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The metaverse, immersive virtual reality and its implications on human behavior

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The metaverse, immersive virtual reality and its implications on human behavior

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Design guidelines for limiting and eliminating virtual reality-induced symptoms and effects at work: a comprehensive, factor-oriented review

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Virtual reality (VR) can induce side effects known as virtual reality-induced symptoms and effects (VRISE). To address this concern, we identify a literature-based listing of these factors thought to influence VRISE with a focus on office work use. Using those, we recommend guidelines for VRISE amelioration intended for virtual environment creators and users. We identify five VRISE risks, focusing on short-term symptoms with their short-term effects. Three overall factor categories are considered: individual, hardware, and software. Over 90 factors may influence VRISE frequency and severity. We identify guidelines for each factor to help reduce VR side effects. To better reflect our confidence in those guidelines, we graded each with a level of evidence rating. Common factors occasionally influence different forms of VRISE. This can lead to confusion in the literature. General guidelines for using VR at work involve worker adaptation, such as limiting immersion times to between 20 and 30 min. These regimens involve taking regular breaks. Extra care is required for workers with special needs, neurodiversity, and gerontechnological concerns. In addition to following our guidelines, stakeholders should be aware that current head-mounted displays and virtual environments can continue to induce VRISE. While no single existing method fully alleviates VRISE, workers' health and safety must be monitored and safeguarded when VR is used at work.

KEYWORDS

virtual reality, ergonomics, cybersickness, visual fatigue, muscle fatigue, acute stress, mental overload, work

1. Introduction

The COVID-19 pandemic conditions have accelerated the democratization of itinerant and remote work (Gajendran et al., 2021), making virtual reality (VR) an attractive alternative to support remote and collaborative office work (Ofek et al., 2020) and fostering the potential for its mass adoption (Grubert et al., 2018; Fereydooni and Walker, 2020; Knierim and Schmidt, 2020). While the potential benefits of VR have been widely reported in the literature, several authors (Keller and Colucci, 1998; Stanney et al., 1998; Sharples et al., 2008; Melzer et al., 2009; Fuchs, 2017, 2018; Souchet, 2020; Anses, 2021; Grassini and Laumann, 2021; Souchet et al., 2022) have stressed the necessity to address potential health and safety-related side effects of VR exposure. We focus specifically on office work use of VR.

Many terms have referred to such adversarial effects in the literature, most notably "cybersickness," "VR sickness," or "Simulator sickness." In this study, we adopt the terms virtual reality-induced symptoms and effects (VRISE) introduced by Cobb et al. (1999) as it elicits a complete picture of the variety of VR side effects. VRISE initially encompasses cybersickness, postural instability, and other effects on psychomotor control, perceptual judgment, concentration, stress, and physical ergonomics (Cobb et al., 1999; Nichols, 1999; Nichols and Patel, 2002). Besides cybersickness, which is the most documented VRISE, the literature highlights four other undesired deleterious effects: visual fatigue, muscle fatigue, musculoskeletal discomfort, acute Stress, and mental overload. We propose to distinguish between cybersickness and visual fatigue. Indeed, cybersickness mostly refers to visually induced motion sickness that negatively impacts oculomotor function (Wang Y. et al., 2019). However, visual fatigue can occur without visually induced motion sickness (Souchet et al., 2022). Additionally, to health and safety concerns, the occurrence of VRISE can also induce a negative user experience (Somrak et al., 2019; Lavoie et al., 2020) and drastically impair performance in the task. For recent reviews of and in-depth discussions of VRISE, see, e.g., Ref Stanney et al. (2020b, 2021b), Howard and Van Zandt (2021), and Souchet et al. (2022).

Despite continuous improvements in the related technologies and the most recent innovations, the literature still provides evidence of VRISE with simulators and virtual environments. For example, Saredakis et al. (2020) found a mean dropout rate of 15.6% (min = 0%, max. = 100%) based on data reported in 44 empirical studies from the 55 selected for their systematic review of cybersickness and VR content impact with a head-mounted display (HMD). More generally, according to Stanney et al. (2021a) some side effects could be experienced even by more than 80% of VR users.

The research on VRISE has revealed that deleterious responses of users to virtual environment (VE) exposure vary widely depending on several factors, among which are the characteristics and capabilities of the users, the system (hardware/software) characteristics, and the implemented tasks to be performed with the VE. Unfortunately, no complete and holistic approaches to these different VRISE-related factors to be considered at the design and evaluation stages of VE development have been provided as far as we know. The literature provides some lists of factors specific to one single VRISE [e.g., for cybersickness, see Davis et al. (2014), LaViola et al. (2017)] or reports on a specific subset of factors that can influence VRISE. The latter include, for example, the visual fatigue caused by stereoscopy (Bando et al., 2012), cybersickness (Mittelstaedt, 2020; Howard and Van Zandt, 2021; Rebenitsch and Owen, 2021), and a panoply of other VRISE issues that could arise with VR usage (Chen et al., 2021). Factors are described, however, at various degrees of detail and completeness with no systematic wording consistency. Further limitations include that it is not always clear whether the claimed factors are grounded on empirical evidence, nor if they were identified in a VR context (Stanney et al., 2020b, 2021b; Howard and Van Zandt, 2021; Souchet et al., 2022). Further shortcomings in the current literature are related to the confounding effects of VRISE on other psychophysiological effects or among them, as recently emphasized (Kourtesis et al., 2019). One VRISE could influence another, but very few direct experimental proofs allow us to appreciate the magnitude of those influences (Alsuraykh et al., 2019; Mittelstaedt, 2020; Sepich et al., 2022; Souchet et al., 2022).

Developing the use of VR at work can result in increased exposure of the population to these multiple side effects and their impact on workers' health and safety (LaViola et al., 2017; Fuchs, 2018; Khakurel et al., 2018; Çöltekin et al., 2020; Olson et al., 2020; Anses, 2021; Ens et al., 2021). Such risks were featured in the European Agency for Safety and Health at Work warning (EU-OSHA, 2019). Thus, it is critical to examine and organize the current knowledge on the whole set of potential VRISE relevant to using VR in a work context. This knowledge includes evidence associated with the various factors involved in VRISE occurrence (e.g., individual, contextual, or technological) and design resources and solutions susceptible to avoiding these effects or at least decreasing their impact and likelihood. In particular, design guidelines and principles provide essential resources. They can be combined with and integrated with all user-centered design processes. Design guidelines and principles have an extended history in human–computer interaction to support user interface decisions, e.g., Smith and Mosier (1986). Design decisions take advantage of extant practical experiences, results from user studies, and applicable experimental findings to promote application consistency. As technology develops, such guidelines have been adapted for or explicitly defined in VR (Gabbard et al., 1999; Stanney et al., 2003b, 2021a; Burkhardt et al., 2006). Particular devices and/or their components have driven guidelines regarding VR dimensions such as haptics (Hale and Stanney, 2004), 3D interaction (LaViola et al., 2017), or HMD's application in general (Vi et al., 2019). Guidelines for domain-specific applications or user profiles such as a therapist user interface (Brinkman et al., 2010), VR games (Desurvire and Kreminski, 2018), VR in human neuroscience (Kourtesis et al., 2019, 2020), and psychology (Vasser and Aru, 2020) or assessments of elderly users (Shamsuddin et al., 2011) have also been proposed. However, existing works provide only a limited and restricted consideration of VRISE directly (Souchet et al., 2022).

In a previous contribution (Souchet et al., 2022), we focused on defining the current state of the art regarding VRISE, emphasizing theoretical aspects and merging existing literature to provide a list of factors believed to influence VRISE. Following this previous publication, this study aimed to report on and organize a comprehensive review of published design guidelines associated with the five short-term VRISE cybersickness (CYB), visual fatigue (VF), muscular fatigue (MF), acute stress (S), and mental overload (MO), focusing on workers and vocational contexts. To assure that our guidelines are practical, we sought to consider typical tasks that office workers would usually undertake using a PC, but in our case using VR. In addition, we want to organize this review so that it is easy to use and apply by researchers, designers, and work professionals. For that purpose, we have ordered existing knowledge by VRISE, type of factors, and potential factors that may impact VRISE. Assessing VRISE factors can further help identify and establish how users, apparatus, and virtual environments each contribute to VRISE occurrence.

TABLE 1 Guidelines for possible individual factors relating to experience with virtual environments (CYB_1 to 4) and users' physical attributes (CYB_5 to 9) influencing cybersickness.

ID_factor Evidence level	Factors	Description	Guidelines
CYB_1 *V*	Experience with a real-world task	Familiarity with tasks (real) in VR before being immersed seems to positively influence symptoms (Porcino et al., 2017; Howard and Van Zandt, 2021)	Acclimating users to tasks before immersing in VR could help reduce side effects occurrence (Howard and Van Zandt, 2021)
CYB_2 *V*	Experiences with a simulator (habituation)	Familiarity with immersive experiences drives users to report fewer symptoms (Howard and Van Zandt, 2021)	Acclimating users to immersive technologies before making them work in VR (Howard and Van Zandt, 2021; Szopa and Soares, 2021)
CYB_3 *VI*	Video gameplay	Users referred to as "gamers" are less susceptible to report high symptoms (Collaboration, 2015; Lanier et al., 2019; Kaplan et al., 2020; Szopa and Soares, 2021; Theresa Pöhlmann et al., 2021; Wang et al., 2021)	Encouraging potential users to play 3D video games to acclimate them to movements (Rebenitsch and Owen, 2021) on a screen they could encounter in VR
CYB_4 *III*	Duration	Cybersickness occurrence is linearly correlated with exposure duration (Duzmańska et al., 2018; Muthukrishna and Henrich, 2019; Rebenitsch and Owen, 2021)	Making short sessions at the beginning and increasing immersion time if users are building habituation. Cybersickness can arise after 5 min especially with very inducing contents (Anses, 2021)
CYB_5 *VI*	Eye dominance	"*Eye dominance refers to the preference to use one eye more than the fellow eye to accomplish a task*" (Ooi and He, 2020). It also seems to apply to binocular stimuli (Han et al., 2018). By stimulating both eyes equally or unequally, some peers think it can mitigate cybersickness (Meng et al., 2020; Hussain et al., 2021)	Eye-dominance-guided foveated rendering could help reduce non-necessary stimuli on the non-dominant eye, reducing symptoms occurrence (Meng et al., 2020; Hussain et al., 2021)
CYB_6 *VI*	Stereoscopic visual ability	See VF_2	See VF_2
CYB_7 *V*	Postural stability	Unstable (posture) users are more likely to become sick in line with Postural instability theory of cybersickness (Risi and Palmisano, 2019a; Stanney et al., 2020b). Although experimental results can sometimes contradict this prediction (Dennison and D'Zmura, 2017, 2018; Arcioni et al., 2019; Risi and Palmisano, 2019b; Kim J. et al., 2021; Litleskare, 2021)	Use questionnaires to determine if users are susceptible to postural instability to adapt exposure to him/her (Risi and Palmisano, 2019a; Stanney et al., 2020b; Howard and Van Zandt, 2021)
CYB_8 *VI*	History of headaches/migraines	Migraine (and Vestibular Migraine) history can predict part of cybersickness symptoms (Wang and Lewis, 2016; Paroz and Potter, 2017; Lim et al., 2018; Stanney et al., 2020a; MacArthur et al., 2021)	Determining if the user has a history of headaches or migraines to adapt exposure to him/her with questionnaires such as Visually Induced Motion Sickness Susceptibility Questionnaire (Keshavarz et al., 2021)
CYB_9 *VII*	Body mass index	The lower the body mass, the higher the reported symptoms (Stanney et al., 2003a, 2020a)	Determining user height and weight (questionnaire) and adapting exposure strategy (shorter duration, more pre-exposure before real work tasks) if more susceptible to present symptoms (Stanney et al., 2020a)

Our study is organized as follows. First, we describe the general method we employed to select articles or written descriptions of each identified factor. Second, a concise definition, symptomology, and prevalence description are distilled for each VRISE. We have based these on existing reviews, systematic syntheses, and meta-analyses. Third, within each VRISE presentation, we point to Tables describing each factor, and guideline, distinguished by three characteristics: (1) individual, (2) hardware, and (3) software. Fourth, within each VRISE presentation, we promulgate general guidelines according to our presented synthesis of existing knowledge. Fifth, we discuss our summated results and explore their advantages and limitations. Sixth, tables that assemble and present descriptions and guidelines by factors regarding each short-term VRISE are displayed.

2. Methods

We conducted a literature search on journal and conference papers related to the five VRISE and published between January 2016 and mid-2021 partially (Primary Elements 5, 6, and 7 are not applied) applying the comprehensive review methodology stated in Ref (Stratton, 2016). The start date was selected because it corresponds to Oculus CV1's commercial release, delineating the moment when HMDs become more widely accessible for laboratories and other facilities and the public. Thus, it allows a targeted overview of contributions incorporating new-generation HMDs. HMDs are not the only devices allowing access to VR content (e.g., cave automatic virtual environment), but we focus on HMDs in the current review.

TABLE 2 Guidelines for possible general demographic factors (CYB_10 to 14) and mental attributes (CYB_15 to 17) influencing cybersickness.

ID_factor Evidence level	Factors	Description	Guidelines
CYB_10 *VII*	Age	Fifty years old and older are more susceptible to report cybersickness than younger people (Arns and Cerney, 2005; Petri et al., 2020; Kim H. et al., 2021). Children aged between 4 and 10 seem less susceptible than adults (Tychsen and Foeller, 2020), although they are practically not susceptible to using VR for work	Take extra care and expose for shorter time users of 50 years old and older to VR (Arns and Cerney, 2005; Petri et al., 2020; Kim H. et al., 2021)
CYB_11 *V*	Gender	Women are supposed to be more susceptible to cybersickness (Grassini and Laumann, 2020; Howard and Van Zandt, 2021). Although, there is no consensus because of contradictory results (Porcino et al., 2020a; MacArthur et al., 2021; Varmaghani et al., 2021). The observed difference is mainly explained by tuning lenses distance not matching womens' IPD (Stanney et al., 2020a)	Choosing HMDs allowing the widest tuning of lenses to match women's IPD and using eye tracking (or psychometric measures) to guide users when they tune the distance between lenses (Grassini and Laumann, 2020; Stanney et al., 2020a; Howard and Van Zandt, 2021)
CYB_12 *V*	Ethnicity	According to some studies (Klosterhalfen et al., 2005; Stanney et al., 2020a,b), Asians are more susceptible than African Americans and Caucasians	Be extra careful with ethnicity identified as being more susceptible to present side effects (Klosterhalfen et al., 2005; Stanney et al., 2020a,b)
CYB_13 *V*	Vision correction	Using glasses and/or contacts makes the user more susceptible to report cybersickness (Rebenitsch and Owen, 2014). However, contradictory results have been found (Rangelova et al., 2020)	Take extra care of users wearing lenses or glasses by encouraging to shorter immersion duration and more acclimation to simulators/3D video games (Rebenitsch and Owen, 2014; Howard and Van Zandt, 2021)
CYB_14 *V*	History of motion sickness	Prior history of motion sickness increase risks of cybersickness (Stanney et al., 2003a; Mittelstaedt et al., 2018; Mittelstaedt, 2020)	Determining if the user has a history of motion sickness to adapt exposure to him/her with questionnaires such as Visually Induced Motion Sickness Susceptibility Questionnaire (Keshavarz et al., 2021)
CYB_15 *VI*	Concentration level	Announced to influence cybersickness but without experimental data (Rangelova and Andre, 2019; Grassini et al., 2021; Rebenitsch and Owen, 2021)	Not clear in the cybersickness literature if "concentration" relates to attention abilities in general (Moran, 1763; Fawcett et al., 2015). Therefore, making sure that users can concentrate on tasks during immersion with eye tracking could help integrate this factor (Clay et al., 2019)
CYB_16 *VI*	Mental rotation ability	Sex differences have been raise (Parsons et al., 2004; Guzsvinecz et al., 2021), although contradicting results exist (Toth and Campbell, 2019). Mental rotation ability could be an unreliable factor affecting cybersickness (Mittelstaedt et al., 2019), although it is listed as possibly impacting symptoms (Stanney et al., 2020a)	Performing mental rotation tests (Shepard and Metzler, 1971). In VR paradigms exist (Csincsák, 2020) and hypothesizing that lower results would advocate for higher cybersickness risks
CYB_17 –	Perceptual style	Perceptual style influencing motion sickness is proposed in an old contribution (Barrett and Thornton, 1968). However, perceptual style is linked to learning style, criticized as a neuromyth (Willingham et al., 2015; Kirschner, 2017)	Since very little experimental proof and this factor might be linked to a neuromyth (Willingham et al., 2015; Kirschner, 2017), it can be ignored for now

The review included the following search terms: ("Virtual Reality") AND ("cybersickness" OR "visually induced motion sickness" OR "visual fatigue" OR "eyestrain" OR "muscle fatigue" OR "musculoskeletal discomfort" OR "stress" OR "acute stress" OR "cognitive load" OR "mental workload") AND work AND ("meta-analysis" OR "systematic" OR "review"). This search was carried out on August 2021 on Scopus and Google Scholar.[1]

A first selection occurred based on titles and abstracts: We excluded those that did not refer to any of the five VRISE. Journal, conferences articles, and book chapters were included in this review if they were complete (i.e., includes a full paper, not just an abstract); the text was in English or French; the data were obtained from adults participants; the experimental tasks mainly were matching office-like tasks (text entry, document editing, reading, proofreading, gathering and processing data, creating graphs and data visualization (e.g., maps, plots), exploring and visually analyzing data, viewing several media (texts, images, videos, 3D objects), creating presentation materials, conducting meetings (public speaking), collaborating with other users in a shared VR environment. Additional papers anterior to 2016 were manually searched when no available review or meta-analysis was found regarding a VRISE or its related factors.

1 Due to the current limitations to 32 words, two requests were done distributing between the Former and latter VRISE.

TABLE 3 Guidelines for possible hardware factors relating to screen influencing cybersickness.

ID_factor Evidence level	Screen factors	Description	Guidelines
CYB_18 *IV*	Resolution/blur	The lower the resolution, the higher could be cybersickness (Palmisano et al., 2017). Although resolution could have a marginal impact (Caserman et al., 2021). Peripheral blurring showed encouraging results at mitigating cybersickness (Lin et al., 2020; Groth et al., 2021a,b)	Preferring HMDs with the highest resolutions—at the time—if possible cybersickness (Palmisano et al., 2017). Applying peripheral blur during movements (Groth et al., 2021a)
CYB_19 *V*	Horizontal and vertical field of view	The peripheral vision field is higher in females than males, increasing flicker likelihood (Davis et al., 2014; Chang et al., 2020; Stanney et al., 2020a; Teixeira and Palmisano, 2021)	Applying a field of view reduction (Groth et al., 2021a) and wider for women to reduce cybersickness during movement
CYB_20 *VI*	Weight of the display	See MF_3 and MF_4 We can hypothesize that displays' weight concurs to tiredness symptoms of cybersickness. However, it is pointed to as having minor effects on cybersickness (Rebenitsch and Owen, 2021)	Depending on HMD design, weight can be divided between various parts of users' heads. Using the lightest HMD might not be the best choice depending on straps (see MF_3 and MF_4). Allowing the user to do frequent breaks can help to recover (Chang et al., 2020)
CYB_21 *V*	Display type	According to Rebenitsch and Owen (Rebenitsch and Owen, 2016), HMD is the VR display type with which users report more cybersickness symptoms	Using HMD only if they are proved to be more efficient for a work task than another display type (Chang et al., 2020; Howard and Van Zandt, 2021)
CYB_22 *IV*	Lag variance	Tracking systems, graphical performance of PC or HMDs (standalone), and communication between hardware and software, in general, can cause latencies in displayed images or feedbacks (Chang et al., 2020; Stanney et al., 2020b). Those lags increase cybersickness symptoms (Rebenitsch and Owen, 2016; Palmisano et al., 2019)	On-screen (visual) latency should be inferior to 17–20 ms, although those values are debatable (Stauffert et al., 2020). Measuring constantly the latency of the virtual environment (Stauffert et al., 2021)

For each VRISE, we identified factors reported as associated with their occurrence and the proposed guidelines when provided. The definition and summary of the theories underlying the occurrence of each VRISE were made based on the most recent reviews or meta-analyses. Within each VRISE, we classified factors and guidelines into three *(1) individual, (2) hardware, and (3) software*, following LaViola (2000).

To better reflect our confidence in *those* guidelines, we graded each with a level of evidence based on Ackley et al. (2008) initially developed to assess nursing care evidences. Common factors occasionally influence different forms of VRISE. Hence, in those cases, crossing all VRISE can be important to envision what should be done to mitigate them.

As all empirical studies did not necessarily report guidelines, we translated the reported results as guidelines when it was the case. Hence, those guidelines are interpretations by the authors.

3. Results

3.1. Cybersickness

3.1.1. Definition

Cybersickness has been defined as "an uncomfortable side effect experienced by users of immersive interfaces commonly used for Virtual Reality. It is associated with symptoms such as nausea, postural instability, disorientation, headaches, eyestrain, and tiredness" (Lavoie et al., 2020).

3.1.2. Prevalence

Stanney et al. (2020b) have reported that at least one-third of users will experience cybersickness, with 5% of these participants presenting severe symptoms while using current HMDs generation, prevalence being almost necessarily contingent upon the technological state of the art (Somrak et al., 2019).

