced visual realism in VR environments fosters a deeper sense of presence, thereby facilitating more effective collaboration.

The absence of realism in avatars, particularly in scenarios where communication was non-verbal, presented challenges to participants. As shown in the objective data, users in the abstract-avatar scenarios took longer to complete tasks, which suggests that avatar realism plays a critical role not only in fostering co-presence but also in enabling smoother collaboration. Participants struggled to use gestures and other non-verbal cues effectively when the avatars lacked human-like features, reflecting prior studies that emphasize the importance of visual embodiment in VR (Ulrike, 2010).

There are challenges and adaptation in non-verbal communication. The related work highlights that realistic avatars and effective communication methods are critical in fostering co-presence and collaboration, particularly when verbal cues are limited. Studies by Simon et al. (2023) and others emphasize that non-verbal cues, such as gestures and facial expressions, play an essential role in social presence but can be challenging when VR fidelity or communication tools are limited (Bovo et al., 2022). Analysis of the responses from the open-ended survey indicating difficulties in interpreting gestures due to lag or limited expression in non-verbal scenarios reflect these findings. Adaptations like physical signaling were used by participants, as supported by Bulu (2012), who noted that social presence is strongly influenced by available communicative resources (Ghasempour, 2024).

5.1.2 Voice communication and collaboration

The second major factor that we manipulated was the presence or absence of voice communication between participants. As expected, the availability of voice communication significantly improved the efficiency of task performance and the overall sense of collaboration. This finding is consistent with extensive research in VR collaboration, which emphasizes the importance of multimodal communication (Tea et al., 2021; Philipp Freiwald et al., 2021). Voice communication allowed participants to quickly coordinate their actions, clarify instructions, and resolve ambiguities during the task, leading to faster completion times and higher collaboration scores in the subjective questionnaires.

In contrast, scenarios in which voice communication was disabled saw lower collaboration scores and longer task completion times. Participants had to rely on non-verbal cues such as gestures, gaze, and avatar movements, which were often insufficient to maintain smooth communication. The objective data supports this, as physiological sensors showed heightened levels of emotional arousal (indicated by skin conductance levels) in scenarios without voice communication, reflecting the greater cognitive and emotional effort required to collaborate under these conditions. These results support findings from (Laine and Lee, 2023), which noted that effective communication is critical for enhancing collaboration in VR settings, and without voice communication, participants faced significant barriers to maintaining coordination and task efficiency.

The literature emphasizes that voice communication significantly improves collaboration by reducing cognitive load and enabling clearer, more immediate exchanges between participants. The responses from participants in the open-ended survey reflect this benefit, with those using audio reporting smoother and more efficient interactions. This aligns with findings that voice communication enhances collaborative VR experiences by facilitating seamless and precise communication, as discussed in related studies (Philipp Freiwald et al., 2021; Steed et al., 2012).

5.2 The role of physiological sensors in measuring collaboration dynamics (RQ2)

A key innovation in this study was the use of physiological sensors to capture real-time data on participant emotions and physical responses during collaboration. This allowed us to explore how physiological synchrony between participants related to their sense of collaboration and co-presence.

5.2.1 Heart rate synchrony as a measure of collaboration

The study found that heart rate synchrony, measured as the correlation between the heart rates of the two participants during the task, was highest in scenarios where voice communication was disabled and participants relied more on non-verbal cues. This is an intriguing result, as it suggests that in the absence of verbal communication, participants become more attuned to each other's actions and emotional states. Higher heart rate synchrony indicates that participants were physiologically aligned, potentially reflecting a heightened state of focus or shared emotional engagement in the task.

This finding aligns with research on physiological synchrony, which has shown that when people engage in collaborative activities, their heart rates and other physiological markers tend to align (Elvezio et al., 2018). The high correlation in heart rates during non-verbal scenarios may reflect a deeper reliance on non-verbal communication and heightened awareness of each other's actions. However, while heart rate synchrony was higher, task completion times were longer and subjective collaboration scores were lower, suggesting that while participants were more physiologically in sync, the lack of verbal communication hindered their ability to effectively collaborate on complex tasks.

5.2.2 Skin conductance as an indicator of emotional arousal

Skin conductance levels (SCL), which measure emotional arousal, were generally higher in scenarios without voice communication and with abstract avatars. This suggests that participants experienced greater cognitive and emotional stress when communication was limited and avatars were less realistic. Higher SCL readings indicate increased emotional engagement, likely reflecting the frustration or effort associated with trying to communicate non-verbally in a collaborative task.

Interestingly, the participants in scenarios with abstract avatars also reported lower overall co-presence scores, suggesting that the increased emotional arousal did not translate into a more immersive or engaging experience. Instead, it may have detracted from their ability to feel fully "present" with their partner, as they were preoccupied with managing the challenges of non-verbal communication. This finding aligns with research by Archer et al. (2022), which found that emotional arousal can negatively impact the sense of presence in VR environments, particularly when users are faced with technical or communicative challenges.

This study's findings align with a broad body of research that highlights the critical role of multimodal communication and avatar realism in fostering effective collaboration and co-presence in VR environments. Previous studies Yasuoka et al. (2022), Tian et al. (2023) have consistently shown that realistic avatars and the availability of voice communication enhance the quality of collaboration and co-presence. Our results confirm these findings, demonstrating that participants were more effective collaborators when they could communicate verbally and when their avatars closely resembled human forms.