3.1.3. Theoretical grounding

The sensory cue conflict proposition is widely accepted compared with competing theories (Lee and Choo, 2013; Stanney et al., 2020b). According to sensory cue conflict, cybersickness appears to occur because of visual–vestibular–proprioceptive conflicts (Roesler and McGaugh, 2019; Staresina and Wimber, 2019; Wong et al., 2019; Hirschle et al., 2020; Klier et al., 2020; Saredakis et al., 2020; Stanney et al., 2020b; Grassini and Laumann, 2021; Howard and Van Zandt, 2021). These inconsistencies are also called sensorimotor conflicts. However, the ecological theory (postural instability) also relies on extensive experimental results (Theorell et al., 2015; Aronsson et al., 2017; Stanney et al., 2020b). According to the ecological theory, humans primarily try to maintain postural stability. Hence, motion sickness expands with postural instability due to the novel environment and motion cues (Stanney et al., 2020b). Therefore, the cue conflict theory defends inconsistencies between perception systems, while the ecological theory defends postural instability, provoking motion sickness.

TABLE 4 Guidelines for possible hardware factors relating to tracking influencing cybersickness.

ID_factor Evidence level	Tracking (hardware)	Description	Guidelines
CYB_23 IV	Method of movement	This factor is possibly the most influencing cybersickness occurrence as objects locomotion in VR provokes vection. Vection and self-movement perception are affecting cybersickness symptoms (Keshavarz et al., 2014; Palmisano et al., 2017; Gallagher and Ferrè, 2018; Chang et al., 2020; Chardonnet et al., 2020; Descheneaux et al., 2020; Kemeny et al., 2020; Stanney et al., 2020b; Yildirim, 2020; Caserman et al., 2021; Fauville et al., 2021)	Several postures and interactions can be used in VR: sitting, standing, and walking (Bellgardt et al., 2017). However, sitting without virtual locomotion seems the most advantageous use of VR in our case (Zielasko and Riecke, 2020). If locomotion is necessary in the virtual environment, the best to reduce potential cybersickness, also relative to users' posture, are in order (Kemeny et al., 2020; Porcino et al., 2020a; Caserman et al., 2021): 1) Avoid continuous movements 2) Field of view reduction during movement 3) Teleportation, although depending on the virtual environment, can be inefficient (Clifton and Palmisano, 2020) 4) Adding "noise" to vestibular cues (Weech et al., 2020) 5) Using tracking of the entire body Depending on locomotion, the transition style can also impact usability (flying can be better than teleporting for spatial awareness) (Coburn et al., 2020)
CYB_24 V	Calibration	Poor calibration increases cybersickness symptoms as users' physical characteristics vary, while hardware allows limited match ranks between it and tracking devices (Davis et al., 2014). Poor calibration can cause delays, lags, and incongruent feedbacks in the virtual environment	Ensuring that tracking devices are correctly calibrated and work with each user (correct size, accurate focus, and correct alignment) (Davis et al., 2014). A checklist of what needs to be calibrated before VR use could help
CYB_25 V	Position tracking error	Head tracking gets worst linearly with use time (Garcia-Agundez et al., 2017). In general, position tracking error can create poor stimuli, feedback, interactions with the virtual environment (Davis et al., 2014)	Testing apparatuses possible tracking errors, using an HMD adapted to the physical space or convertibly (Garcia-Agundez et al., 2017; Chang et al., 2020)
CYB_26 V	Tracking method	Part of last generation HMDs still depend on external trackers. Depending on the tracking method, the error rate can variate and impact interaction. Therefore, influencing other tracking factors and movements (Chang et al., 2020)	If locomotion needs to be very accurate, content creators should consider HMDs' tracking method since it impacts further other factors influencing cybersickness (Chang et al., 2020). Tracking should match a >60 Hz refresh rate (Davis et al., 2014)
CYB_27 VI	Head movements	Head rotation and translation movements can impact cybersickness (Palmisano et al., 2017, 2020). The more head movements, the more cybersickness risks, although some tolerance is possible (Kim J. et al., 2021). Head movements can be correlated with tasks and stimuli distance (depth) (Pöhlmann et al., 2021)	Allowing users to take a break in head movements during VR use (Kim J. et al., 2021)

3.1.4. Guidelines considering cybersickness factors

Rebenitsch and Owen (2021) have proposed 50 factors influencing cybersickness occurrence in VR. Unfortunately, in doing so, they do not limit to this relevant literature. However, they reuse Davis et al.'s (2014) list and align with the factors that Howard and Van Zandt (2021) noted. Mittelstaedt (2020) also proposed a synthesis. We selected Rebenitsch and Owen's (2014) factors list because it postulates more factors than other comparable publications. Each table lists one type or subtype of factor that could influence cybersickness:

- Individual factors related to experience with virtual environments and users' physical attributes are given in Table 1; general demographic factors and mental attributes are listed in Table 2.
- Hardware factors relating to screen are provided in Table 3, tracking in Table 4, rendering in Table 5, and non-visual feedback in Table 6.
- Software factors relating to movement in Table 7 and appearance and stabilizing information in Table 8.

3.2. Visual fatigue

3.2.1. Definition

Visual fatigue can be defined as: "*physiological strain or stress resulting from excessive exertion of the visual system*" (Somrak et al., 2019). Sheppard and Wolffsohn (2018) reference the list of symptoms identified by the *American Optometric Association.* These include eyestrain, headache, blurred vision, dry eyes, and pain in the neck and shoulders.

TABLE 5 Guidelines for possible hardware factors relating to rendering influencing cybersickness.

ID_factor Evidence level	Rendering (hardware)	Description	Guidelines
CYB_28 *V*	Stereoscopic rendering	Stereoscopy seems to increase cybersickness symptoms (Isaza et al., 2019; Palmisano et al., 2019). It collaborates with vection (Chang et al., 2020)	Using bi-ocular images (same image for each eye), not stereoscopy (Isaza et al., 2019; Palmisano et al., 2019)
CYB_29 *V*	Inter-pupillary distance	The HMD's lenses range of adjustment mismatch user's IPD (Stanney et al., 2020a). Women are more susceptible to cybersickness because of the impossibility of matching lens distance with IPD. Also see VF_4	Stanney et al. (2020a) call for HMD adjustable lenses matching more than 99% of IPDs in the general population, ranging from about 50 to 77 mm. Preferring HMDs with the widest lenses distance tuning. Measuring users' IPD with psychophysical tests or eye tracking to help them tuning HMDs correctly
CYB_30 *V*	Screen distance to the eye	In an HMD, screen distance is constant, very close to users' eyes, and stimuli are physically projected at a longer distance with lenses (Watson and Hodges, 1995). Accommodation occurs on the screen, while vergence occurs on objects at various depths (Souchet, 2020). The closer the screen or projected screen, the harder for the eyes to accommodate without diplopia. Also see VF_3	Using HMDs with lenses projecting images at a comfortable distance: <2 m (Patterson, 2009) Applying "on-screen" parallaxes to alleviate vergence-accommodation conflict (Fuchs, 2017) Not displaying stereoscopy (Souchet, 2020)
CYB_31 *V*	Update rate	Users are in constant interaction with the virtual environment by providing inputs that induce feedback. That feedback occurs by updating the current virtual environment's stimuli (objects, movements, sounds…). A slow update rate can create incongruence between users' inputs and the virtual environment's feedback (Davis et al., 2014). Current HMD generation allows an images update rate of 60–144 Hz. Update (or refresh) rate could have a minor impact on cybersickness (Rebenitsch and Owen, 2017, 2021; Porcino et al., 2020b; Saredakis et al., 2020; Caserman et al., 2021)	Current HMDs are usually allowing a 90 Hz image update rate Preferring HMDs with the highest update (refresh) rate if possible (Davis et al., 2014) Avoiding interactions requiring numerous changes and feedbacks in the virtual environment to reduce incongruence in synchronization between inputs and changes in the virtual environment (Davis et al., 2014)

3.2.2. Prevalence

Visual fatigue is already a significant issue in everyday work, with a large population at risk estimated at around 50% (Nesbitt and Nalivaiko, 2018). Close-up work on computer screens is an issue regarding dry eyes, ametropia, and accommodation or vergence mechanisms (Lackner, 2014). New-generation HMDs still continue to cause visual fatigue (Koohestani et al., 2019; Wang Y. et al., 2019; Descheneaux et al., 2020; Kemeny et al., 2020; Caserman et al., 2021; MacArthur et al., 2021) alongside visual discomfort (Lambooij and IJsselsteijn, 2009; Sheppard and Wolffsohn, 2018; Ang and Quarles, 2020; Descheneaux et al., 2020; Yildirim, 2020). HMDs seem to create higher visual fatigue than PC, tablets, or smartphones (Souchet et al., 2018; Hirota et al., 2019; Descheneaux et al., 2020; Hirzle et al., 2020). However, as HMDs could summate with other screen usages, more prolonged exposure to screens, in general, leads to increasingly negative symptoms on the visual system (Souchet et al., 2019).

3.2.3. Guidelines considering visual fatigue factors

Fourteen factors influence visual fatigue occurrence based on our update (Souchet et al., 2022) of Bando et al. (2012)'s list. Each table lists one type or subtype of factor that could influence visual fatigue:

- Individual and hardware factors influencing visual fatigue are shown in Table 9.
- Software factors influencing visual fatigue are provided in Table 10.

Factors inducing visual fatigue are not, in most cases, the central focus of peers for reducing VRISE. Therefore, further research is recommended in order to draw more precise and quantified guidelines.

3.3. Muscle fatigue and musculoskeletal discomfort

3.3.1. Definition

Muscle fatigue has been defined as an: "*exercise-induced reduction in the ability of a muscle or muscle group to generate maximal force or power*" (Yoon et al., 2020). Muscle fatigue frequently arises with screen work (Souchet et al., 2021).

3.3.2. Prevalence

Repetitions of excessive muscular loads can lead to musculoskeletal disorders and are the most common (almost 24% of EU workers) work-related problem in Europe (Cho et al., 2017). Neck, shoulder, forearm, and hands pain as well as upper and low back pain, prove to be the primary disorders associated with office work (Guo et al., 2017, 2019; Han J. et al., 2017; Bracq et al., 2019). Sitting while performing computer work can be associated with short-term adverse effects, such as physical discomfort (Yu X. et al., 2018). Symptoms associated with prolonged use of computers are neck and wrist pain as well as backache (Zhang et al., 2020c). Such symptoms are likely to also arise in VR. However, the majority of the associated literature

TABLE 6 Guidelines for possible hardware factors relating to non-visual feedback influencing cybersickness.

ID_factor Evidence level	Non-visual feedback (hardware)	Description	Guidelines
CYB_32 *VI*	Type of haptic feedback	Haptic feedback allows adding acceleration cues, therefore, movement information (Porcino et al., 2020b). Adding haptic stimuli doesn't always positively affect cybersickness (Plouzeau et al., 2017; Gonçalves et al., 2020). But it also appears that it can reduce cybersickness (Liu et al., 2019)	Adding haptic feedback (e. g., vibrations) related to movement could alleviate cybersickness (Plouzeau et al., 2017; Gonçalves et al., 2020)
CYB_33 *VII*	Ambient temperature	HMDs themselves produce heat and can lead to thermal discomfort (Wang Z. et al., 2019). It can impact eyes tear films (Turnbull et al., 2019). Ambient temperature doesn't always impact cybersickness symptoms (Saeidi et al., 2021). Devices to stimuli thermoception exist (Han P. H. et al., 2017; Günther et al., 2020; Lee et al., 2020; Liu et al., 2021b). Airflow seems to reduce cybersickness (D'Amour et al., 2017; Harrington et al., 2019) but not always (Paroz and Potter, 2018)	No clear guidelines can be drawn from the literature on the most suitable temperature for VR use. Thermoception depends on what part of the body is at stake (Kim et al., 2017; Viana and Voets, 2020) and relative temperative adaptation duration depending on inside and outside delta. Devices stimulating users' thermoception could generalize. Ideal ambient temperature for VR use is not clear. 37°C is the average human internal temperature. Stimuli that increase to fever temperature could participate in cybersickness symptoms. We can hypothesize that wearing an HMD can get uncomfortable, mainly because the device also produces heat while functioning
CYB_34 *VII*	Olfactory feedback	Smell doesn't always impact cybersickness, whether positively or negatively (Narciso et al., 2019). But it can reduce symptoms (Ranasinghe et al., 2020)	Olfactory stimuli could help drive visual attention, impacting movement perception (Tsai et al., 2021) Researches still need to address how olfactive stimuli can influence or not cybersickness
CYB_35 *VII*	Audio feedback	Audio-visual mismatches could participate in cybersickness, although no clear proof exists (Siddig et al., 2019; Widyanti and Hafizhah, 2021). Therefore, audio feedback needs to be coherent as it could influence cybersickness. However, few contributions address this issue	Create matching audio-visual cues in virtual environments to allow spatial congruency and coherent movement perception (Stanney et al., 2020b)

concerns sports activity and is relatively less concerning office work tasks. Many experiments on muscle fatigue and/or musculoskeletal discomfort are assessed primarily using smartphones, tablets, and computer screens. Rarely do these employ HMDs, although the trend is changing.

3.3.3. Guidelines considering muscle fatigue and musculoskeletal discomfort factors

Fifteen factors have been identified (Souchet et al., 2022) as influencing muscle fatigue and musculoskeletal discomfort frequency of occurrence based on the current synthesis of existent work. Each table lists one type, or subtype, of factor that may influence muscle fatigue and musculoskeletal discomfort:

- Individual and Hardware factors influencing muscle fatigue and musculoskeletal discomfort are provided in Table 11.
- Software factors influencing muscle fatigue and musculoskeletal discomfort are described in Table 12.

Clear information about muscle fatigue and musculoskeletal discomfort associated with VR exposure remains problematically scarce. Only a few works using PC or smartphone provide coherent findings for HMDs. However, the body part mobilized here, the tension experienced with HMDs and the interaction device use might not be equivalent. Therefore, we sought to extrapolate information from screen uses to provide guidelines. Muscle fatigue and musculoskeletal discomfort depend on specific task characteristics (Alabdulkader, 2021), making generalization challenging to validate.

3.4. Acute stress

3.4.1. Definition

Stress can be defined as a: "*condition in which an individual is aroused and made anxious by an uncontrollable aversive challenge*" (Gandevia, 2001). Acute stress represents a sudden or short time exposure incident (trauma, perceived threat, death of a loved one, job loss, etc.). Acute stresses are often juxtaposed with chronic stress, the latter being long-term effects (European Agency for Safety Health at Work, 2007; Coenen et al., 2019).

3.4.2. Prevalence

Current knowledge does not allow us to define acute stress prevalence induced by VR use specifically outside of wild task-specific aspects and technostress. Introducing VR at work without the proper training could trigger techno-complexity (see S_3 in Table 13) and add up to all the other apparatus workers already use, which might trigger techno-overload (see S_4 in Table 13). One wide use of VR is remote meetings. Public speaking is stress-inducing, but it seems higher with VR (Helminen et al., 2019; Zimmer et al., 2019). Acute stress, in general, impairs executive

TABLE 7 Guidelines for possible software factors relating to movement influencing cybersickness.

ID_factor Evidence level	Movement (software)	Description	Guidelines
CYB_36 *IV*	Rate of linear rotational acceleration	Linear rotational acceleration influences cybersickness (Kim et al., 2017; Paroz and Potter, 2018; Harrington et al., 2019; Clifton and Palmisano, 2020; Kemeny et al., 2020; Weech et al., 2020; Kirollos and Herdman, 2021)	Use a low rate of linear rotational acceleration, and if higher are necessary (Kemeny et al., 2020; Viana and Voets, 2020), introduce them gradually
CYB_37 *V*	Self-movement speed and rotation	Proprioception is the sensation of body position and movement (Narciso et al., 2019). Whether the user is moving or not, while the visual feedback induces movement, the self-movement speed and rotation can mismatch those feedback (Lin et al., 2020; Ranasinghe et al., 2020). It mainly seems that humans have preattentive processing of visual self-motion information (Tsai et al., 2021) and gaze stabilization strategy during self-motion to control our body (Siddig et al., 2019). User's representation (avatar) can influence proprioception depending if legs and arms are present in 1st-person perspective or if the user is represented in 3rd-person perspective (Kemeny et al., 2020; Kim J. et al., 2020; Terenzi and Zaal, 2020; Widyanti and Hafizhah, 2021) See also CYB_38	Encourage low self-movement speed and rotation by users. When walking in VR, 1.4 m/s is recommended (Paroz and Potter, 2018; Kemeny et al., 2020). These factors depend on locomotion technique (Rebenitsch and Owen, 2016; Boletsis, 2017; Plouzeau et al., 2018; Tuthill and Azim, 2018; Tian et al., 2020; Paik et al., 2021; Rantala et al., 2021) Since few investigations have been conducted in office-like work situations on which avatar's characteristics are the most suitable, the only guideline would be to allow the user to choose between 1st-person perspective or 3rd-person perspective
CYB_38 *V*	Vection	Four competing definitions of vection exist. We align with the definition of vection, stating it is: "*a visually mediated subjective experience of self-motion*" (Palmisano et al., 2015; Kim and Park, 2020). Vection could be influenced by cognitive factors and individual traits (field dependence and depersonalization) (Schmitt et al., 2021). Some results point that strong vection can lead to reduced cybersickness (Fawcett et al., 2015; D'Amour et al., 2021). Therefore, vection is seen as a possible way to alleviate cybersickness (Stanney et al., 2020b). Vection doesn't seem causal to visually induced motion sickness (Kuiper et al., 2019; Chow et al., 2021). A large Field of view can impact vection (de Winkel et al., 2018; van der Veer et al., 2019). See CYB_23 and CYB_37	See CYB_23 and CYB_37
CYB_39 *VI*	Altitude above terrain	Manipulating view height can impact body parts perception (Widyanti and Hafizhah, 2021)	Matching user's real height in the virtual environment and feedback adapted to virtual terrain variation (Widyanti and Hafizhah, 2021)
CYB_40 *VI*	Degree of control	Uncontrolled movements could influence cybersickness as users' can't predict the environment and resulting self-motion (Nesbitt and Nalivaiko, 2018; Evin et al., 2020; Weech et al., 2020). However, when tested directly as a cybersickness factor, the degree of control doesn't always have influence (Matsuda et al., 2021; Shi et al., 2021)	Avoiding uncontrolled movements (Matsuda et al., 2021; Shi et al., 2021)

functioning (Calik et al., 2022). According to LeBlanc (Eltayeb et al., 2009), stress diminishes the efficiency of selective attention (Heidarimoghadam et al., 2020; Frutiger and Borotkanics, 2021). Stress can also impair working memory and has been suggested to enhance memory consolidation (Baker et al., 2018). Stress has been observed to impair memory recall/retrieval (Borhany et al., 2018; Shannon et al., 2019). Therefore, we can assert that stress can act to impair work performance when fulfilling tasks in VR. And, of course, these effects are dependent on task typologies. At the occupational level, stress impacts workers' health, performance, and wellbeing (Sesboüé and Guincestre, 2006; Fink, 2016). It can lead to depressive symptoms (Fink, 2007), burnout symptoms (Shields et al., 2016), hypertension (LeBlanc, 2009), and/or type 2 diabetes mellitus (Bater and Jordan, 2020). Stressors can therefore impact VR adoption as they affect task completion novelty and the spectrum of tasks' typology.

3.4.3. Guidelines considering acute stress factors

Based upon our synthetic assessment of previous works, several factors are identified as influencing acute stress occurrence. We focused on nine of these (Souchet et al., 2022). They are couched in terms of office-like tasks. Each table lists one type of factor that influences acute stress:

- Individual and hardware factors influencing acute stress are shown in Table 13.
- Software factors influencing acute stress are given in Table 14.

Depending on the tasks at hand, the interactions, and the relevant interfaces, acute stress in VR can arise accordingly. Just considering the possibility of stress while using VR may already help create safe working conditions and promote more benevolent

TABLE 8 Guidelines for possible software factors relating to appearance (CYB_41 to 46) and stabilizing information (CYB_47 to 50) influencing cybersickness.

ID_factor Evidence level	Factors	Description	Guidelines
CYB_41 *IV*	Screen luminance	See VF_6	See VF_6
CYB_42 *IV*	Color	See VF_14	See VF_14
CYB_43 *VI*	Contrast	High contrast levels could lead to higher cybersickness symptoms (Zhang et al., 2010; Kemeny et al., 2020; Campos et al., 2021)	Selecting HMDs depending on their screen technology (OLED, LCD) allowing the best contrasts to control optical variables of the virtual environment. Trying to display low contracts (Campos et al., 2021)
CYB_44 *V*	Scene content or scene complexity	Adding complexity (more visual cues) could drive higher cybersickness symptoms, impacting motion perception (Allue et al., 2016; Porcino et al., 2017; Hu et al., 2019; Islam et al., 2020)	High content variation and complexity should be avoided (Porcino et al., 2017; Hu et al., 2019; Islam et al., 2020). Minimalist interfaces could help at reducing cybersickness symptoms
CYB_45 *VI*	Global visual flow	Visual flow influences walking speed (Mohler et al., 2007; Salinas et al., 2017). During walking, the velocity of visual self-motion feedback seems to impact gait (Janeh et al., 2017). Globally, navigation speed influences symptoms (So et al., 2001; Kwok et al., 2018). Optical flow can also influence head displacement (Fujimoto and Ashida, 2020). Globally, humans seem more nauseous when watching intermittently moving and static visual objects (Chang et al., 2020). Sensitivity to motion parallax cues drives more sensitivity to cybersickness (Fulvio and Rokers, 2021). In HMDs, FoV also influence the amount of visual stimuli user perceive, see CYB_19	Use low locomotion speed. When visual flow reproduces walking stimuli, starting at a 5 m/s speed could activate cybersickness (So et al., 2001)
CYB_46 *IV*	Orientation cues	The direction of visual flow influences cybersickness (moving forward induce more cybersickness than moving backward) (Gavgani et al., 2017). Globally, users can be disoriented in VR as conflicting visual and vestibular cues are displayed (Coburn et al., 2020; Palmisano et al., 2020; Porcino et al., 2020a; Tian et al., 2020; Yildirim, 2020; Chang et al., 2021) Since head tracking provides most orientation cues, poor tracking can induce mismatching cues, see CYB_25	Adding a visual cue in the virtual environment as a reference (both body representation and surrounding objects) (Funk et al., 2019; Petri et al., 2020). However, more orientation cues (realism) can drive more cybersickness (Rebenitsch and Owen, 2016). Allowing users to choose the avatar's perspective, viewing distance, and preview where they will land if teleporting (Cmentowski et al., 2019; Zhang et al., 2020a). Allowing users to choose the locomotion technique
CYB_47 *IV*	Focus areas	Focus areas outside the central vision can participate in cybersickness as peripheral vision is more sensitive to flicker (Descheneaux et al., 2020) See also CYB_11	Content should focus on users' central vision and near peripheral corresponding to 30° eccentricity angle horizontally (Bhise, 2012; Hussain et al., 2020; Wu et al., 2021) Using foveated rendering or FOV restrictor (depending on eye tracking) (Adhanom et al., 2020) See also CYB_11
CYB_48 *VI*	The ratio of virtual to real world	Being static in the real world while moving in VR impacts cybersickness, and the more differences (ratio) between real and virtual cues, the more symptoms (Saredakis et al., 2020). Real-world reference to give fixed stabilization information can positively impact cybersickness while moving in VR (Chojecki et al., 2021) This ratio can also concern virtual object size and distance compared to reality	Putting a fixed virtual "object" corresponding to a real "object" as a reference point for locomotion, object size, and depth (Chojecki et al., 2021) See also CYB_49
CYB_49 *VI*	Independent visual backgrounds	Moving background induce cybersickness (Jeong et al., 2019; Oh and Lee, 2021)	Having a fixed background in the virtual environment (Hemmerich et al., 2020; Rebenitsch and Owen, 2021)
CYB_50 *IV*	Siting vs. standing	Standing rather than sitting increases the chances to provoke cybersickness (Merhi et al., 2007)	Several postures and interactions can be used in VR: sitting, standing, and walking (Bellgardt et al., 2017). Sitting without virtual locomotion seems the most advantageous use of VR at work (Zielasko and Riecke, 2020)

TABLE 9 Guidelines for possible individual (VF_1 to 3) and hardware (VF_4 to 7) factors influencing visual fatigue.

ID_factor Evidence level	Factor	Description	Guidelines
VF_1 *VI*	Age	Visual acuity seems to drop starting at 55–59 years (Radner and Benesch, 2019). Accommodation decreases with age, and around 40 people present presbyopia (Charman, 2008; Lambooij et al., 2009). Precision abilities of stereopsis diminish with increasing age (Schubert et al., 2016). Stereoscopic acuity decreases with increasing age (Zaroff et al., 2003). Pupil diameter decreases with increasing age, especially at low luminance (Guillon et al., 2016). Tear production decreases with age (Blehm et al., 2005) and dry eyes symptoms increase with age (Ding and Sullivan, 2012; Coles-Brennan et al., 2019; Tellefsen Nøland et al., 2021). Contradicting results show an impact of age on visual fatigue: it decreases with increasing age (Larese Filon et al., 2019) similar within age groups (Sánchez-Brau et al., 2020; Lin et al., 2021) increases with increasing age (Ranasinghe et al., 2016)	At 40 and more, visual functions seem to decrease. Therefore, this population could be more at risk. However, younger (under 40) seem to be more subject to visual fatigue Taking breaks (Chang et al., 2020)
VF_2 *III*	Stereoscopic visual ability (stereo-blindness)	Part of the population is "stereo-blind." These individuals are missing or have immeasurable binocular depth perception. The proportion of concerned individuals varies according to tested populations and measurement conditions from 2.2% to 32% (Lambooij et al., 2009; Bosten et al., 2015; Hess et al., 2015). Poor stereo acuity drives higher visual fatigue (Ramadan and Alhaag, 2018)	Test users' stereoscopic ability before VR exposure with clinical tests that can also be implemented directly in VR (Piano et al., 2016; O'Connor and Tidbury, 2018; Jeon and Choi, 2019; Kara et al., 2020; Cárdenas-Delgado et al., 2021): normal stereoscopic acuity is 20 arc seconds (Steinman et al., 2014), 50 arc seconds to 400 arc seconds can be considered as poor stereoscopic acuity (Deepa et al., 2019) If users are stereoblind or have very low ability, don't display stereoscopic images
VF_3 *III*	Vergence-accommodation conflict	Stereoscopy induces the vergence-accommodation conflict (Ukai and Howarth, 2008; Bando et al., 2012). This conflict also arises with HMDs and provokes visual fatigue (Souchet et al., 2018, 2021; Yuan et al., 2018; Matsuura, 2019)	Don't display stereoscopic images as benefits at displaying them are not always obvious (Souchet et al., 2018; Saracini et al., 2020). Display biocular images. Avoid negative parallaxes if you need to use stereoscopy (Liu et al., 2021a). Ensure that disparity is constant (not changing all the time) (Speranza et al., 2006; Cai et al., 2017; Jacobs et al., 2019; Shen et al., 2019; Souchet et al., 2019) Make sure that virtual objects appear "on screen" (close to null disparity) to make vergence closer to accommodation (Fuchs, 2017). For other devices displaying stereoscopy, a viewing distance of 2 m or more are advised (Patterson, 2009): in HMDs, it advocates for objects in stereoscopy to be 2 m from the viewer Create a region of interest focus, applying blur on regions outside of interest (Carnegie and Rhee, 2015; Porcino et al., 2020b; Caputo et al., 2021) Try to make accommodation matching vergence with eye tracking (Hasnain et al., 2019)
VF_4 *IV*	Optical misalignment (between HMD lenses and eyes)	Lenses not matching user IPD provokes visual fatigue (Hibbard et al., 2020; Stanney et al., 2020a; Wang X. M. et al., 2020)	Choosing HMDs allowing the widest tuning of lenses to match the user's IPD (Stanney et al., 2020a; Wang X. M. et al., 2020). Measure IPD to guide users when they tune the distance between lenses (eye tracking can help) (Chang et al., 2020; Hibbard et al., 2020)
VF_5 *IV*	Geometrical distortion (especially for 360° video when acquisition mismatches display)	Geometrical distortions (in position, shape, color, brightness, camera misalignment) induce visual fatigue (Bando et al., 2012; Gao et al., 2018; Xia et al., 2019; Hwang and Peli, 2020). Viewing angles can impact visual discomfort in HMDs (Iskander et al., 2019; Ha et al., 2021)	Check for any geometrical distortion and correct it (Jones et al., 2015; Gao et al., 2018; Scarfe and Glennerster, 2019)
VF_6 *IV*	Luminance	In an HMD, lighting depends on screen luminance, and since the Field of view is limited, peripherical vision is dark (Lin C. W. et al., 2020) The brighter the stimuli displayed, the higher visual fatigue (Wang et al., 2010; Benedetto et al., 2014; Cai et al., 2020; Erickson et al., 2020; Hamedani et al., 2020; Wang K. et al., 2020) Luminance contrasts between the display and the surrounding induce visual fatigue (Leccese et al., 2021) Pupil dilations can result in an enhanced perceptual experience of brightness (Sulutvedt et al., 2021)	For reading in an office, standards for room lighting are set between 500 and 750 lx (Liu T. et al., 2017) Using a computer display screen at night (from 18:00 to 23:00), Xie et al. (2021) advise setting screen luminance at 28cd/m^2 (5%screen brightness) and a (text-background) luminance contrast not lower than 0.725 Zhou Y. et al. (2021) argue for ambient illuminance and screen luminance levels in the range of 13.08–62.16 lx and 20.63–75.15 cd/m^2. For instance, Oculus rift DK2 can reach a maximum of 94 cd/m^2. 28 cd/m^2 seems the most comfortable in HMDs (Ha et al., 2017)

(Continued)

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TABLE 9 (Continued)

ID_factor Evidence level	Factor	Description	Guidelines
			Luminance between scenes in HMDs should be harmonized to avoid very different brightness leading to higher discomfort (Ha et al., 2020) Apply dark mode with compensated luminous intensity (Vasylevska et al., 2019) Calibration of HMDs' screens (Toscani et al., 2019) Patterson (2009) advise interocular luminance differences and interocular contrast differences at less than 25%
VF_7 *VII*	Blue light (range from 400 to 490 nm)	Blue light implies less accommodation (Panke et al., 2019). It can impact (Anses, 2019) myopia (positive or negative) and dry eye syndrome It induces visual fatigue (Rabin et al., 2020; Zhang et al., 2020b). 480 to 490 nm disturb circadian rhythms during the evening, impacting sleep (Wahl et al., 2019), making users more susceptible to visual fatigue (Munsamy and Chetty, 2020)	Reducing blue light with a filter (Chiu and Liu, 2020). Although proofs of efficiency are still missing, blue-blocking lenses could be a solution (Singh et al., 2021; Vagge et al., 2021)

work conditions. VR allows for teleporting users to a stress-relieving environment [natural surrounds (e.g., trees, grass, indoor biophilic environment) as well as light conditions (Van den Berg et al., 2015; Liu M. Y. et al., 2017; Yin et al., 2018; Hedblom et al., 2019; Wang et al., 2019; Huang et al., 2020; Kerous et al., 2020; Li C. et al., 2020; Park et al., 2020; Shuda et al., 2020; Li et al., 2021), music (Sokhadze, 2007; Nakajima et al., 2016; Yu C. P. et al., 2018; Paszkiel et al., 2020; Yin et al., 2020)]; and could help alleviate the above-described symptoms via this capacity (Thoma et al., 2013).

3.5. Mental overload

3.5.1. Definition

Mental workload can be defined as "*a subjectively experienced physiological processing state, revealing the interplay between one's limited and multidimensional cognitive resources and the cognitive work demands being exposed to*" (Young et al., 2015; Ahmaniemi et al., 2017; de Witte et al., 2020) indicated that overload "*occurs [. . .] when the operator is faced with more stimuli than (s)he is able to handle while maintaining their own standards of performance.*"

3.5.2. Prevalence

Current knowledge does not allow us to define mental overload prevalence induced by VR use specifically outside of wild task-specific aspects. But, mental fatigue appears to be higher in VR as compared to conducting the same tasks in real offices (Van Acker et al., 2018). Furthermore, VR induces a higher mental workload than PC (Lim et al., 2013; Zhang et al., 2017; Broucke and Deligiannis, 2019; Makransky et al., 2019). But, contradictory results regarding mental workload have been observed (Porcino et al., 2017). For example, VR presents a lower cognitive demand for geo-visualization and trajectory data exploration than PC usage (Collaboration, 2015; Kaplan et al., 2020; Szopa and Soares, 2021), and a higher mental workload does not always negatively impact task performance (Tian et al., 2021). As mental overload is especially contingent on task characteristics, relying only on a general model provides only general assertions. Examples exist in air traffic control (Young et al., 2015), driving (Paxion et al., 2014; Tobaruela et al., 2014), as well as work in nuclear power plants (Wickens, 2017). Therefore, we here consider primarily two factors (general enough to apply to a wide variety of tasks). However, (Wickens, 2017) have previously considered 26 factors that could influence mental workload. In VR, task characteristics impact mental workload, via interactions and interfaces. We thus focus especially on time pressure and task difficulty.

3.5.3. Guidelines considering mental overload factors

Based on our present synthesis of previous works, Table 15 features time pressure and task difficulty as these are the main factors influencing mental overload.

TABLE 10 Guidelines for possible software factors influencing visual fatigue.

ID_factor Evidence level	Software	Description	Guidelines
VF_8 *III*	Duration of display use	The longer HMD use, the higher visual fatigue (Yuan et al., 2018; Yue et al., 2018; Guo et al., 2019, 2020; Szpak et al., 2020; Marshev et al., 2021)	Visual fatigue symptoms can start after 10 min of use. About 20 min will induce visual fatigue. Therefore, breaks might occur every 15 min to prevent visual fatigue (Yuan et al., 2018; Yue et al., 2018; Chang et al., 2020)
VF_9 *IV*	Binocular disparity (possible and comfortable fusion)	High disparity can be fused without diplopia, but high disparity induces visual fatigue (Shibata et al., 2011; Patterson, 2015; Fuchs, 2017). Negative parallaxes lead to higher visual fatigue than positive (Sun et al., 2020)	Shibata et al. (2011) assume that the maximum and minimum relative distance of the comfort zone is between 0.8 and 0.3 D Apply $\pm 1.0^{\circ}$ disparity to avoid visual fatigue (Bando et al., 2012; Matsuura, 2019; Hibbard et al., 2020) However, according to Patterson (Patterson, 2009), fusion is possible from 80 arc minutes for high spatial frequencies and up to 8° for low spatial frequencies images
VF_10 *IV*	Motion parallax	Moving objects can induce more visual discomfort (Speranza et al., 2006). The more dynamism in videos, the more visual fatigue (Kweon et al., 2018). Vertical parallax induces visual fatigue (Sugita et al., 2019). However, motion parallax from head movement reduces visual discomfort (Kongsilp and Dailey, 2017) See also CYB_37 and CYB_45	Prefer slow-motion parallax cues in the virtual environment and avoid discontinuity (Speranza et al., 2006; Kweon et al., 2018; Sugita et al., 2019)
VF_11 *VII*	Texture gradients	Conflicting texture gradient could lead to more visual fatigue as those cues play a role in stereopsis (Lambooij et al., 2009; Su et al., 2018). Too sharp textures, when supposed to be far from the user, would be "unnatural" depth cues. Texture gradients can also inform about object orientation (Leroy, 2016), and if conflicting with other orientation cues and motion, it could participate in visual fatigue See also VF_10 and CY_46	When textures are determinant depth cues, make sure to reproduce gradients close to real visual perception to give orientation information (Leroy, 2016) See also VF_10 and CY_46
VF_12 *IV*	Occlusion	Objects hiding part of another will make it appear as "closer" to the viewer. If the object is supposed to be behind has other depths cues that make it closer, it could influence visual fatigue (Pietroszek, 2015; Leroy, 2016). The cues are ambiguous. When stereoscopy is displayed, since FoV in HMDs is limited, objects with negative parallax would be partially "cut" by limited FoV	Make sure to avoid ambiguous occlusion. Reducing the number of 3D objects can help. Reducing overlapping objects can help (Sidenmark et al., 2020), especially when you are supposed to reach and touch this object (Yu et al., 2021) Make sure that objects with stereoscopic cues are mainly located in the central vision
VF_13 *IV*	Blur	Blur can drive vergence and accommodation (Lambooij et al., 2009; Sweeney et al., 2014). Therefore, blurring objects where the visual system is supposed to rely on vergence and accommodation cues could lead to more symptoms	Apply blur in images carefully, not on objects of interest but on other objects in the scene to avoid driving unwanted accommodation (Lambooij et al., 2009; Sweeney et al., 2014) Also see CYB_18
VF_14 *IV*	Colors	The more frequent color changes, the higher visual fatigue (Kim et al., 2016) Color temperature seems to impact visual fatigue (Wang K. et al., 2020) Stereoscopic acuity can increase with increasing color discrimination ability (Koctekin et al., 2020) Color also has a link with luminance: see VF_6 and VF_7	Avoid highly changing colors Avoid highly saturated colors (Kim et al., 2016) Prefer low luminance colors See VF_6 and VF_7

4. Discussion and limitations

We have provided a review featuring human factors and ergonomic approaches that have considered 90 factors that are proposed as impacting VRISE. More particularly, we considered 50 factors related to cybersickness in VR. Additionally, we examined fourteen factors involved with visual fatigue in VR and 15 related to muscle fatigue and musculoskeletal discomfort in VR. Finally, we identified nine factors for acute stress when working in VR, alongside two factors critical for mental overload assessment in VR.

General guidelines that designers should follow for a healthy, safe, and performant user experience at work:

- Design environments such that users can fulfill most of their tasks within 20-min interval to reduce cybersickness and visual fatigue occurrence.

TABLE 11 Guidelines for individual (MF_1 and 2) and hardware (MF_3 to 7) factors influencing muscle fatigue.

ID_factor Evidence level	Factor	Description	Guidelines
MF_1 *VI*	Age	Age as a muscle fatigue factor is unclear due to the lack of relevant data (Speed et al., 2018; Mahdavi et al., 2020) Older (≥55) persons have a stronger resistance to muscle fatigue during sustained and intermittent isometric contractions than younger persons (Smith and Mosier, 1986; Gabbard et al., 1999; LaViola, 2000; Nichols and Patel, 2002; Stanney et al., 2003b, 2020b, 2021a,b; Hale and Stanney, 2004; Burkhardt et al., 2006; Avin and Frey Law, 2011; Bando et al., 2012; Davis et al., 2014; LaViola et al., 2017; Khakurel et al., 2018; Alsuraykh et al., 2019; EU-OSHA, 2019; Kourtesis et al., 2019; Vi et al., 2019; Wang Y. et al., 2019; Çöltekin et al., 2020; Mittelstaedt, 2020; Olson et al., 2020; Saredakis et al., 2020; Chen et al., 2021; Ens et al., 2021; Howard and Van Zandt, 2021; Rebenitsch and Owen, 2021; Sepich et al., 2022). Shoulder abduction shows similar results (Collins and O'Sullivan, 2018). Aging doesn't rime with muscle strength loss (Kenny et al., 2016). Globally, older adults and males are more resistant to fatigue than adults and females (Wan et al., 2017). However, exercise performance decreases with aging, consequent to lower tolerance to peripheral fatigue (Zarzissi et al., 2020). Concurrent cognitive demand reduces more older adults' endurance (handgrip) than youngers' (Shortz and Mehta, 2017). Older workers perform less high-intensity physical activity than younger workers after work-related fatigue (Bláfoss et al., 2019). Older office workers also report higher general pain (Shariat et al., 2018) Bimanual coordination performance with imposed speed for task complexion seems more complex for older (Lambooij and IJsselsteijn, 2009; Sheppard and Wolffsohn, 2018; Souchet et al., 2018; Ang and Quarles, 2020; Hirzle et al., 2020; Yildirim, 2020; Caserman et al., 2021; MacArthur et al., 2021) people (Roman-Liu and Tokarski, 2021)	Avoid gestures that require strength for workers older than 55 (Roman-Liu and Tokarski, 2021) Consider that younger workers (Smith and Mosier, 1986; Gabbard et al., 1999; LaViola, 2000; Nichols and Patel, 2002; Stanney et al., 2003b, 2020b, 2021a,b; Hale and Stanney, 2004; Burkhardt et al., 2006; Bando et al., 2012; Davis et al., 2014; LaViola et al., 2017; Khakurel et al., 2018; Alsuraykh et al., 2019; EU-OSHA, 2019; Kourtesis et al., 2019; Vi et al., 2019; Wang Y. et al., 2019; Çöltekin et al., 2020; Mittelstaedt, 2020; Olson et al., 2020; Saredakis et al., 2020; Chen et al., 2021; Ens et al., 2021; Howard and Van Zandt, 2021; Rebenitsch and Owen, 2021; Sepich et al., 2022) might need shorter VR exposure due to fatigue resistance (Avin and Frey Law, 2011) Consider that too fatiguing VR use might reduce older workers' physical activity after work (and then impact general health) (Bláfoss et al., 2019)
MF_2 *VI*	Body mass index	Non-obese, overweight, and obese participants performing isometric contractions for shoulder flexion and trunk extension seems to have similar strength (Cavuoto et al., 2019). Body mass index doesn't seem to impact muscle fatigue (Russeng et al., 2020). However, low back pain severity (office workers) appears higher for individuals with a high body mass index (Shariat et al., 2018). Overweight/obese workers are more likely to present musculoskeletal pain and related symptoms in the shoulders (Moreira-Silva et al., 2013). Obese adults show shorter endurance duration than normal-weight adults only at lower intensities, larger and more postural muscles of the shoulder, and low back (Mehta and Cavuoto, 2017)	Users with obesity might be more likely to present muscle fatigue. According to this factor, adapting interactions for less tiring gestures could help prevent fatigue (Li G. et al., 2020)
MF_3 *IV*	HMD weight	HMD weight seems to add physical stress on the cheekbone and back of the head (Kim and Shin, 2018; Yan et al., 2019). Wearing a helmet during screen use induces neck pain (Le et al., 2021)	Chose the lighter HMD, or try to alleviate weight (Kim and Shin, 2018; Yan et al., 2019)
MF_4 *VI*	Belts (attaching HMD to head)	The lower the number of belts, the high perceived physical s0tress on the neck because of HMD's weight (Song et al., 2019)	Choose HMDs with more belts and support (Song et al., 2019) Add extra belts on HMDs
MF_5 *VI*	Interaction devices	Users can interact with their head movements, bare hands or controllers, and "laser pointers (Pietroszek, 2018; Dombrowski et al., 2019; Lu et al., 2019)" Interactions requiring bimanual coordination can be challenging for older persons (Roman-Liu and Tokarski, 2021). Depending on controllers' weight, they can participate in muscle fatigue and impact task performance comparably to induced fatigue in Dupuis et al. (2021)	If the user gets tired of interaction, consider input amplification (Wentzel et al., 2020). Allowing controllers' (or any other interaction device) sensitivity control by the user (Dombrowski et al., 2019) Be careful with mid-air interactions for both hands and controllers When possible, don't make users having to use both hands or controllers at the same time

(Continued)

TABLE 11 (Continued)

ID_factor Evidence level	Factor	Description	Guidelines
MF_6 *V*	Position tracking error	The optimal center of mass position of HMDs varies depending on a user's posture (Chihara and Seo, 2018; Ito et al., 2019; Sun et al., 2019). Therefore, position tracking error would lead user's to compensate head (and other body parts) posture, leading to muscle fatigue See also CYB_7 and CYB_25	Prevent position tracking errors See CYB_7 and CYB_25.
MF_7 *IV*	HMD resolution	Depending on the task, here proofreading, resolution can contribute to physical stress (Kim and Shin, 2018)	Choose the HMDs with the highest resolution Consider foveated rendering (Patney et al., 2016; Alexandrov and Chertopolokhov, 2021; Franke et al., 2021) See also CYB_18

- Provide an "exploration phase," so that users can preview the fundamentals of their interactions, as well as experiencing local system feedback to reduce cybersickness and mental overload occurrence.
- Provide the user with a virtual assistant to adapt both interactions and interfaces to reduce mental overload occurrence.
- Limit movements within the virtual environment and display stereoscopy only when tasks require explicit depth cues to reduce cybersickness and visual fatigue occurrence.
- Create display features by considering user is sitting but allowing them to stand and walk on occasion to reduce muscular fatigue and musculoskeletal discomfort occurrence.
- Emphasize teleportation with guides for orientation if re-location within the virtual environment is necessary to reduce cybersickness.
- Allow users to customize their experience in the virtual environment (e.g., avatar, interface, and interactions) to reduce cybersickness, mental overload, and acute stress occurrence.
- Provide a monitoring toolkit that is based on questionnaires and psychophysiological measures, which allows to determine a user's susceptibility to side effects and to detect while they are immersed to reduce all VRISE occurrence.
- Provide stress-relieving procedures: these include, but are not limited to, nature (trees, grass, indoor biophilic environment), daylight, and relaxing music to reduce acute stress occurrence.