However, our study also contributes new insights to the field by exploring the role of physiological synchrony as a novel measure of collaboration dynamics. While much of the existing research has relied on self-reported data and task outcomes to assess collaboration, our use of heart rate and skin conductance data provides a more objective measure of how participants responded to the collaborative task in real time. This adds a valuable dimension to the understanding of VR collaboration, suggesting that physiological measures can complement traditional metrics to provide a more holistic view of user experiences in virtual environments.

Furthermore, this study extends the literature by exploring how the absence of voice communication, coupled with abstract avatars, impacts both the subjective and objective measures of collaboration. While prior research has emphasized the importance of realism and communication, few studies have explicitly tested these factors in combination to examine how their absence affects both task performance and emotional responses.

5.3 Implications for VR design in collaborative tasks

The findings of this study have several practical implications for the design of future VR systems, particularly in contexts where collaboration and co-presence are critical, such as remote teamwork, virtual education, and training simulations. First, the results underscore the importance of providing users with realistic avatars and enabling multiple modes of communication. The combination of high-fidelity avatars and voice communication significantly enhances both the objective outcomes of collaboration (e.g., task completion times) and the subjective experience of presence and teamwork.

Second, the study highlights the potential of using physiological sensors as a means of evaluating the effectiveness of VR systems. Heart rate synchrony and skin conductance offer valuable insights into how users respond to different aspects of the virtual environment, such as the level of realism and the availability of communication tools. Incorporating these metrics into the design and evaluation of VR systems could help developers create more immersive and effective collaborative experiences.

Finally, the study suggests that future VR systems should consider the cognitive and emotional load that non-verbal communication places on users. In scenarios where voice communication is not feasible, designers should explore alternative communication methods (e.g., gesture recognition, haptic feedback) to facilitate collaboration and reduce the emotional strain associated with non-verbal interaction.

5.4 Limitations and future research directions

While this study provides valuable insights into the dynamics of co-presence and collaboration in VR, it is important to acknowledge its limitations. The relatively small sample size and the short duration of the experiment may limit the generalizability of the findings. As a result this study serves as a pilot study to understand if it makes sense to continue on this path for a study with a larger sample size. Future studies should aim to replicate these results with a larger and more diverse participant pool to ensure that the findings hold across different populations and settings.

Additionally, the study focused on a single task (the Soma cube puzzle in CoCoVR), which may not fully capture the range of collaborative activities that users engage in within VR environments. Future research could explore how different types of tasks (e.g., creative problem-solving, competitive games) affect collaboration and co-presence, and whether the findings from this study generalize to other types of interactions.

While the use of physiological sensors provided valuable insights into emotional and physical responses, future studies could explore additional physiological measures, such as EEG or facial expression tracking, to gain a more comprehensive understanding of how users respond to VR collaboration.

Despite efforts to neutralize the effects of individual differences on the experiment, the human factor inevitably influences the data and overall experience. For instance, participants needed to physically move and adjust Soma cube parts in the game. Those with backgrounds in piloting aircraft found it easier to communicate with their partners about how to rotate the puzzle parts due to their spatial awareness and communication skills. Moreover, participants' past experiences and mentalities may have also affected their performance. Some users exhibited frustration when unable to communicate verbally during a scenario, while others viewed it as an intriguing challenge and sought the fastest way to complete the task, leading to significantly different outcomes. Furthermore, investigating long-term interactions in VR environments could provide insights into how presence and collaboration evolve over time. Incorporating more complex tasks and multisensory feedback (e.g., scent or tactile feedback) could further enhance the understanding of presence and collaboration in virtual environments.

6 Conclusion

This study presents an extensive study on collaboration and co-presence metrics in virtual reality, culminating in the design of a comprehensive experimental procedure. This study has demonstrated that both avatar realism and communication modalities play a crucial role in shaping the dynamics of collaboration and co-presence in VR environments. Through a combination of subjective user feedback and objective sensor data, an examination of the dynamics of collaborative interactions in VR environments was performed. The methodology integrates both qualitative and quantitative measures to provide robust insights into human-computer interaction within shared virtual spaces. The findings highlight the potential of using physiological measures to assess collaboration dynamics and suggest that future VR systems should prioritize realistic avatars and multimodal communication to enhance user experience. Furthermore, the study demonstrates that physiological synchrony, measured through heart rate monitoring and EDA sensors, can serve as a novel indicator of effective collaboration. This finding suggests a new avenue for assessing team dynamics in VR.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/Supplementary Material.

Ethics statement

Ethical approval was not required for the studies involving humans because Ethical approval was not required for this study because the research involved the use of a non-invasive, commercially available virtual reality system with adult participants, where no sensitive personal data was collected, and no interventions or manipulations beyond typical VR interactions were performed. The study focused on the observation and analysis of standard user interactions within a VR environment, without exposing participants to any risks, discomfort, or psychological stress beyond what they would normally encounter in everyday use of VR technology. Moreover, all participants were fully informed about the nature of the study and gave their consent to participate. As a result, the study falls within the category of minimal risk research, which does not require formal ethical approval under the guidelines of our institution. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study. No potentially identifiable images or data are presented in this study.

Author contributions

SY: Data curation, Investigation, Methodology, Software, Validation, Visualization, Writing–original draft, Writing–review and editing. : SO: Conceptualization, Funding acquisition, Investigation, Methodology, Resources, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing.

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Conflict of interest

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.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frvir.2024.1478481/full#supplementary-material

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