General guidelines that employers should follow for a healthy, safe, and effective use of virtual environments:

- Train workers to employ hardware and software effectively. This allows habituation and desensitization for the riskiest populations regarding cybersickness, reduces technostress that can provoke acute stress, and promotes an optimal degree of mental workload to reduce mental overload occurrence.
- Rethink and recast working tasks such that they can be readily adapted to virtual environments and their constraints to reduce acute stress and mental overload occurrence.
- Monitor workers' psychophysiological reactions in the virtual environment to record data to establish use benefit/risk ratios to reduce each VRISE occurrence.
- Have workers fill out anonymous questionnaires that inform about their individual susceptibility to VRISE.

General guidelines that workers would be informed of to sustain a healthy, safe, and effective use of virtual environments:

- Cease using virtual environments when symptoms of cybersickness, visual fatigue, muscle fatigue, and stress are experienced or task performance breakdowns occur.
- Take breaks following the use of virtual environments (take micro-naps, where possible walk beyond the bounds of the workplace, go drink water, seek "natural" spaces, listen to relaxing music or any and all combinations thereof) to reduce all VRISE symptoms.
- For those beyond 40 years of age, consider the individual to be might be more susceptible to elements of these side effects.
- Those with pathologies and/or particularities (e.g., eye diseases, overweight, neuroatypical, epilepsy, balance issues, muscle issues, and cognitive particularities), should be considered more susceptible to specific side effects of virtual environments.

Some prior guidelines have been suggested for discrete factors to promote healthier, safer, and more efficient work with virtual environments (Gabbard et al., 1999; Stanney et al., 2003b, 2021b; Burkhardt et al., 2006; Bando et al., 2012; Lanier et al., 2019; Muthukrishna and Henrich, 2019; Chen et al., 2021). However, most of these works concentrated on only one VRISE at a time. Frequently, they are not clear on the level of confidence associated with each guideline. However, to build on these previous works, we categorized factors into three types: individual, hardware, and software. With our tables, readers and stakeholders can easily refer to the present work as a guide for their design or use of virtual environments. Hence, the present offering is the most substantial and comprehensive assessment for the VR community. This is because it encompasses the greatest assemblage of information while providing the most practical and useful survey and recommendations.

TABLE 12 Guidelines for software factors influencing muscle fatigue.

ID_factor Evidence level	Software	Description	Guidelines
MF_8 *VI*	Duration of immersion	Mobile touch screen device use duration is associated with increased musculoskeletal discomfort (Toh et al., 2017; Zirek et al., 2020). Findings are similar for computer use: neck pain (Keown and Tuchin, 2018; Coenen et al., 2019). This can also apply to VR (Lee and Han, 2018; Li M. et al., 2020). Ten minutes of VR use can be enough to induce musculoskeletal discomfort (Arif et al., 2021)	Limit use duration (Sesboüé and Guincestre, 2006). Depending on the task (i.e., laparoscopic tasks), symptoms can appear after 15 min of use (Li M. et al., 2020) or even after 10 min (Arif et al., 2021) See also CYB_4 and VF_8
MF_9 *VI*	Object angle location	Shoulder flexion angle, neck flexion moment, muscle activities of the neck and shoulder, and excessive vertical target locations when interacting with targets at several angles in the 3D environment are likely to drive musculoskeletal discomfort (Kim and Shin, 2018; Penumudi et al., 2020). Texting on a smartphone can induce neck pain due to head angle (Lee et al., 2015). Depending on screen position angle, neck pain can arise (Szeto and Sham, 2008). Lowering the head too much seems to apply too much tension on the neck	Objects should be placed at the center (central vision), slightly to the right for those to interact with often, slightly below the horizontal line for keyboards, and slightly to the left for alerts or elements requiring users' refocussing (Zhou et al., 2021)
MF_10 *VI*	Gesture amplitude	Interaction gestures play a role in musculoskeletal discomfort depending on their amplitude (Li G. et al., 2020; Penumudi et al., 2020). Show that physical fatigue is higher in VR than the same task in reality (Ahmed et al., 2017)	Avoid interactions requiring too wide gestures (Li G. et al., 2020; Penumudi et al., 2020)
MF_11 *V*	Tasks repetition	Repetitive movements during screen work, especially keyboard and mouse, contribute to musculoskeletal symptoms (Coenen et al., 2019). On tablets, typing with a virtual keyboard can induce muscle fatigue (Lin M. I. B. et al., 2020). However, adaptation redistributing muscle demand could alleviate the strain of repetitive gestures (Pritchard et al., 2019)	Try to allow breaks from repetitive movements in interaction metaphors: e.g., hand, wrist, harm resting, shoulder and head resting loops by relying on eye tracking interactions (Majaranta, 2012; Majaranta and Bulling, 2014; Clay et al., 2019; Silva et al., 2019; Stanney et al., 2020b)
MF_12 *VI*	Head rotations required	HMD increases the head rotation during editing tasks compared to a computer screen, leading to neck discomfort (Kim and Shin, 2018). However, not moving the head (static neck flexion) for 10 min can induce neck pain (Mousavi-Khatir et al., 2018). Watching a video in VR could lead to not move the head for that long	Avoid continuous head rotations Avoid stationary heads for 10 min and more. As demonstrated by multiple monitors (PC), having multiple "regions of interest" can be more comfortable during work (Gallagher et al., 2021). However, using three screens showed a decrease in work performance (Iskander et al., 2018). In VR, giving users' freedom to choose the size and position of virtual displays can alleviate pain (Mcgill et al., 2020). Try to facilitate a neutral neck posture (Emerson et al., 2021). Concentrating interactions and feedback at the central vision might help
MF_13 *VI*	General posture	Prolonged smartphone use for texting induces rigid posture, increasing tension at the neck-shoulder level if the neck shows excessive flexion (D'Anna et al., 2021). Increased neck flexion (PC) angles drive higher activity in the upper trapezius muscle leading to neck and shoulder discomfort (Szeto et al., 2005)	Promote neutral posture (D'Anna et al., 2021) Avoid 3D object position, regions of interest that induce prolonged non-neutral postures (Davis et al., 2014; Shannon et al., 2019)
MF_14 *IV*	Sitting or standing	Quasi-standing work can provoke muscle fatigue (Wall et al., 2020). Walking seems more physically (neck) demanding than sitting when using smartphones (Flores-Cruz et al., 2019; Yoon et al., 2021). However, mobile device use drives lower extremity pain while sitting (Legan and Zupan, 2020). Sitting at work for hours provokes discomfort in all body regions over time (Baker et al., 2018; Waongenngarm et al., 2020)	Sitting could avoid too much muscle tension while performing office-like tasks in VR However, since prolonged sitting is also an issue, allowing the user to stand and/or walk while immerged could alleviate the downside of sitting (Ding et al., 2020)
MF_15 *IV*	Body parts representation and feedback (avatar)	Modifying postural/gesture feedbacks of a user's avatar in VR unconsciously drives the motor and muscular adjustments (Bourdin et al., 2019). This could lead the user to take postures or perform gestures leading to muscle fatigue	Create the most accurate feedback on the avatar's posture and gesture (Bourdin et al., 2019) Modify feedbacks to compensate user's non-neutral posture for reducing possible pain

TABLE 13 Guidelines for possible individual (S_1 and 2) and hardware (S_3 and 4) factors influencing acute stress.

ID_factor Evidence level	Individual	Description	Guidelines
S_1 *VII*	Age	Older workers appear more resilient to work-related stress (Hsu, 2019) Stress's negative impacts on memory performance are lower in older people (Hidalgo et al., 2019), although this doesn't reveal at the meta-analytic level (Shields et al., 2017). Similarly, older people seem less impacted by acute psychosocial stress (Vallejo et al., 2021) Stressful work is linked to slightly more sickness absence among older workers (Götz et al., 2018) Older workers or those with longer professional have greater difficulties with the increase of technological complexity for executing tasks (techno-complexity) (Marchiori et al., 2019)	Consider that younger workers could be more sensitive to induced stressors in VR working tasks (Hsu, 2019). Consider attributing fewer complex tasks or less socially stressful tasks to younger workers Older workers could be more susceptible to techno-stress (see also S_3 and S_4) (Marchiori et al., 2019). Consider attributing fewer complex tasks in VR to them
S_2 *II*	Body Mass Index (BMI)	A weak association between work stress (occupational level) and high BMI exists (Kouvonen et al., 2005; Magnusson Hanson et al., 2017). However, there are contradictory results (Myers et al., 2021) Obesogenic behaviors seem to induce higher perceived stress (Barrington, 2012) Psychosocial stress is positively associated with body mass index gain (Harding et al., 2014)	Consider that people with high BMI could be more sensitive to acute stress (Barrington, 2012; Harding et al., 2014)
S_3 *VII*	Techno-complexity	Techno-complexity defines the inherent quality of an ITC, which drives employees to feel that their computer skills are inadequate. Symptomology is poor concentration, irritability, memory disturbances as well as exhaustion. Since VR at the workplace is new for most workers, it is reasonable to presume it could lead to techno-complexity stress. Workers will have to constantly learn how to use this ICT (Tarafdar et al., 2019). But coping with VR induced Techno-complexity results in stress responses at the occupational level (Dragano and Lunau, 2020; Tarafdar et al., 2020; Weinert et al., 2020)	Train workers correctly to in-VR tasks, virtual environment's interactions, and interfaces to prevent techno-complexity (Tarafdar et al., 2019)
S_4 *VI*	Techno-overload	Techno-overload defines "*simultaneous, different streams of information that increase the pace and volume of work*" (Atanasoff and Venable, 2017). Inside this techno-overload, the "information overload" dimension (Nisafani et al., 2020) could apply in the context of data analyses in VR. Since VR is new for most workers and implies side effects, we can predict a high demand psychologically and physiologically (Atanasoff and Venable, 2017; Zhao et al., 2020)	Adapt information streams to lower-down techno-overload and consider cybersickness, visual fatigue, and muscle fatigue to make more difficult application tools, thus, inducing stress (Atanasoff and Venable, 2017; Zhao et al., 2020)

The occurrence of acute stress and mental overload can be influenced by many further factors than those presented in our guidelines. Moreover, the factors and associated guidelines for all five VRISE are based on current knowledge. Further theoretical and experimental contributions are still needed to explain VRISE better by encompassing its inherent complexity. We must be aware that some factors are similar across VRISE (Souchet et al., 2022). We present them for each short-term VRISE to emphasize those similarities and better demonstrate confounding effects that remain to be addressed.

Some guidelines do not apply to all workers as we purposely selected only office-like tasks to contextualize our current contribution to the ergonomics of VR. However, very few existing works have been directed at tackling VRISE. Currently, the primary uses of VR lie in video games (entertainment in general) and training (see Cockburn et al., 2020). Consequently, our guidelines are sometimes based on observations, not directly on experiments using virtual environments for work or VR. Part of our guidelines still rests upon low evidence. Cybersickness is the VRISE with the most robust evidentiary basis. However, most meta-analyses, as well as systematic reviews, are founded upon questionnaire responses. Questionnaires appear to be the most utilized approach for all VRISE. Therefore, confidence in tested techniques to reduce VRISE relies, to the present time, less on objective measurements than might be preferred (Souchet et al., 2022).

Moreover, experimental quality and reproducibility need improvement in the VR field, which is valid for psychology and human-computer interaction in general (Chang et al., 2020; Petri et al., 2020; Gilbert et al., 2021; Halbig and Latoschik, 2021; Biener et al., 2022). Therefore, designers, employers, and workers should be cognizant that some factors tackled here and the associated guidelines are sometimes a direct transposition from the scientific literature that has not directly tackled VRISE or the work context. Such literature might suffer from shortcomings. However, it also means that part of the guidelines can be generalized to other contexts than work: i.e., entertainment

TABLE 14 Guidelines for possible software factors influencing acute stress.

ID_factor Evidence level	Software	Description	Guidelines
S_5 *V*	Time pressure	Time pressure defines an (Denovan and Dagnall, 2019): "*insufficient time available to complete necessary tasks.*" This insufficient time available is an individual perception of the amount of time necessary to fulfill a task (Ordóñez et al., 2015). It is a challenging stressor that can be coped via extra efforts, leading to strain and exhaustion (Prem et al., 2018). Time pressure can impact performance negatively to resolve math problems (Caviola et al., 2017). E.g., time pressure during investigations reduces the number of hypotheses tackled (Alison et al., 2013; Kim S. et al., 2020). Time pressure can be a stressor that impairs performances (less with procedural tasks) (McCoy et al., 2014; Prasad et al., 2020). It can impact response time, e.g.to make a decision (Korporaal et al., 2020). But, defining a deadline has a positive effect on decision-making. Taking decisions under time pressure is usually presented as having a negative impact (Ordóñez et al., 2015). Time pressure negatively impacts performance (Arora et al., 2010) and decision-making (Modi et al., 2020) See also MO_1	Extend time to fulfill a task in VR to avoid inducing stress and impacting work performances (Arora et al., 2010; McCoy et al., 2014; Prasad et al., 2020) Evaluate specifically how time pressure can benefit specific tasks in VR See also MO_1
S_6 *IV*	Task difficulty	Task difficulty, which encompasses multitasking, negatively influences task performances as it requires a higher mental load (de Dreu et al., 2019; Bretonnier et al., 2020; Modi et al., 2020) Difficulty can also enhance task performance or not change performance (Song et al., 2011; Main et al., 2017) Difficulty can be seen as a stressor (Atchley et al., 2017) Seel also MO_2	Reduce task difficulty in VR to prevent acute stress or frustration via dynamic adaptations to the user or helping agents (Gupta et al., 2020; Halbig and Latoschik, 2021) Seel also MO_2
S_7 *II*	Public speaking	Workers can suffer from public speaking anxiety, common in the general population (Ebrahimi et al., 2019; Marcel, 2019; Gallego et al., 2022). Public speaking induces acute stress, even in healthy adults without public speaking anxiety, and is used with the Trier Social Stress Test (TSST) to study stress in-lab (Allen et al., 2017; Labuschagne et al., 2019; Narvaez Linares et al., 2020). Immersive virtual environments replicating the TSST showed a higher cortisol reactivity than non-immersive (Helminen et al., 2019; Zimmer et al., 2019). Stress-induced with the TSST can impact decision-making (Pabst et al., 2013). Meetings can be in English, like in multinational corporations where workers present foreign language anxiety (Aichhorn and Puck, 2017; Kelsen, 2019; Kim et al., 2019). Presentations in front of peers, debating and, decision making can be seen as a stressor. It applies in VR (Barreda-Ángeles et al., 2020)	Adapt audience feedback to lower down speaking anxiety (Allen et al., 2017; Labuschagne et al., 2019; Narvaez Linares et al., 2020) Provide help in the interface to lower stress at public speaking, especially when using a second language
S_8 *VI*	Exposure to distressing material	Distressing materials are stressors that can lead to secondary traumatic stress (Perez et al., 2010; Holt and Blevins, 2011; Ludick and Figley, 2017; Molnar et al., 2017; Sprang et al., 2019). It seems legitimate to hypothesize that such induced stress could impair task performances while in VR. Proper training and desensitization with time may reduce risks for workers to present Secondary Traumatic Stress and cope with it: e.g. police workers (Perez et al., 2010; Fortune et al., 2017; Grant et al., 2019). However, while working in VR, distressing material might induce acute stress workers need to cope with while performing tasks	Allow users to control exposure to distressing materials by applying filters on images, videos (Perez et al., 2010)
S_9 *IV*	Noise	In an office, we can speculate the noise is intermittent (Reinten et al., 2017): speech, phones ringing, software sound design, typing, printing, and walking sounds. These noises contribute to stress at the workplace (Jahncke and Hallman, 2020). Background noise in an office and conversation ranges from 50 to 70 dB (Abouee-Mehrizi et al., 2020). Irrelevant speech noises to a given task and unpredictability impair task performance (Szalma and Hancock, 2011; Marsh et al., 2018; Vasilev et al., 2018). Noise contributes to distraction and disturbance (Vasilev et al., 2018; Abbasi et al., 2020; Jahncke and Hallman, 2020; Minutillo et al., 2021). Noise in a shared VR environment could distract and disturb work (Zeroth et al., 2019)	Create sound control options for users to create a quiet environment. Reduce interface sound feedback, other users' conversations in a collaborative environment (Zeroth et al., 2019)

and skills training. The median evidence level crystallizes this: five for cybersickness, four for visual fatigue, six for muscular fatigue, five for stress, and six for mental overload. We applied a scale from the medical field which hasn't been created for ergonomics issues, and proof that it is entirely relevant in this very case is low. Mainly because most scientific experiments in

TABLE 15 Guidelines for two possible factors influencing mental overload.

ID_factor Evidence level	Factor	Description	Guidelines
MO_1 *VII*	Time pressure	Time pressure is associated with a higher mental workload (Hendy et al., 1997; Wang et al., 2016) and negatively affects task performance (Palada et al., 2018; Rieger et al., 2021) See also S_5	Consider giving more time to fulfill tasks in VR than on PC Try to measure the ideal (required) time necessary for a task to avoid imposing irrelevant time pressure (Liu and Li, 2020) Give a deadline for a task See also S_5
MO_2 *V*	Task difficulty	See also S_6 Basic interactions and interfaces can influence task difficulty (Yan et al., 2017; Geiger et al., 2018; Speicher et al., 2018; Zielasko et al., 2019; Biener et al., 2020; Gao et al., 2021; Wagner et al., 2021; Wu et al., 2021). Spatialization within VR seems to reduce mental workload only if tasks require such cognitively-related resources (Filho et al., 2018, 2020; Wismer et al., 2018; Armougum et al., 2019; Bernard et al., 2019; Broucke and Deligiannis, 2019; Baceviciute et al., 2021) Multitasking (Ahmad et al., 2021), especially interruptions (Cheng et al., 2020; Mcmullan et al., 2021) impacts negatively performance due to higher mental workload. Incongruent (with the primary task) emails (Addas and Pinsonneault, 2018), notifications (Tan et al., 2020) distract users	Consider reducing tasks' difficulty by: Reducing multitasking (fewer notifications, no incongruent emails during a given task) and allow users to predict multitasking (Ewolds et al., 2021) Testing interactions and interfaces to make sure they do not require unnecessary working memory solicitations by using questionnaires such as the NASA-TLX (Hart and Staveland, 1988; Hart, 2006; Grier, 2015; Hertzum, 2021) can be used only using spatialized information and interaction if the tasks require it Provide virtual assistant, visual cues, and feedback on how users are fulfilling tasks and their mental workload to help them focus on the primary task (Weng et al., 2017; Borghouts et al., 2020) Consider adapting interactions and interfaces based on the user's characteristics or preferences (Chen et al., 2019) In collaboration requiring object localization by speaking, avoid the spatial configurations diagonally in front and behind speakers (Milleville-Pennel et al., 2020) Allow users to train enough at tasks, interactions, and interfaces See also S_6

VR very rarely follow a large multisite randomized controlled trial methodology.

One major limitation of this study is that we concentrated on short-term VRISE. However, working in VR implies daily use, and a pre-print (Biener et al., 2022) documented VR work for 1 week. VR appears to be worse than PC working. Cybersickness is a concern, and some participants even dropped out of the study. The advantages and disadvantages of VR's long-term use are yet to be drawn. Following the present guidelines might help foster advantages, but they cannot delete disadvantages.

Another major limitation of our contribution is the included papers. We stopped inclusion in the review with papers published in mid-2021. However, several relevant papers were published at the end of 2021, in 2022, and at the beginning of 2023. Those relevant publications include guidelines for each VRISE, side effects mitigation technics, prediction and detection of side effects. This fosters the need for the research community to critique and update these guidelines.

Future valuable contributions regarding VRISE factors and guidelines to reduce any such impacts include the following:

1) Increasing experimental contributions testing influences of each factor on VRISE with high-quality methods using within-subject, between-subject, and crossover designs,
2) Increasing considered VRISE to allow a better risk/benefit ratio consideration to use VR or not,
3) Increasing experimental contributions regarding tangles between VRISE,
4) Advancing automatic VRISE detection based on psychophysiological measurements,
5) Contributing to publications looking at the big picture of VR via systematic reviews and meta-analysis,
6) Updating the current guidelines with stronger evidence.

Although important to follow our guidelines, stakeholders should remain aware that current HMDs and virtual environments will most likely induce cybersickness, visual fatigue, muscle fatigue, acute stress, and mental overload. Currently, no existing method can fully alleviate these VR side effects. Therefore, detecting and adapting the virtual environment based on psychophysiological measurements (Smith and Du'Mont, 2009) could help better individualize and optimize the user experience. A better understanding of all VRISE risks will allow a benefit/risk ratio assessment to decide when to use virtual environments or not.

Author contributions

AS, DL, J-MB, and PH contributed to conception and design of the review. AS wrote the first draft of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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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.

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All it takes is empathy: how virtual reality perspective-taking influences intergroup attitudes and stereotypes

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Research in the past decade has demonstrated the potential of virtual reality perspective-taking (VRPT) to reduce bias against salient outgroups. In the perspective-taking literature, both affective and cognitive mechanisms have been theorized and identified as plausible pathways to prejudice reduction. Few studies have systematically compared affective and cognitive mediators, especially in relation to virtual reality, a medium posited to produce visceral, affective experiences. The present study seeks to extend current research on VRPT's mechanisms by comparing empathy (affective) and situational attributions (cognitive) as dual mediators influencing intergroup attitudes (affective) and stereotypes (cognitive). In a between-subjects experiment, 84 participants were randomly assigned to embody a VR ingroup or outgroup waiting staff at a local food establishment, interacting with an impolite ingroup customer. Results indicated that participants in the outgroup VRPT condition reported significantly more positive attitudes and stereotypes towards outgroup members than those in the ingroup VRPT condition. For both attitudes and stereotypes, empathy significantly mediated the effect of VRPT, but situational attributions did not. Findings from this research provide support for affect as a key component of virtual experiences and how they shape intergroup perceptions. Implications and directions for further research are discussed.

KEYWORDS

perspective-taking, intergroup attitudes, empathy, stereotypes, virtual reality

1. Introduction

Virtual reality (VR) has often been touted as an "empathy machine" (Bevan et al., 2019; Barbot and Kaufman, 2020; Hassan, 2020). Through avatar embodiment with visuo-motor synchrony in VR, the user perceives themselves as inhabiting the body of someone else, regardless of actual differences between the user and avatar (Yee and Bailenson, 2007; Tham et al., 2018). This process enables virtual reality perspective-taking (VRPT) (Herrera et al., 2018; Loon et al., 2018; Mado et al., 2021). VRPT of an avatar with a different salient identity from the player can lead to significant improvements in attitudes toward these identities—including Black people (Peck et al., 2013; Banakou et al., 2016; Behm-Morawitz et al., 2016), women (Lopez et al., 2019), the homeless (Herrera et al., 2018), and immigrants (Chen et al., 2021c). However, some studies found no effect on reducing bias against outgroups (Groom et al., 2009; Hasler et al., 2017). One reason for these inconsistent findings may be a limited understanding of the specific psychological mechanisms underlying the effects of VRPT, and how to best optimize these mechanisms for positive intergroup outcomes.

Theoretically, perspective-taking has both cognitive and affective mechanisms (Todd and Galinsky, 2014). Empirical studies comparing affective and cognitive mechanisms are somewhat inconsistent and have only been conducted in a non-VR context. Cognitively, perspective-taking has been found to subvert general attributional biases for behavior (Regan and Totten, 1975; Vescio et al., 2003; Hooper et al., 2015). In the intergroup context, people tend to attribute undesirable actions made by their ingroup to unstable, external factors and those made by an outgroup according to stable, internal traits (Pettigrew, 1979). Subverting this tendency, perspective-taking can encourage people to attend to context-specific, situational factors shaping outgroup behavior as they would do for their own ingroup (Todd et al., 2012). In a series of studies, Vescio et al. (2003) experimentally induced the non-VR perspective-taking of stigmatized group members and found that an increase in situational attributions for outgroup behavior positively mediated the effect of perspective-taking on affective attitudes toward the outgroup. To our knowledge, only one study has tested the role of behavioral attributions in the context of VRPT. Contrary to results found for non-VR perspective-taking, in this study, attributions did not explain the effect of VRPT on perceptions of a racial minority group (Chen et al., 2021b).

On the other hand, an affective mechanism, empathy, has been studied extensively as a link between perspective-taking and intergroup bias. Empathy has been identified as an outcome of both VRPT and non-VR perspective-taking (Decety, 2007; Shih et al., 2013; Herrera et al., 2018; Boehm, 2020). In a longitudinal study, Herrera et al. (2018) discovered that the VRPT of a homeless person induced greater empathy, more durable positive attitudes over time, and greater willingness to sign a petition supporting the homeless when compared against a less immersive non-VR perspective-taking manipulation. This study did not test the role of empathy as a mediator, however. Other studies found empathy to indeed mediate the effect of non-VR perspective-taking on intergroup perceptions (Batson et al., 1997; Vescio et al., 2003; Shih et al., 2009). However, Todd and Burgmer (2013) found that empathy did not mediate the effect of non-VR perspective-taking on implicit attitudes, although perspective-taking did lead to an overall increase in empathic arousal toward the outgroup.

One reason for these divergent findings on empathy and attributions may be how studies manipulate perspective-taking. Non-VR studies that found a mediating effect of empathy (e.g., Batson et al., 1997; Shih et al., 2009) asked participants to focus on how a member of stigmatized outgroup might be thinking or feeling, before presenting them with a narrative about this outgroup member (Batson et al., 1997). In contrast, Todd and Burgmer's (2013) manipulation did not provide relevant information about an outgroup member's hardships or struggles on the basis of their identity. The absence of information that typically warrants concern or compassion in this study may have weakened the inducement of empathy.

Furthermore, only one study thus far has directly compared empathy and attribution style as mediators for the same non-VR perspective-taking manipulation (Vescio et al., 2003). Vescio and colleagues found both mediators to be significant, and attributions had a stronger and more consistent mediating effect than empathy. This comparison, however, was primarily based on an assessment of which indirect effect size appeared larger, rather than a pairwise contrast analysis to ascertain whether one indirect effect was greater than another to a degree of statistical significance (Preacher and Hayes, 2008; Hayes, 2017). To the best of our knowledge, no studies have tested VRPT's influence on cognitive attribution style, nor statistically compared empathy and attribution style as mediators simultaneously in the relationship between VRPT and intergroup perceptions.

The present study aims to apply Vescio and colleagues' theoretical approach in a VRPT context by examining empathy and attribution style as dual mediators of the effect of VRPT on two commonly used measures of intergroup prejudice—attitudes (affective) and stereotypes (cognitive)—toward an immigrant outgroup. For parsimony, we use the term "attitudes" to refer to *affective* attitudes (i.e., feelings directed toward an outgroup) specifically throughout this paper, acknowledging that "attitudes" has been used to refer to both affective and behavioral aspects in past work.

Although other affective and cognitive mechanisms (e.g., self-other overlap) may contribute to the effects of VRPT, we focus on empathy and situational attributions primarily due to the precedent set by Vescio and colleagues, who did the same in a non-VR context, as well as our aim to test mechanisms that are sufficiently distinct from one another. There is some debate about whether self-other overlap, for example, closely overlaps with and may not be entirely distinct from certain facets of empathy (Preston and Hofelich, 2012). As such, comparing empathy with self-other overlap (instead of attribution style) as mediators may be less informative due to their relatively high amount of shared variance.

Aligning with past research, participants embodied a VR character, enabling perspective-taking of an outgroup immigrant who experiences a microaggression in their workplace. In the control condition, participants take the perspective of an ingroup character in the same scenario. We propose the following hypotheses:

> *H1*: VRPT of an outgroup character will lead to significantly more positive attitudes and stereotypes than VRPT of an ingroup character.
>
> *H2*: Affective empathy positively mediates the effect of VRPT of an outgroup character on attitudes and stereotypes.

Due to the lack of empirical evidence supporting the mediating role of situational attributions in the VRPT literature, we propose the following as research questions instead of hypotheses:

> *RQ1*: Do situational attributions mediate the effect of VRPT of an outgroup character on attitudes and stereotypes?
>
> *RQ2*: Are there significant differences between the indirect effects of outgroup VRPT via empathy and situational attributions on attitudes and stereotypes?

2. Materials and methods

2.1. Participants

A total of 84 Singaporean participants, with an age range of 19 to 33 years old, were recruited from a public autonomous research university in Singapore. The sample allows for 80% power to detect a both a significant medium-sized positive experimental effect

($f = 0.22$) and correlation ($r = 0.27$). Recruitment emails for participation were send out to a random selection of 15 student email lists provided by the university. All participants identified as being Singaporean Chinese, of whom 51 were female (60.7%) and 33 were male (33%). Participants were compensated with either course credit (for students) or SGD $10 gift cards. Prior to recruitment, this study received ethics approval from the Institutional Review Board of (university suppressed).

2.2. Design and procedure

This study featured a one-way between-subjects experimental design, in which participants were randomly assigned to take the perspective of either a Chinese immigrant from the People's Republic of China (PRC; outgroup VRPT, $n = 46$) or a Singaporean Chinese citizen (ingroup VRPT, $n = 38$) in VR. Recent studies have found that Chinese immigrants from PRC face significant prejudice in Singapore, and compared to other immigrant groups (e.g., Indians, Americans), are typically stereotyped to be the least warm and poses the greatest symbolic threat (Ramsay and Pang, 2017; Chen et al., 2021a). Despite sharing ethnic lineage with the Chinese-majority demographic of Singapore, PRC Chinese are often viewed to have a less modern culture than Singaporeans and do not speak English well (Ang, 2018).

The VR environment used was a lunchtime food court simulation. The participant embodied a waiting staff with the first-person viewpoint, using an HTC Vive headset. The interaction in VR environment is done through voiceover and in English. A voiceover narration, recorded by a native North American speaker, guided participants through 3 scenes. The English accents of the embodied VR characters and NPCs were matched with their nationalities and were different from the narrator's accent. The first scene aimed to enhance embodiment. Participants started in a room facing a mirror to establish familiarity with their avatar and visuo-motor synchrony. They were able to see their face and body while interacting with the VR environment. Participants were instructed to interact with their character's belongings in front of them, which included a Singaporean citizen's identity card in the ingroup VRPT condition, or a foreign worker's identity card in the outgroup VRPT condition.

In the second scene, participants were tasked with serving incoming customers by taking orders and interacting with ingredients placed on the cooking counter. The food court was crowded and the various customer NPCs' ethnicities reflected a typical lunchtime crowd in Singapore. In both conditions, the narrator prefaced that the participant's character is fluent in Mandarin Chinese, but may struggle to understand complex orders in English. Participants then encountered one irritable non-playable character (NPC) customer, whose order their character failed to understand initially. The NPC customer was a Singaporean Chinese female and her voice exhibited frustration toward the participant in both conditions.

In the final scene, while tasked with cleaning tables, participants received a phone call from their child—who either had a PRC Chinese accent (outgroup VRPT condition) or a Singaporean Chinese accent (ingroup VRPT condition)—requesting money for a school trip. This scene was designed to highlight the struggles faced by the participant's character in financing their child's education.

2.3. Measures

Participants completed a pre-VR and post-VR questionnaire that captured their stereotypes and attitudes toward the immigrant outgroup (PRC Chinese). Attributions and empathy were only measured in the post-VR questionnaire.

2.3.1. Attitudes

Attitudes were measured both pre- and post-VR using an affective feeling thermometer scale (Alwin, 1997). Participants were asked to "indicate their attitudes towards PRC Chinese" across three dimensions: "cold (1)…warm (100)," "unfavorable (1)…favorable (100)," and "negative (1)…positive (100)." A higher score on the scale indicates more positive attitudes toward the outgroup (pre-VR: $M = 56.08$, SD = 20.99, Cronbach's alpha = 0.92; post-VR: $M = 61.33$, SD = 20.54, Cronbach's alpha = 0.95).

2.3.2. Stereotypes

A series of semantic differential items (Osgood et al., 1975) measured the valence of participants' stereotypical beliefs about the outgroup in both pre- and post-VR questionnaires. Each item presented two opposing adjectives, on each side of a 7-point Likert-type scale. Items included "rude (1)…polite (7)" and "dishonest (1)…honest (7)." A higher score on the scale indicates less negative stereotyping (pre-VR: $M = 3.79$, SD = 0.99, Cronbach's alpha = 0.87; post-VR: $M = 4.18$, SD = 0.98, Cronbach's alpha = 0.90).

2.3.3. Situational attributions

In the post-VR questionnaire, a series of bipolar scale items adapted from Miller et al. (1981) asked participants to rate how natural it is for PRC Chinese to engage in negative or undesirable behaviors on a 7-point Likert-type scale. Items included "rude by nature (1)…rude only when the situation calls for it (7)" and "inherently quarrelsome (1)…quarrelsome only when they have to be." A higher score on this scale suggests more situational, versus dispositional, attributions made about negative outgroup behavior ($M = 5.93$, SD = 1.03, Cronbach's alpha = 0.82).

2.3.4. Affective empathy

In the post-VR questionnaire, participants indicated their level of agreement with three items adapted from Davis (1980) interpersonal reactivity index. These items assessed affective empathy toward the outgroup following VRPT, including items such as "I felt compassion for the Chinese PRC," "I felt sorry for the Chinese PRC," and "I felt protective towards the Chinese PRC" ($M = 4.52$, SD = 1.74, Cronbach's alpha = 0.91).

2.3.5. Manipulation check

To ensure that participants were cognizant of which characters they played in the VR scenario, the post-VR questionnaire asked participants to report the correct group identity of the character they embodied—the Singaporean Chinese, or the PRC Chinese. Those in the ingroup VRPT condition were significantly more likely than those in the outgroup VRPT condition to correctly report embodying the ingroup character, X^2 (1, 84) = 80.05, $p = 0.000$.

Correlations between all variables are presented in Table 1.

TABLE 1 Descriptive statistics, reliability, and correlations between all measured variables.

	M	SD	*α*	1	2	3	4	5	6
Pre-VR									
1. Attitudes	56.09	20.99	0.92	1					
2. Stereotypes	3.79	0.99	0.87	0.58**	1				
Post-VR									
3. Attitudes	61.33	20.54	0.95	0.79**	0.51**	1			
4. Stereotypes	4.18	0.98	0.90	0.42*	0.67**	0.63**	1		
5. Empathy	4.52	1.74	0.91	0.19	0.14	0.42**	0.38**	1	
6. Attributions	5.93	1.03	0.82	0.35**	0.54**	0.39**	0.59**	0.23*	1

M, mean; SD, standard deviation; α, Cronbach's alpha. *$p < 0.05$; **$p < 0.01$.

3. Results

Two between-subjects ANCOVA tests with a Bonferroni post-hoc correction were conducted to assess the effect of outgroup embodiment on both attitudes and stereotypes (taken from the post-VR questionnaire), controlling for baseline measures (recorded in the pre-VR questionnaire). Conventions in pre-post experimental designs suggest that an ANCOVA testing experimental effects on post-test measures, while adjusting for pre-test measures, typically leads to the most unbiased estimates when compared to alternative approaches (e.g., ANOVA on just post-test measures, repeated-measures ANOVA to estimate an effect on changes from pre- to post-test (O'Connell et al., 2017)). An ANCOVA on post-test scores also affords greater power in randomized experimental studies than a repeated-measures ANOVA assessing a change in scores over time (Van Breukelen, 2006). By controlling for pre-VR baseline scores, we are able to rule out the possibility that observed differences of our VRPT manipulation are due to baseline differences in prejudice.

As predicted by H1, VRPT of an outgroup led to both significantly more positive feeling thermometer scores, $F(1, 81) = 7.89$, $M_{\text{diff}} = 7.58$, SE = 2.67, $p = 0.006$, (2.21, 12.96), $\eta_p^2 = 0.09$, and stereotypes directed towards the outgroup, $F(1, 81) = 8.12$, $M_{\text{diff}} = 0.45$, SE = 0.16, $p = 0.006$, (0.13, 0.76), $\eta_p^2 = 0.09$.

Prior to conducting our primary mediation model, we first tested whether the VRPT manipulation had significant effects on empathy and situational attributions in separate *t*-tests. Compared to participants in the control condition, participants exposed to the VRPT manipulation reported higher levels of empathy for the PRC Chinese, $t(82) = 7.30$, $M_{\text{diff}} = 2.20$, SE = 0.30, $p = 0.000$, but did not make significantly more situational attributions for negative PRC Chinese behavior, $t(82) = 0.16$, $M_{\text{diff}} = 0.04$, SE = 0.23, $p = 0.87$.

To test our main hypotheses and research questions, we conducted parallel mediation analyses using PROCESS (Hayes, 2017) Model 4 on SPSS v24 with 5,000 bootstraps to compare how affective empathy and situational attributions mediate the effect of VRPT on both attitudes and stereotypes. Baseline scores for each dependent variable were set as covariates to examine the effect of the VRPT manipulation and our proposed mediators independent of baseline prejudice. To assess the statistical difference between two parallel mediators, we utilized (Hayes, 2017) normal theory approach that constructs a bootstrapped 95% confidence interval around the estimated difference between two indirect effects.

The overall model predicting feeling thermometer scores was significant, $F(4, 79) = 44.90$, $R^2 = 0.69$, $p = 0.000$. The total effect of VRPT was significant, $b = 7.58$, SE = 2.70, $t(82) = 2.81$, $p = 0.006$, (2.21, 12.96), and this effect was primarily driven by the indirect effects in the model, as the direct effect of the manipulation was not significant, $b = 1.18$, SE = 3.38, $t(82) = 0.35$, $p = 0.73$, (7.92, 0.58). Supporting H2, empathy produced a significant positive indirect effect, as the bootstrapped confidence interval included zero, $b = 5.47$, SE = 2.31, (1.20, 10.35), but the same effect was not found for situational attributions, $b = 0.16$, SE = 0.44, (−0.66, 1.13) (see Figure 1). A contrast analysis also revealed that empathy had a significantly greater indirect effect on feeling thermometer scores than situational attributions, $b_{\text{diff}} = 0.26$, SE = 0.11, (0.05, 0.49).

The model predicting semantic-differential stereotypes was also significant, $F(4, 79) = 26.03$, $R^2 = 0.57$, $p = 0.000$. The total effect of outgroup VRPT was significant, $b = 0.45$, SE = 0.16, t = 2.85, $p = 0.006$, (0.13, 0.76), including a non-significant direct effect, $b = 0.18$, SE = 0.19, $t(82) = 0.98$, $p = 0.329$, (−0.19, 0.56) and a significant positive indirect effect of empathy, $b = 0.24$, SE = 0.11, (0.02, 0.47), supporting H2. The indirect effect of situational attributions was not significant, $b = 0.02$, SE = 0.06, (−0.07, 0.15) (see Figure 2), and empathy produced a significantly greater indirect effect on stereotypes than attributions, $b_{\text{diff}} = 0.21$, SE = 0.11, (0.01, 0.44).

4. Discussion

The results extended literature on perspective-taking (Peck et al., 2013; Banakou et al., 2016; Chen et al., 2021c) by comparing the affective and cognitive mediators underlying VRPT's effect on prejudice. It was found that VRPT of an immigrant outgroup, when compared to VRPT of one's ingroup, contributes to improved attitudes and reduced negative stereotypes toward the outgroup (supporting H1). Specifically, the effect of VRPT on both attitudes and stereotypes was positively mediated by feelings of empathy toward the outgroup character (supporting H2). Affective appeals are effective in tackling biases rooted in both affect and cognition (Edwards, 1990). Perspective-taking of an outgroup character in distress may trigger the affective experience of experiencing another's struggles as if it they were one's own. These findings are in line with previous studies on non-VR perspective-taking. For example, Dovidio et al. (2004) found, among a host of affective and cognitive variables, that parallel empathy—shared feelings of anger and injustice with a victimized target—to be the only significant mediator influencing racial attitudes. They did not test situational attributions as a mediating variable.

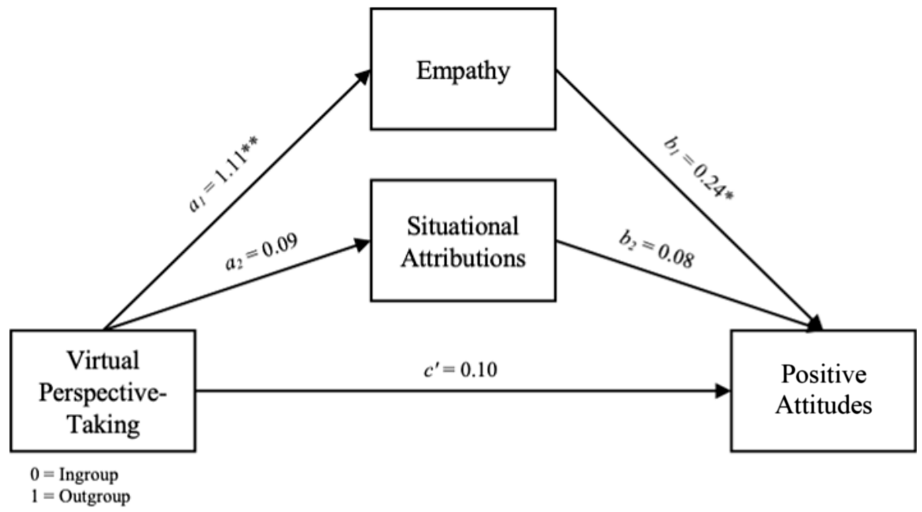

FIGURE 1
Parallel mediation model on positive attitudes toward the outgroup.

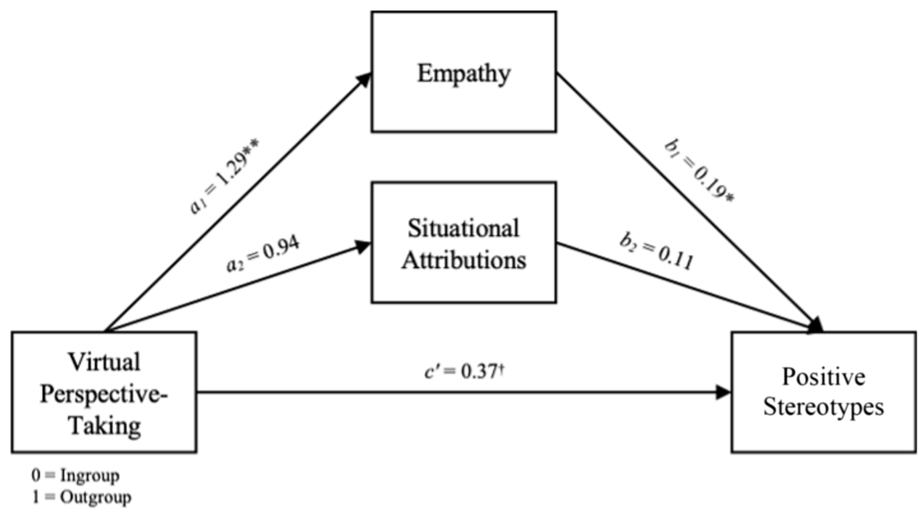

FIGURE 2
Parallel mediation model on positive stereotypes toward the outgroup.

To the best of our knowledge, this study provides the first empirical test of empathy and situational attributions as dual mediators of VRPT's effect on measures of prejudice. In an earlier study that compared cognitive and affective mechanisms underlying VRPT (Chen et al., 2021b), participants were randomly assigned to focus on their own emotions (affective perspective-taking) or thoughts (cognitive perspective-taking) when embodying an ethnic minority avatar in VR. In this case, situational attributions did not mediate the effect of cognitive perspective-taking on attitudes toward the minority outgroup. The present study advances this approach by testing both empathy and situational attributions as potential mediators of the *same* VRPT manipulation. Responding to RQ1, we found that situational attributions did not mediate the effect of outgroup VRPT on either attitudes or stereotypes.

It is possible that the act of perspective-taking, regardless of the group target, was sufficient to "train" a general situational focus when explaining others' behavior, thus producing minimal differences in attribution levels between the two conditions. The average degree of situational attributions made about outgroup behavior in both the ingroup VRPT ($M = 5.91$, $SD = 5.94$) and outgroup VRPT conditions ($M = 5.95$, $SD = 1.08$) was relatively high, more than two scale points higher than the midpoint of 3.5. Perspective-taking may have led to transfer effects, where greater attentiveness to situational cues may have extended from one target group to another (Vezzali and Giovannini, 2012; Lolliot et al., 2013). Indeed, applying thinking patterns or skills learned in one context to another is an active, cognitive process, rather than an automatic one (Wright et al., 2008). Thus, the cognitive processes triggered by perspective-taking may have encouraged a situational attribution style more generally, regardless of target group identity. In contrast, the automatic processes underlying affective empathy may be target-specific. Further research should unpack these divergent affective and cognitive mechanisms, and whether they can be generalized beyond a specific target group (Mado et al., 2021). In response to RQ2, an analysis of pairwise comparisons showed that the indirect effect of empathy on attitudes was significantly greater than that of situational attributions. This study provides further empirical support for the role of affective perspective-taking mechanisms.

Notably, our findings diverge from Vescio et al. (2003) study, which not only found significant mediating effects for both empathy and situational attributions in a non-VR context, but also found situational attributions to carry the stronger effect. These differences may be due to the *medium* of perspective-taking. While non-VR perspective-taking manipulations require participants to actively imagine what another person might be thinking or feeling, VR's immersive affordances and ability to viscerally showcase affective stimuli may preclude the need for this level of effortful cognition (Shin, 2018). A meta-analysis of 43 experiments found that VR is effective in inducing feelings of compassion or concern for others. However, VR is less effective in inducing the cognitive component—the acknowledgment of another person's thoughts or feelings (Martingano et al., 2021). While affective empathy can be induced automatically and spontaneously through evocative stimuli (Neumann and Strack, 2000; Yu and Chou, 2018), cognition requires more active attention and mentalizing (Gilovich et al., 2000; Roßnagel, 2000). As such, by providing users with vivid sensory experiences that leave little room for imagination, VRPT may more effectively tap into the automatic processes constituting affective empathy. Additionally, VRPT may effectively "do all the work" for participants—by literally putting participants in the perspective of another, VRPT precludes any cognitive effort. Conversely, providing perspective-takers with a less immersive stimulus—such as a written testimonial or narrative (Vescio et al., 2003; Batson et al., 2016), may require more deliberate cognitive engagement, including shifts in attribution style.

This study offers important theoretical insights into the competing mechanisms of VRPT in shaping prejudice, but it is not without design limitations. The absence of a "true control" where no perspective-taking took place makes it difficult to compare findings with non-VR perspective-taking studies. Future experimental replications should include a non-perspective-taking condition single out latent effects of VRPT on attribution style. Furthermore, while empathy and attributions feature prominently in the literature on perspective-taking and intergroup biases, other affective and cognitive mediators may be considered for a fuller picture (Dovidio et al., 2004). Follow-up studies with a more robust sample size may test the relative indirect effects of other variables such as the well-studied concept of self-other overlap and cognitive empathy. To empirically test the importance of a perspective-taking medium, the direct and indirect effects of outgroup VRPT on intergroup bias should also be directly compared against those of non-VR perspective-taking, where an outgroup viewpoint is imagined.

Although we were sufficiently powered to detect a moderate experimental effect, the lack of power to detect a small effect may have hindered our ability to detect a significant indirect effect of VRPT via a shift in attributions. Our sample was also limited to a student population, and further research should test how this model generalizes to a more diverse sample of participants.

Lastly, we acknowledge that the self-evaluative measures used to capture prejudice are limited due to social desirability concerns, and may not necessarily inform intergroup behaviors and outcomes (Brauer, 2023). Although self-report measures capture specific facets of prejudice and intergroup emotions in the most face-valid manner, future work could triangulate these measures with physiological metrics. One study, for example, measured alertness toward stereotypical vs. non-stereotypical portrayals of different ethnic groups in VR using an electroencephalogram (EEG) (D'Errico et al., 2020). Another aspect that can contribute insights to the field is the nonverbal aspect of participants' reactions, which were not measured in the current study. Bodily movements and expressions are key signals of emotion (Reed et al., 2020). VR researchers could benefit from coding non-verbal emotion expressions of empathy during VRPT experiences to provide convergent evidence for the influence of VRPT on prosocial emotions. To further understand how emotions are communicated during VR experience, future research should also consider the works on multimodality of communication (Mehu and van der Maaten, 2014). Recording the bodily reactions of the participants in terms of agreement and disagreement can be used to triangulate with self-report measures (Poggi et al., 2011) in order to provide robust research findings.

Data availability statement

The datasets presented in this article are not readily available because it is restricted by the grantor. Requests to access the datasets should be directed to chenhh@ntu.edu.sg.

Ethics statement

The studies involving humans were approved by NTU-Institutional Review Board. 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.

Author contributions

VC: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Writing–review & editing, Writing–original draft. GI: Methodology, Writing–original draft, Writing–review & 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.

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Virtual fashion experiences in virtual reality fashion show spaces

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Introduction: Virtual reality (VR) provides a new fashion space and fashion experience. This study focuses on immersive VR and fashion shows to empirically explore the VR fashion space and fashion experience. Insights specific to fashion have not been presented in as much depth in the literature; thus, the current findings are particularly valuable and insightful.

Methods: This study employed three immersive VR (IVR) fashion show stimuli and in-depth interviews according to a semi-structured questionnaire. Collected data were analyzed based on the concept of VR space and VR experience derived through literature research.

Results: The VR fashion space was divided into three types and VR experiences of cognitive presence, sensible immersion, emotional immersion, and aesthetic interaction were derived accordingly. First, the physical representation of a fashion show induced a cognitive and emotional sense of presence, in which users felt as though they had moved to the same time and place as those at the fashion show. Second, participants experienced cognitive confusion owing to the differences with *a priori* experiences in the fashion show space (i.e., reality and imagination coexist). Third, participants transcended the limitations of physical reality while in the fashion show space of pataphysics (which was realized with human imagination), and they moved beyond the stage of confusion that is experienced while facing realistic objects to connect to creative inspiration.

Discussion: The difference in the properties of VR space may be associated with distinct VR fashion experiences. The findings suggest that (1) *a priori* elements such as sociocultural contexts and personal experiences differ in the experiential dimension of virtual space, (2) the VR fashion show space induces a psychological experience between brand and consumer, and (3) creative inspiration and exploratory play can be greatly induced in a user if the immersive fashion space is further from the original source.

KEYWORDS

virtual fashion experience, fashion show, virtual fashion space, cognitive presence, sensible immersion, emotional immersion, aesthetic interaction

1 Introduction

Humans accumulate experience when interacting with space, which is a medium through which the world is perceived (Tuan, 2011). Space is signified through dynamic interrelationships between itself and the various elements that constitute it (Lefebvre, 1991). As space is not just a static, physical background, attention needs to be paid to its active aspects.

Virtual reality (VR) spaces provide humans with virtual spaces, with social functions that are similar to space in reality (Barreda-Ángeles and Hartmann, 2022). For example, VR can facilitate social interactions between people who are geographically distant, enabling collaboration. Humans accumulate novel experiences in this new space. A VR space can provide an environment that is either similar to reality or one that is completely new. The space allows users to feel an immediate sense of immersion, even more so than the sense of presence in the real world and physical reality, and this virtual human experience is real (Pelet et al., 2017). Therefore, the experiential impact that the new digital environment has on humans needs to be determined.

VR affects fashion shows, which are a site for the presentation of fashion and serve as a means of communication between fashion brands and audiences. Space has not been given the same consideration as clothes vis-à-vis fashion shows. Yet, fashion shows cannot be held without space. It is an important component in developing and conveying the concept and image of a fashion collection (Mendes, 2019). Various places have been used effectively to convey the fashion show's image and concept (Strömberg, 2019). VR technology allows users to access fashion shows at any time and from any place. Advances in communication infrastructure such as the Internet of Things and 5G technology support this, and a Metaverse world that can be accessed from anywhere in the world is opening up. VR spaces based on the properties of digital media share the characteristics of imagined and physical images (Wideström, 2019). They transcend regional, cultural, and temporal boundaries and have unique spatial characteristics that cannot be experienced in a physical space. Thus, VR fashion show spaces can affect the fashion experiences of users.

Fashion studies have focused on topics such as the use of virtual environment technology in the development of fashion stores and designs and the effect they have on user experience. Park et al. (2018) showed that VR fashion stores have a positive impact on users' shopping behavior vis-à-vis enjoyment and purchase intention. Sina and Wu (2023) revealed that the appropriate use of design elements in VR fashion stores leads to high results regarding consumers' emotions, perceptions, and satisfaction levels. Lighting color and color temperature in a 360-degree VR space are also related to consumers' shopping motivation. Jung et al. (2021) noted that expanding the experience of a luxury fashion show (which had been allowed to a small, limited audience previously) to the public would popularize luxury items.

These findings are significant as they suggest that human perception and experience of the fashion industry can be affected by the relevant VR technology. However, a fashion show differs from a fashion store with regards to purpose, content, and experience. Fashion shows provide fashion images, communication, and entertainment. VR fashion show spaces allow various interactions between brands, designers, and users to create new meaning for fashion shows and novel fashion experiences. Therefore, investigating such content is meaningful as it will expand on previous studies to present a new perspective.

This study focused on immersive VR environments and students majoring in fashion. Immersive VR (IVR) uses wearable devices such as head-mounted displays (HMDs; Shahrbanian et al., 2012). Ricci et al. (2023) noted that IVR was associated with higher hedonic and utilitarian values, and better user experience when compared to general VR. IVR provides higher levels of sense of presence, immersion, and emotion than does general VR (Kerrebroeck et al., 2017). The experiential dimension could differ based on user characteristics; users with higher levels of openness to experience (Costa and McCrae, 1997; which is a prominent characteristic of artists) experience a deeper aesthetic experience through the sense of presence in VR (Starkey et al., 2021). Therefore, fashion students are required to have emotional and sensory experiences that will enhance their IVR experiences compared to general students.

This study investigated users' fashion experiences in IVR fashion show spaces, in which VR and an HMD are used. VR fashion show spaces refer to the virtual realm in which fashion shows are conducted using IVR technology. This study explored the following research questions: First, how are VR spaces and experiences defined? Second, what kind of fashion experiences do users have in VR fashion shows? A framework of analysis was prepared through a literature review for research question 1. For research question 2, in-depth interviews were conducted with undergraduate fashion students with higher levels of immersion to analyze users' virtual fashion experiences through VR fashion shows.

2 Literature review

2.1 The VR space as an experience-creating medium

2.1.1 Perspectives and characteristics of space

Space is the realm or world in which certain substances and objects can exist or events can occur and is simultaneously universal and abstract. It is a medium that defines human thoughts and forms individuals' unique experiences (Buttimer and Seamon, 2015). Space is formed in the relationship between an object and the human who perceives and recognizes it (Ashihara, 1981).

Experiences are formed during a human's interactions with a given space. This sociological approach to space explains the interactions between people, space, and human behavior rather than focusing on the meaning of physical backgrounds. This approach is useful in establishing a conceptual framework to unpack human experiences in VR space.

There are many discussions on space from a sociological perspective. The first is the space of physical interactivity. Space is not an abstract entity that is distinct from the objects existing within it; it can only be understood through concrete events or objects (Choi, 2016). Löw and Weidenhaus (2017) defined space as a relational arrangement of social goods and living beings existing in places. Space does not exist independently. It is formed by exchanges that take place among the sociocultural background, and the actors and products within it. Therefore, space is created by social institutions and actors and cannot exist independently from these elements. Simmel (2005) paid attention to the kinds of spatial experiences that people undergo in a city, and the cognitive functions that take place, and found that the meaning of space is created, and interactions are amplified through human engagement. Space is nothing in itself but becomes full through interactions and gains meaning vis-à-vis individuals and social groups (Schroer, 2010).

The second is the space of fluidity and dynamism. Modern society is flexible and fluid because of its fast pace and advancements in information technology. Bauman (2005) distinguished this from the solidity of the modern era and described the spatial characteristics of modern society as being liquid. He considered a city an intensely liquid space that is not fixed in one space and is consistently moving owing to the loose solidarity between the individualized elements constituting the liquid. Advancements in information technology cause changes in social patterns and create new spatial logics called the Space of Flow (space–time created by the fluidity of changes among social institutions, cultures, and members; Castells, 2010). Therefore, space is not fixed and eternal, but rather expands, integrates, and fractures in its relationship with changing social institutions, cultural contexts, and members.

The third is the space of symbolism. Foucault presented the concept of heterotopia; for example, everyday spaces such as public baths, prisons, and colonies embody either deviant ideals within the institutions of modern society or incompatible utopian concepts (Foucault, 1967). This interpretation disproves the idea that space has a symbolic meaning. Lefebvre (1991) considered space a social product and stated that it can control or influence human consciousness and behavior. The framework of social space was based on trialectics, which includes representations of space as perceived through human activities, cognitive space such as lifestyles, and space of representations that is experienced with a combination of symbols and images (Lefebvre, 1991). It is a view of space as a social product and its representation differs from the second perspective in terms of the formative identity of space. Soja (1989) stated that space is formed as material spatial practices that reproduce the actual form and concrete patterns of lifestyles, which are transformed into an imaginary conceived space that becomes conceptual and is expressed symbolically, changing into a lived space that is structured by the experiences of individuals or groups. These discussions suggest that space is created by humans, the agents of action, and can be symbolically realized through interactions with social institutions. Thus, space is a result of human interaction and a social construct.

Accordingly, this study approaches the spatial characteristics of VR space by considering the properties of digital space in the next chapter based on the three perspectives regarding the concept of space.

2.1.2 Approach to fashion shows and VR spaces

By reviewing previous studies on digital media spaces (Choi and Park, 2019; Suh, 2020) to determine their characteristics, this study identified the following: ambiguity and extensibility of space–time boundaries; complexity and flexibility of information; virtuality of reality; interactions that enable two-way communication between information providers and users; and ease of access to information. These characteristics are classified as follows by comprehensively considering the properties of space examined earlier (Table 1).

First, the space of physical representation is the space in which the real world's physical appearance is projected and reconstructed. Although VR space is artificial, it is reproduced by reflecting reality (Lombard et al., 2006; Deng et al., 2019). New media interacts with old media (Bolter and Grusin, 2000). Second, the mixed space of reality and imagination is the space in which reality and virtuality coexist, which is characterized by the flexibility and dynamism of information, and in which space and time are not clearly separated. Modern space has a complex and fluid character and breaks away from the existing fixed concept of space and time owing to the rapid exchange of information and advances in the media (Bauman, 2005). Digital media spaces are characterized by a property of variability that differs from physical space and old media (Manovich, 2001). Therefore, the VR space has a mixed character that encompasses all these properties, in which reality and virtuality coexist owing to the variability and fluidity of digital images. For example, while components of the traditional fashion show reproduce the space–time of reality in the VR space, they construct a new fashion show space by creating an ideal object or by transforming the existing appearance. Third, the space of pataphysics is based on symbolic creation. The term pataphysics was proposed by Alfred Jarry and refers to an area of study that extends beyond metaphysics, and to the virtual nature of things based on imagination (Bok, 2002). Space in pataphysics cannot exist in reality but is realistically created by human imagination. Modern society is a world of simulacra in which reality has been replaced by symbols (Baudrillard, 1994). This VR space is the space of symbolic ideals in which symbolic objects are realized without material substance. The spatial characteristics of pataphysics are significant in the image-oriented fashion industry as they can express images that designers want to convey without limitations and communicate with users.

2.2 VR experience

Humans accumulate new experiences by interacting with various elements surrounding digital media. For example, digital images have a color range different with nature, which means it gives humans supernormal stimulation. VR technology also provides opportunities to travel to outer space and other places. As an example of VR fashion show, the 21FW Balenciaga collection—set in universe and in the form of a 3D virtual video game—was presented and audiences could easily access it anytime, anywhere.

The VR resulting from digital media is a 3D environment that is reproduced to enable physical experiences as in the real world. In the VR space, users can navigate the space as they do in real life, interact with objects, and experience one or more of their five senses being stimulated in real time (Burdea and Coiffet, 2003). While more recent studies (Freeman et al., 2019; Rathinam et al., 2019) have focused on the possibility of VR technology to help human psychological treatment and physical rehabilitation, there is a lack of research that identifies emotional and aesthetic experiences, especially in fashion

TABLE 1 The characteristics of VR space.

Social space	Digital media space	VR space
Physical interaction	- Interaction - Ease of access	Space of physical representation
Fluidity and dynamism	- Complexity and flexibility of information - Ambiguity and extensibility of space-time boundaries	Mixed space of reality and idea
Symbolism	Virtuality	Space of pataphysics

studies, regarding the circumstances of the advanced IVR environment.

Thus, this study explored the virtual fashion experience through the concept of space and virtual experience. For this, a framework was built through a literature review about the concept of space as its focus, previous studies on the relationship between brands and users, and relevant studies on VR experiences, summarizing the results (Table 2).

2.2.1 Cognitive presence

The sense of presence refers to the psychological experience of feeling as though you are in a specific space in the virtual world or perceiving created objects, people, and events as being real (Lombard et al., 2006). The sense of presence can be divided according to the degree of interaction between the user and virtual space and media. Among the subdivisions, the cognitive sense of presence refers to the experience of perceptual illusion, in which the user mistakenly feels as though it is a real physical environment or object owing to the physical stimulations provided by digital media. This is a cognitive experience in which the user feels they are physically present in a specific space and perceives various information through sensory stimulations (Biocca and Levy, 2000); the cognitive sense of presence causes a user to experience place illusion, in which they feel as though they are in a specific place by experiencing the virtual space even though they are not actually present (Slater, 2009).

As a sense of presence is based on sensory information, it increases when the media provides more detailed and elaborate information as if in real life (Lombard and Ditton, 1997). It is classified as the characteristics of media systems that generate a sense of presence concerning vividness and interactivity (Steuer, 1992). If high and intense levels of sensory information are acquired in the VR space, it causes high levels of vividness (Li et al., 2002). Interactivity refers to the degree to which a user can affect the content and form of a mediated environment in real time, and it is determined by the speed at which user inputs are reflected, as well as their range, and how natural the mapping is (Steuer, 1992). For example, naturalness in a VR environment is related to high fidelity and it enhances the sense of presence (McMahan et al., 2012). Therefore, interactivity can be increased by high levels of fidelity in the VR space, in which elaborate, realistic, and sensory expressions are possible.

Although not much research on the effect of interaction in the VR space exists, there have been some studies on VR related to sports (Sigrist et al., 2015; Vogt et al., 2015). According to them, the sense of presence is related to the electroencephalogram and was highest in the interactive VR condition, showing that interactive VR produces physical performance in a highly competitive spirit. However, the impact of the high fidelity of VR fashion presentation and user experience has not been proven yet.

2.2.2 Sensible immersion

Immersion refers to the state in which the user's perceptual and psychological awareness are almost completely cut off from the outside world while participating in VR, and the pleasurable experience of being transported to an elaborately simulated place, alongside the sensory, emotional experience of being surrounded by a completely different reality that takes over their attention and sense organs (Murray, 1997). It is the flow that is experienced owing to external stimuli, and it is primarily used to describe the experience of using VR devices (Cheng et al., 2017). This study examined the characteristics of immersion by distinguishing between sensory and emotional immersion. Sensory immersion refers to the range of sensory channels involved in virtual simulation (Kim and Biocca, 2018). Using purely sensory receptors such as one's sight and hearing to acquire information also increases the immersion effect when compared to using one type of sensory channel. It can further focus on the sensory properties of the garment as an object. Thus, this study aimed to determine whether users obtain tactile effects in non-contact situations of VR.

2.2.3 Emotional immersion

Emotion is a personal response to internal or external stimuli that is caused by a somewhat specific cause or event; it provides information on a specific object or situation (Payne and Cooper, 2001). Sensory organs sense external stimuli and the sensed information is transmitted to the brain, which undergoes mental processes called emotions and reactions. The implicit memories of a person, psychological experiences, feelings that are expressed as emotions through external physical stimuli, and the resulting high-level emotional responses are sensibilities (Han and Choi, 2020). A user can experience human senses and emotions through the VR space, without directly induced stimuli and events, which is the plausibility illusion (Slater, 2009). Although sensibilities and emotions can be discussed separately, this study uses the term emotion to collectively define psychological responses that are distinct from perception. Users of the VR space experience emotional immersion through objects and emotions such as joy and sadness (Han and Choi, 2020).

Emotional immersion is closely related to sensory experience. The sense of space and distance are related to creating emotional experiences in themselves (Diemer et al., 2015; Peperkorn et al., 2015). Facial expressions are effective in inducing emotions (Han, 2018), and

TABLE 2 The dimension of VR experience in VR space.

Brand experience	VR experience		VR experience in VR space
Perception	Presence	Authenticity	Cognitive presence
Sense	Immersion		Sensible immersion
Emotion		Interaction	Emotional immersion
Behavior	Emotion Simulation		Aesthetic interaction

the hyper-realistic expression of digital humans in virtual space induces interest and pleasure; through this satisfaction, the level of immersion increases owing to intrinsic rewards and the sense of self-achievement, even if there are no special goals or extrinsic rewards (Kim and Seo, 2017).

Thus, visual expressions bring about emotional immersion. In fashion presentations, emotional communication such as fashion images is important. This study revealed how users gain virtual fashion experiences through the emotional immersion provided by the IVR environment.

2.2.4 Aesthetic interaction

The aesthetic experience refers to an attitude, perception, experience, or interest related to art appreciation (Wanzer et al., 2020). "Aesthetic" refers to a sensory experience that is related to the visual form, texture, harmony, order, and beauty of an artifact (Venkatesh and Meamber, 2008), and is an ideal experience characterized by an aesthetic quality that is distinct from everyday experiences (Marković, 2012). This experience arises from the dynamic interactions between the perceptions of objects and processing of perceived information and is formed with the addition of judgment and evaluation (Venkatesh et al., 2010). It is influenced by culture, reference groups, and personal taste (McCracken, 2005).

Aesthetic experience is not only limited to exhibitions and works of art; it is also found in various areas of activity such as in sports, games, and exploration (Csikszentmihalyi and Robinson, 1990). It refers to the element of pleasure that is based on the understanding of the object. Norman (2002) stated that the aesthetic experience in the goods and services system includes the immediate sense of the object and the joy and pleasure that are experienced in the process of comparing the characteristics to the information saved in one's memory.

An aesthetic interaction refers to the dynamic exchange of information, such as product characteristics and sensory and cognitive experiences that include user behavior between the person and artifact contexts (Locher et al., 2010). Instead of being seen as a unilateral experience, an aesthetic interaction should be considered an active and agentic concept in which information is shared between humans and objects. Kang (2023) analyzed the aesthetic experience of the VR exhibition and showed that the IVR exhibition was highly evaluated in the emotional and intellectual factors than the VR exhibition. Ma et al. (2023) showed that education using VR technology can foster children's aesthetic creativity. These provide important grounds suggesting that IVR can affect aesthetic experience and creativity. Nevertheless, the aesthetic experience of fashion presentation in an IVR environment has not been considered so far.

The experience of aesthetic interactions is appropriate to define this complex experience as a separate characteristic for examining the user's experience of VR fashion show spaces. This is because each experiential element in the VR space can appear in a complex manner unlike in real spaces, and because the nature of fashion, unlike other fields, has aesthetics that reflect the internal experience of external objects. This study examined the experience of aesthetic interactions in the VR space separately concerning experiences such as the sensory and emotional pleasure regarding objects, and the psychological state of satisfaction with fashion collections and brands as consumer goods.

3 Materials and methods

3.1 Participants

Interviews were conducted in a controlled laboratory on campus. Denzin and Lincoln (2003) argued that content was more important than the number of cases and suggested no more than 10 cases. Consequently, this study selected 21 participants, with 7 per stimulus (Table 3). Participants were recruited through purposive and snowball sampling. Recruitment notices were distributed through social media and in-depth interviews were conducted with respondents. According to Lee and Park (2018), those who prefer communicating with new communication technologies are in their 20s and 30s. Thus, this study selected male and female participants in South Korea who were in their 20s, majoring in fashion/clothing, and had experience watching fashion shows or videos, but had no experience with VR. Those who satisfied the necessary conditions and expressed their intention to participate were selected (Table 3). This study received ethics approval from an institutional review board (no. 7001066-202301-HR-003).

3.2 Stimuli and devices

Of the case selection methods suggested by Jason and John (2008), a typical method was used to select the most representative cases,

TABLE 3 Participants.

No.	Age (years)	Sex	Stimuli
1	26	M	S1
2	21	M	S1
3	24	M	S1
4	26	M	S1
5	21	F	S1
6	27	F	S1
7	23	F	S1
8	22	F	S2
9	23	F	S2
10	22	F	S2
11	25	F	S2
12	25	F	S2
13	25	M	S2
14	24	F	S2
15	23	F	S3
16	24	F	S3
17	22	F	S3
18	27	M	S3
19	22	F	S3
20	23	F	S3
21	23	F	S3

All were undergraduates majoring in clothing and textiles except for no. 6 (postgraduate in fashion design). No one had any VR experience.

which were 360-degree VR fashion shows that had the three types of characteristics vis-à-vis virtual space. The following method was used to select the stimuli: In January 2023, keywords combining "360," "VR," and "fashion show" were entered on YouTube VR to search for fashion shows of different brands that had the highest number of likes and that clearly showed each of the three characteristics of virtual space. Accordingly, three videos were selected. Fashion show spaces comprise models, runway clothes, music, lighting, stage, venue, and the audience (Kim and Ahn, 2016; Kim, 2018). Accordingly, stimuli were selected by considering whether the elements of the traditional fashion show were reproduced, transformed, and maintained; these stimuli were created according to the characteristics of a VR space when the above material elements of the fashion show were converted to digital images.

Stimulus 1, Dior's 2017 Spring/Summer Haute Couture Show, was produced by recording the live fashion show so that participants could watch the show as a 360-degree video from an audience perspective. The concept of this show was a labyrinth, and the space was constructed using grass and trees inside a tent that was set up in the Musée Rodin Garden (Mower, 2017). It was a fashion show space that reproduced the appearance of physical reality. Stimulus 2, Prada's 2021 Spring/Summer Womenswear Show, was held without an audience and comprised a stage that was blocked off on all sides by digital screens and curtains. As with Stimulus 1, this space had a variable and flexible appearance as the viewer's perspective was not fixed in place and the background moved at different stages. Digital screens were set up on the walls of the space to create another fashion show scene. It was a mixed space comprising a blend of reality and virtuality. Stimulus 3, TTSWTRS's Technological Singularity Show, was produced in 2020. This fashion show displayed the transformation of objects, animals, and human figures into virtual objects and backgrounds that were made using digital images. A space of manufactured objects is one of pataphysics, which is expressed beyond the limitations of reality through interactions between the human imagination and VR technologies.

Although there are several types of IVR display devices, Oculus Quest 2 was used from among the wireless HMD devices that allow a wearer to move freely. This device was selected because it had a reduced weight and more comfortable, ergonomic design when compared to previous devices that could be attached to the wearer's head. Released in 2020 by Meta, the Oculus Quest 2 comprises a VR headset and controller, and the screen can be moved while wearing the VR headset, by using the controller and neck movements.

3.3 Detailed interview questions

For feelings such as the sense of presence that users experience in VR, many consider that subjective statements are the standard method of measurement (Ijsselsteijn et al., 2000). Therefore, this study conducted in-depth interviews and used the participants' statements for data analysis. Semi-structured questionnaires were used to facilitate detailed conversations in an open environment without any constraints (Karanika and Hogg, 2010). The questionnaire comprised items that could determine the characteristics of the VR experience. Items were referenced from previous studies on experience (Pinker, 1997; Shedroff, 2001; Mascarenhas et al., 2006), VR experience and space (Ji et al., 2022), and the sense of presence and immersion in VR environments (Steuer, 1992; Narciso et al., 2019; Kim and Choo, 2023) (Table 4).

3.4 In-depth interview and methods of data collection and analysis

In a qualitative study, it is important to create a favorable atmosphere by building rapport with participants so that they can express themselves freely (Boyce and Neale, 2006). Two moderators who were students majoring in clothing and textiles helped build rapport with participants to create a relaxed atmosphere and encourage them to speak so that they would voluntarily share and interact with each other. In-depth interviews were conducted in the following manner: (1) Before watching the stimuli, participants were asked simple questions about themselves; (2) Participants who were going to experience VR were given an explanation on using the HMD, and a simple simulation was conducted to help them understand the device and learn how to operate it; and (3) After watching the stimuli (for approximately 3 to 4 min), participants were interviewed for 30 min using the prepared questionnaire. Their responses were recorded and transcribed using Naver CLOVA NOTE, an automatic recording program. The responses were moved to Microsoft Word for refinement and preparation of the data. Data were analyzed using qualitative methods. Participants' responses were recorded in writing and compared with the key concepts and characteristics that were derived through the literature review. Data analysis was conducted in line with Giorgi (2004), where: (1) the content of the descriptions was understood in full, (2) the content of participants' descriptions were organized into meaningful units, (3) the organized words were transformed into academic expressions and the themes and central meanings were determined, and (4) the central meanings were identified and categorized into groups.

4 Results

4.1 Virtual fashion experience representing space-time

4.1.1 Cognitive sense of the place

In Stimulus 1, which comprised a 360-degree video of a real-life show, participants described experiencing place illusion, in which they felt as though they were with the audience in a specific place in which the fashion show was being held.

> "The background was green and felt like a field. It felt like the spectators were sitting on a path in the field, and it was so realistic that I felt I was there" (Participant 7).

> "If I turned my head just a little, I could see people right next to me talking to and looking at each other, so it felt like I was with the audience…It felt like I was in Paris so it somehow felt like I was dreaming!" (Participant 4).

These responses demonstrate that with the reproduction of the stage, background, and audience in the VR fashion show space,

TABLE 4 Detailed interview questions.

Item		Question
Basic question		□ Age, occupation, education level, residence, use of social and digital media, and experience watching fashion shows □ Reason for watching fashion shows and what is expected of them
Dimension of experience	Perception	□ What did you learn from watching the fashion show? □ What had you known about the brand and design previously? □ How does it compare to watching a fashion show on social media?
	Sense	□ Did the models and objects in the video feel three-dimensional? Why do you think so? □ How was the visual texture of the runway outfits, models, audience, etc.? □ How was the music in the fashion show space? □ How were the form and visual texture of the stage, background, and props? Please describe them in detail.
	Emotion	□ How did you feel after watching the fashion show? □ Did any images come to mind? Why is that? □ What was the most memorable thing after watching the video and how did it make you feel? Why is that?
	Behavior	□ How was the process of putting on the head-mounted display? □ Did you move your body while watching the video? If so, how did you move and why?
	Aesthetic	□ Has the image of the brand or design changed from what you originally experienced before? If so, how? □ Did you find anything particularly interesting while watching the video? Why is that? □ Please describe the physical characteristics or the impressions of what you saw in the fashion show space such as the models, stage, background, and runway outfits. Was anything particularly impressive? Why is that?
Sense of presence		□ Did you feel like you were in the fashion show space with other people and objects? Why is that? □ Did you feel like you were in the fashion show space?
Immersion		□ Did you ever forget that you were in this place (laboratory)? □ Did you feel like you could touch the models, stage, or the audience around you in the video? If you felt a similar feeling, please describe it. Why is that?

participants were fully aware that it was a fashion show. Rather than focusing on the details of elements such as the runway outfits and models, they were fascinated by the atmosphere in the space, and experienced the cognitive sense of presence, wherein they felt as though they were in the venue, which was actually in another region.

4.1.2 Assimilation into the fashion show

In the space of Stimulus 1, participants were reminded of brands or images they had seen on other visual media, and fashion images were formed in addition to the atmosphere of the fashion show that was provided by the VR space.

> "The location of the fashion show felt like a spring garden, and the floral atmosphere felt a lot like old-fashioned dresses" (Participant 6).
>
> "There were a lot of dresses, and I thought of the image of a spring picnic" (Participant 4).
>
> "The brand generally had a luxurious and elegant image" (Participant 7).

Participant 7 linked the fashion image to that of the brand. The VR fashion show space is a container in which fashion images are created through the interactions of each component and the user's overall *a priori* experience, perception, and emotional response. As the space of a reproduced fashion show captures the appearance of a specific reality, participants had the emotional experience of forming fashion images based on previous experiences and then relating them to the brand identity. Participants said that they felt a sense of belonging to the brand as it felt as though they had attended a fashion show that was only open to a few people.

> "I looked around a lot because it felt like I was experiencing a fascinating fashion show in the forest. I was surprised to see that famous actors were there, too!" (Participant 3).
>
> "It felt novel and exclusive. I felt like I was watching the fashion show after getting a VIP seat invitation from the director" (Participant 1).

Experiencing a fashion show in which a specific time and place was reproduced created a sense of closeness among all the elements that shared the same space and time. This is a state of brand attachment that was formed in the fashion show space, wherein one created an emotional bond in the way they would with someone close to them (Thomson et al., 2005). It represented an emotional experience.

4.1.3 Contextual understanding of runway outfits

During the fashion show, participants could see three-dimensional runway outfits and perceive their form, color, and texture. However, instead of remembering the outfits in detail, they appeared to try to understand the outfits in the context of the fashion show space.

> "I saw a female model, and I was impressed because the stage and outfit that the model was wearing matched so well!" (Participant 7).
>
> "It was nice to be able to see environmentally friendly outfits that fit the atmosphere of the fashion show" (Participant 3).
>
> "It was different from the style of the brands I know, but it was good in that it showed various sides and reflected the changes by the trend" (Participant 1).

These responses contrasted the purpose of watching a fashion show, as participants had articulated in the beginning of the interview. Participants who were majoring in clothing and textiles stated that they occasionally watched fashion shows to gain information on outfits. However, in the reproduced VR space, participants were more immersed in the space and atmosphere than in the clothes and demonstrated the aesthetic experience of trying to understand the outfits in the context of the space.

The VR fashion show space, which is a physical representation of the original in real life, allows users to experience a representation of reality. Through this representational space, the user shows that they are forming an emotional bond by observing the fashion show in the context of brand identity and the sociocultural context that they perceive in reality and being immersed rather than focusing on fashion information.

4.2 Virtual fashion experience of mixed reality and virtuality

4.2.1 Cognitive confusion

Participants experienced cognitive confusion, in which all the objects constituting this mixed space were considered artificially created virtual objects.

> "I was mistaken about whether seeing real three-dimensional models was virtual reality or reality. I looked into the model's eyes, and even though they were a fake person, I got goosebumps because they looked real" (Participant 10).

In Stimulus 2, some objects that comprised the digital screens and stage were created virtually. However, the models, runway outfits, and stage were real. Participants could not tell the difference. These responses suggest that although an enclosed virtual space that is blocked from the outside world can increase the psychological experience of immersion for users, it can cause them to experience cognitive confusion (where reality is considered virtual) if users are not given sufficient clues that relate to the physical reality.

4.2.2 Sensory and emotional immersion of closeness

As with perception, the process of judging a situation begins with the senses (Lokesh et al., 2022). In the VR fashion show space, the movements of models and perspectives caused sensory experiences such as the three-dimensional effect and sense of distance. The elements of a fashion show, such as a model's walk, differ from other mediums of fashion presentation as dynamism is emphasized. In the case of VR fashion shows, the dynamism provides a three-dimensional effect and a sense of space.

> "I felt a strong sense of three-dimensionality. When the model came back, I felt like I could touch them if I reached out, and I felt like I was in the fashion show space with them" (Participant 9).
>
> "The models made eye contact with me as they walked by, and it seemed like they were really looking at me and that the model was aware of me" (Participant 10).

Visual elements that are presented can have an effect on inducing emotions (Diemer et al., 2015; Peperkorn et al., 2015). An approach that reflects the sense of space and distance concerning visual perception acts to induce emotions; facial expressions also induce emotions (Han, 2018). As they felt that the models were walking by them, participants said that they experienced a sense of three-dimensional space and presence. Some said that they felt scared or a sense of familiarity because of the models' eyes or expressions.

> "The models' eyes and expressions seemed a bit three-dimensional, and they felt real as they came closer. I was overwhelmed when I saw the models' eyes and the fashion together" (Participant 10).
>
> "When they approached me, I could feel it so vividly, like they were going to reach me right away, and it felt like having a friend right in front of me!" (Participant 8).

Regarding the eyes of digital humans, the addition of mutual interactivity, emotional expressions, visual processing technology, and biological characteristics can increase levels of immersion in visual immersion, self-purposefulness, concentration, and external insensitivity (Yun et al., 2020). Participants' responses demonstrate that when the model's eyes faced them and they came closer, this induced emotional experiences such as a sense of fear or familiarity. Although Stimuli 1 and 3 had dynamism, which is a component of fashion shows, when there is not enough information on the space (that is, when it is difficult to understand the space in the sociocultural context of reality), this suggests that there could be higher levels of emotional experience concerning the fashion objects.

4.2.3 Authenticity of a fashion image

The new information and emotional experiences that are acquired in the VR fashion show space have an impact on the perceived image of the fashion brand. Participants recalled the fashion image of the brand they had known and explained that experiencing a VR fashion show that mixed reality and imagination either renewed their brand image or strengthened the existing one.

> "I think the feeling of models walking up and making eye contact with me made me focus on the show more, and made me feel good because it felt like they were holding the show just for me" (Participant 8).

> "It did not have that feeling that was characteristic to the brand. It had a very bright feeling…The show rather felt friendlier and a little different" (Participant 10).

Participants did not stop with these emotional experiences. They went on to connect them with their evaluation of the fashion brand. This is connected to fidelity, which is a measure of how well virtual environments represent the real world (Meyer et al., 2012), and is also strongly related to realism (Bowman and McMahan, 2007). In the VR fashion show space, in which reality and virtuality are mixed, participants said that low levels of fidelity increased virtuality and created doubts regarding brand originality.

> "The overall quality of the fashion show I watched on YouTube was very high…but this somehow did not feel like Prada" (Participant 14).

It appears that participants felt more confused about the brand identity when they were not sufficiently provided with information that is generally well-known.

> "As there wasn't a logo or anything to symbolize the brand, I did not think anyone would know that they were that brand's clothing" (Participant 10).

> "I do not think I ever felt like it was a real stage…so I really did not think it was that brand" (Participant 11).

The VR fashion show space (in which there is a mix of reality and imagination) creates a new space–time that has fluidity and dynamism, and is a mix of the real and virtual. This fashion show space makes it difficult to understand objects based on the user's past experiences, which is the sociocultural context of reality. Therefore, participants experienced immersion that was dependent on sensory elements, and as a result, the technology of graphics such as fidelity affected the authenticity of objects. This way, a fluid space can become an obstacle for users who are trying to immerse themselves in a brand (that is, trying to maintain the relationship between a brand and consumer; Gundlach et al., 1995), which is because the solidarity with the history, tradition, and identity that the brand built in reality weakens in this space. However, it is meaningful as it creates aesthetic experiences in which fashion images (that are strengthened or decreased) can be perceived or experienced through individual subjective insight and new spaces.

4.3 Virtual fashion experience of pataphysics

4.3.1 Connection to creative inspiration

Although participants experienced a sense of presence as though they were in the same fashion show space as others, they considered the objects they observed unrealistic because they had neither seen nor touched them and could not touch them outside of the show. As a result of this "unreality," participants said that they became curious about how the elements of an ideal fashion show space are created, and said that they felt inspired.

> "As the video moved with me when I turned my head and moved my gaze, it really felt like I was in a fashion show…First, I felt it was a little unrealistic because the video's composition and flow were unrealistic, and I had never experienced it and could not touch it" (Participant 21).

> "I wonder how the graphics were implemented so well…It makes me wonder how long it must have taken to make this great video with the designs…I thought that it could be expressed in a more fun way if it was done this way" (Participant 16).

Before watching, participants majoring in the field of fashion stated that they ordinarily acquired new ideas and information through fashion shows. These responses demonstrate that unfamiliar images can provide new visual stimulation and cognitive experiences to a greater degree than when compared to other stimuli; this shows that they could provide material for creative inspiration concerning academic and work-related activities.

4.3.2 Aesthetic exploratory play

Exploratory behavior obtains information on stimuli. Exploration is divided into specific exploration, in which a new object is manipulated and tested using one's senses, and diverse exploration, which is a long-term and continuous exploration that takes place internally after an object's characteristics have been identified (Hutt, 1971). Unlike exploratory behaviors, which are driven by external stimuli, playing is a multifaceted behavior that is driven by intrinsic motivation. It takes place after the information has been acquired and feelings of pleasure are induced in the process, and not in the results. With exploratory play, a combination of exploration and play takes place. It refers to the behavioral pattern that appears after a new object is observed based on an *a priori* experience related to the said object. The unfamiliar emotions that participants experienced in Stimulus 3 resulted in the behavior of collecting information by moving the field of view to various angles. Through this experience, participants explained that they became more curious about the brand's concept and level of completeness of the content. This is similar to the exploratory play that young children engage in while exploring a new world.

> "It was the first time I had seen a model or clothes three-dimensionally, so it felt like I was on a new amusement park ride" (Participant 21).

Participants' physical activity in the VR fashion show space was limited to their eye movements. However, they were seen to acquire audiovisual information with virtual objects regardless of material achievements and physical behaviors. Even if participants could not use their will to control the situation directly, they used the information they acquired by guessing the connectivity between the fashion show's components to see the fashion show as a work of art and understand its concept, which was an aesthetic exploratory experience.

The fashion show space of pataphysics, which was realized with human imagination, is an imaginary space that comprises a combination of images that are somewhat far from the experiential symbolism of lifestyles and social groups. This space (where the relationship between the social signifiers and the signified are disconnected) provides aesthetic experiences in which users engage in new exploratory play and dynamic interactions take place between fashion images and the users' aesthetic exploration.

5 Conclusion

5.1 Summary and discussion

This study approached the VR space with three characteristics based on the perspective of social space and proposed that differences in spatial character led to differences in the fashion experiences of users.

First, the fashion show space, which is a physical representation, induced a cognitive and emotional sense of presence, in which users felt as though they had moved to the same time and place as those of the fashion show. Through this fashion show space, users experienced aesthetic interactions in the cultural context, in which runway outfits were interpreted by connecting them to the atmosphere of the representational space. Jung and Ko (2023) explored the experiences of luxury fashion brands and determined that the components of the virtual fashion space are related to virtual experiences such as immersion, presence, and interaction. *A priori* elements such as sociocultural contexts and personal experiences differ in the experiential dimension of virtual space. Stimulus 1 was the reproduction of a real luxury brand fashion show, and it was determined that the user became immersed by connecting the fashion images that were accumulated in reality to the virtual space. This immersion played a large role in forming the emotional bond that is referred to as a sense of belonging.

Second, in the mixed fashion show space (in which reality and imagination coexist), participants experienced cognitive confusion owing to the differences with *a priori* experiences. Participants' sensory experience was connected to the formation of the brand's image and emotional experiences. The three-dimensionality and a sense of space that occurs in enclosed spaces provided by VR technology induce a psychological experience in which the user feels as though they have a special and intimate relationship with the brand. Given that the stimuli are fashion shows of luxury brands, it is unusual that an emotional experience of intimacy is induced concerning a private relationship, which is unlike the sense of belonging in a representational space. Jung et al. (2021) argued that VR technology reflects a utopia in which traditional luxury fashion shows (that had been characterized by privilege and status in the past) can be experienced equally. This could lead to different consequences based on the properties of the space.

Third, participants transcend the limitations of physical reality while in the fashion show space of pataphysics (which was realized with human imagination) and that they move beyond the stage of confusion that is experienced while facing realistic objects to connect to creative inspiration. Unlike other spaces, the fashion show space of pataphysics is far from social symbolic meanings and is a space that results from the creator's imagination. In virtual space, which is difficult to understand in the sociocultural context of reality, the user engaged in active exploratory behavior to acquire new information and underwent aesthetic experiences concerning aesthetic exploration. This confirmed the results of Kim and Choo (2023), who found that experiences of shopping in VR increased levels of perceptual curiosity and creativity in consumers. Research findings suggest that creative inspiration and exploratory play can be induced in a user to a greater degree if the immersive fashion space is further from the original source and if the relationship between the signifiers and the signified is further disconnected.

5.2 Implications and limitations

Studies in the field of fashion that have dealt with fashion experiences through IVR technology have primarily focused on fashion stores or consumer experiences. This study presented the characteristics of new virtual spaces created by media technology, and empirically determined the differences in fashion experiences in each virtual space. It followed a more detailed approach to the virtual experience and subdivided it. This study provides a basic framework for research on fashion content production and interactions with users in the Metaverse, which has been used increasingly in recent years. Therefore, this study makes an academic contribution by expanding the field of digital fashion design, which is still in its early stages, by narrowing the research gap.

The VR fashion show spaces of pataphysics provide creative motivation and aesthetic experiences of exploratory play. Unlike previous studies that focused on the environment of fashion stores (whose primary purpose is sales), and consumption behavior and intention, this study focused on fashion show environments. Current fashion shows are significant as they are communication channels that convey brand concepts and designers' creativity. Experience is an important mechanism for improving professionalism (Dreyfus and Dreyfus, 1986), and the VR space can create a variety of experiences. Therefore, the current findings suggest that IVR fashion shows, and the spatial experience of pataphysics, could have an educational effect and help enhance the professionalism of students majoring in fashion, who are required to have abundant creative sensibilities. Future research should focus on its educational effects.

IVR technology changes the way that traditional fashion shows communicate. This study demonstrated that VR fashion shows play a positive role in fashion media by interacting with users, building a sense of closeness, and creating new fashion images. This is unlike previous fashion shows, which used a few unilateral methods of delivery. Unlike in the real world, in which new designers can be placed at a disadvantage when compared to luxury fashion brands that have a long history and tradition, VR fashion show spaces can give them the opportunity to effectively expand into new markets.

Although physical fashion shows only last for about 20 min, there are concerns about the negative environmental effects they have, such as the vast amount of energy that is used and their heavy carbon footprint (Webb, 2022). Holding VR fashion shows can minimize their impact on the physical environment, and contribute to the development of a sustainable fashion industry by enhancing diversity in the industry, which is centered on mainstream fashion companies.

This study has some limitations. First, it did not adequately examine how technical problems in the devices used to experience VR fashion shows can affect a user's fashion experience. Pallavicini et al. (2020) found that the images, sounds, and interactions of VR experience devices induced positive or negative reactions. Marsh et al. (2001) explained that the effect of sense of presence decreased and emotions such as discomfort and fear could be induced if interactions with the user were not smooth and the images on the device or screen were difficult to discern owing to issues such as slow buffering speeds. Some experienced problems with image quality owing to the Wi-Fi connection during the experiment, whereas some complained of discomfort owing to the weight of the device. Therefore, future research should exclude the technical limitations of the experience devices. Second, there could be differences in perception and cognition by sex (Rosa et al., 2014). Future research can evaluate differences based on sex and individual perceptions. Third, the experiment was conducted with fashion students; thus, there could be individual differences in students' personalities and the results may not be generalizable to students in other fields. According to Dewey (2007), experience is formed by the interaction between the reciprocity of external conditions and subjective internal conditions. Thus, different dimensions of VR experience could be derived if other populations were targeted (e.g., consumers, other fashion professionals, or tourists).

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving humans were approved by the Institutional Review Board in Changwon National University (no. 7001066-202301-HR-003). 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.

Author contributions

SK: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

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

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Uncovering the connection between ceiling height and emotional reactions in art galleries with editable 360-degree VR panoramic scenes

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Introduction: This study investigates the relationship between ceiling height and emotional responses in art galleries, using editable 360-degree VR panoramic scenes. Prior research has explored the influence of spatial dimensions on general emotions, but the specific impact of ceiling height in art gallery settings, particularly on discrete emotions, remains understudied.

Methods: The study utilized 360-degree panoramic photo scene modeling to modify ceiling heights within virtual art galleries, assessing emotional responses through self-report measures. Participants were presented with virtual art gallery environments featuring varying ceiling heights. Two studies were conducted: Study 1 involved absolute emotion rating across different ceiling heights, and Study 2 focused on selecting ceiling heights based on assigned emotions.

Results: The data revealed that ceiling height significantly impacts specific emotions, notably disgust and joy. Lower ceiling heights generally evoked higher levels of fear and anger, while higher ceiling heights were associated with increased joy. The impact on other emotions like sadness, surprise, and disgust was more nuanced and varied across different ceiling heights.

Discussion: The findings highlight a complex relationship between ceiling height and emotional responses in art galleries. The study demonstrates the efficacy of using editable 360-degree VR panoramic scenes in environmental psychology and architecture research, offering insights into how spatial dimensions influence emotional experiences in architectural settings.

KEYWORDS

ceiling height, editable 360-VR panoramas, emotional response, art galleries, environmental psychology, architectural design, virtual reality (VR)

1 Introduction

The built environment profoundly influences individual perceptions and experiences of spaces. Specific architectural characteristics, such as ceiling height and noise, influence occupant emotions and wellbeing (Reddy et al., 2012; Vartanian et al., 2013; Lyu and Kim, 2017; Soltani and Kirci, 2019; Mir et al., 2022). Acknowledging the role of architecture in evoking emotions has become a topic of increasing interest, contributing to the creation of spaces that stimulate positive experiences and enhance quality of life (Zeisel, 2006; Pallasmaa, 2011; Lee, 2022). This focus on emotional dimensions of architecture is part of a wider trend that aims to cultivate environments promoting human wellbeing (Altomonte et al., 2020).

Art galleries, museums, and other exhibition spaces are environments where emotional experiences are closely intertwined with architectural design, as the presentation of artworks or exhibits and the spatial dimensions of these spaces can affect visitors' emotional responses (Alelis et al., 2013; Kühnapfel et al., 2023). Understanding the relationship between ceiling height and emotional response in these settings can help architects create spaces that better cater to the needs of the exhibited items and enhance visitors' emotional experiences.

Virtual reality (VR) has emerged as a powerful tool for studying architectural experiences, offering researchers the capability to create immersive, controlled environments in which participants can explore and react to various design features (Kuliga et al., 2015). The 360-degree panoramic photo scene modeling technology, in particular, offers a level of control similar to 3D modeling techniques (Luo et al., 2019). In our study, we utilize this technology to specifically modify ceiling heights within the virtual art galleries, enabling us to examine their impact on occupants' emotional responses.

In this study, we aim to assess the relationship between ceiling height and emotional response in art galleries using editable 360-degree VR panoramic scenes. By examining how different ceiling heights affect participants' emotions, we hope to contribute to the broader understanding of the role of spatial dimensions in architectural design and their influence on emotional experiences. Additionally, the use of innovative VR technology will allow us to explore the potential of editable 360-degree panoramic photo scene modeling as a valuable research tool in the field of architecture and design.

This paper is organized as follows: First, we review relevant literature on the relationship between architectural features and emotional responses, with a particular focus on ceiling height. Second, we describe the methodology used in our study, including the creation of editable 360-degree VR panoramic scenes and the assessment of participants' emotional responses. Third, we present our findings, highlighting the specific emotions that were significantly impacted by ceiling height and discussing the potential influence of exhibited works on emotional responses within an art gallery context. Lastly, we conclude by summarizing our findings and proposing directions for future research.

By investigating the relationship between ceiling height and emotional response in art galleries through editable 360-degree VR panoramic scenes, we aim to provide valuable insights for architects, designers, and researchers interested in understanding the complex interplay between built environments and human emotions.

2 Literature review

The impact of architectural features on human emotions and cognition is an area of growing interest. This literature review focuses on the relationship between ceiling height and emotional responses, as well as the use of 360-degree panoramic photo scene modeling in architectural research. By examining existing studies and addressing research gaps, we aim to provide a foundation for our investigation into the influence of ceiling height on emotional response in art galleries through editable 360-degree VR panoramic scenes.

2.1 Perception and response to ceiling height

Ceiling height has been a subject of interest in architecture and environmental psychology, with numerous studies exploring its influence on human perception and behavior (Meyers-Levy and Rui, 2007; Guimarães et al., 2013; Mofrad, 2014; Vartanian et al., 2015; Cha et al., 2019). Recent research has begun to examine the connection between ceiling height and emotional response. This literature review delves into the perception of and response to ceiling height, providing a foundation for studying its impact on emotional responses in art galleries, specifically through 360-degree VR panoramic scenes.

The Cathedral Effect describes the relationship between perceived ceiling height and cognition, wherein high ceilings promote abstract thinking and creativity, while low ceilings encourage concrete and detail-oriented thinking (Meyers-Levy and Rui, 2007). Expanding on this concept, research has found that rooms with higher ceilings and open spaces are more likely to be judged as beautiful, activating brain structures related to visuospatial exploration, attention, and perceived visual motion, while enclosed rooms elicit exit decisions and activate emotional response regions in the brain (Vartanian et al., 2015). Building on this research, studies have found that participants in high-ceiling environments experience more positive emotions, while those in low-ceiling spaces report more negative emotions (Cha et al., 2019). These emotional differences are thought to be linked to the sense of spaciousness and freedom associated with high ceilings and the feelings of confinement related to low ceilings.

In terms of thermal comfort, studies have examined the influence of floor-to-ceiling height on human comfort in residential units, concluding that the ideal height falls between 2,700 mm and 2,800 mm (Mofrad, 2014). Furthermore, it has been demonstrated that a 20 cm decrease in ceiling height led to a 1°C temperature increase (Guimarães et al., 2013). Research utilizing a height-matching method to assess the perceived height of ceilings with varying lightness found that lighter ceilings appeared significantly higher than darker ones (von Castell et al., 2014). This method avoids metric judgments, indicating that the impact of ceiling lightness on perceived height is a direct perceptual effect rather than a cognitive one. Collectively, these studies emphasize the relevance of ceiling height on human perception and emotional response.

The literature on ceiling height and emotional response is expanding, with an increasing number of studies leveraging virtual reality (VR) technology. One of the primary reasons for the adoption of VR in these studies is the difficulty of manipulating ceiling height within the same physical space while controlling for other factors. In real-world environments, changing ceiling heights while maintaining other architectural elements constant is often challenging, if not impossible. Therefore, VR has emerged as one of the preferred tools for studying the relationship between ceiling height and emotional responses, as it allows researchers to create controlled environments where ceiling height can be easily manipulated while keeping other factors constant.

2.2 360-degree panoramic photo scene modeling

Virtual reality (VR) technology offers a solution to this issue by providing immersive and realistic environments, which in turn allows for a broader range of possibilities when studying the impact of architectural features on emotions. In emotion research using virtual reality, three main methods are typically employed to create virtual environments: computer-generated 3D models, 360-degree panoramic photos, and 360-degree panoramic videos.

Each of these methods has been proven effective in influencing emotions through various studies. For instance, one study developed an emotion recognition system for affective states evoked through immersive virtual environments using computer-generated 3D models, achieving accuracies of 75.00% for arousal and 71.21% for valence (Baños et al., 2006). Another study explored the effects of virtual nature exposure on subjective vitality using 360-degree panoramic photos, finding that individuals with high levels of cognitive reappraisal experienced significant and positive effects (Theodorou et al., 2023). Lastly, a comparison of emotions and sense of presence elicited by an immersive 360-degree video of a landscape to those evoked in a real-life contemplative scenario of the same landscape found that emotions and sense of presence in the virtual condition were largely comparable to those experienced in the real-life condition, with only minor differences in anger and amusement levels (Alelis et al., 2013).

In architectural perception and response research within virtual reality, researchers often use 3D models for controllable study environments or opt for 360-degree panoramic photos for increased realism at the expense of control. Recently, the emergence of 360-degree panoramic photo scene modeling has provided a balanced approach between realism and control for researchers studying ceiling height. This technique allows the manipulation and editing of 360-degree panoramic images, enabling the creation of virtual environments and augmented reality experiences. It combines panoramic photography and 3D modeling, creating an interactive and immersive experience. Panoramic texture mapping and panoramic 3D reconstruction are two essential technologies in the fields of computer graphics and computer vision, facilitating the creation of virtual environments and augmented reality experiences (Pintore et al., 2019; Walmsley and Kersten, 2020).

Panoramic texture mapping is a technique that maps 2D textures, such as panoramic images, onto a scene's 3D model, creating the illusion of a panoramic environment. This method has been widely used in virtual reality and video game applications, creating realistic and immersive environments (Zou et al., 2018; Luo et al., 2019; Pintore et al., 2021). On the other hand, panoramic 3D reconstruction involves using computer vision and machine learning algorithms to infer a scene's 3D structure from single or multiple panoramic images and create a 3D model of the scene (Liu et al., 2015; Nebiker et al., 2016; Xu et al., 2017). Panoramic texture mapping is simple and fast, requiring only basic image processing techniques. However, its performance is limited to the appearance of the environment and does not provide information about its geometry or depth (Pan et al., 2011). In contrast, panoramic 3D reconstruction captures both the appearance and geometric shape of the environment, creating a more comprehensive representation. This method requires more advanced techniques, such as machine learning algorithms, and is more time-consuming and computationally intensive. However, the current state of technology for panoramic 3D reconstruction has limitations in accurately reproducing the realism of the environment.

In summary, 360-degree panoramic photo scene modeling is a promising technique for researching architectural perception and response in virtual reality. This method combines the advantages of panoramic photography and 3D modeling, providing a balance between realism and control. This approach offers a technological foundation for creating editable 3D models using 360-degree panoramic photos.

2.3 Addressing the research gaps and formulating hypotheses

In the existing literature on the impact of ceiling height on human emotions, several research gaps have been identified, emphasizing the necessity for an enhanced approach. First, some studies rely on 3D models to simulate ceiling heights (Cha et al., 2019), which may not accurately represent real-world environments. Using 3D models might limit the ecological validity of research findings since they lack the authenticity and complexity of real-world spaces. Methods that better replicate real environments, such as editable 360-degree panoramic scenes, should be considered for simulating architectural settings.

Second, previous research has often focused on comparing only two ceiling heights or different heights with varying scenes (Vartanian et al., 2015; Cha et al., 2019), and the selection of these heights may lack a clear rationale. The limited range of ceiling heights studied might not fully capture the entire scope of potential impacts on human emotions. A more systematic investigation of different ceiling heights is needed, with clear rationales for their selection, to better understand the emotional impact of ceiling heights.

Moreover, most studies use absolute emotional values; however, emotions are influenced by multiple factors. As highlighted in a particular study (Liang et al., 2018), it is important to integrate both direct person-independent (absolute emotions) and relative person-dependent (relative emotions) approaches for emotion recognition, providing a more comprehensive understanding of the impact of ceiling heights on emotions. Based on these identified gaps, we propose the following hypotheses:

1. There is a significant relationship between ceiling height and emotional responses in art galleries, with higher ceiling heights eliciting more positive emotions and lower ceiling heights eliciting more negative emotions among gallery visitors.
2. Utilizing editable 360-degree panoramic scenes to simulate various ceiling heights in art galleries effectively replicates real-world environments, thereby inducing emotional changes in viewers. This approach will be used to investigate the impact of ceiling height variations on participants' emotional responses, demonstrating the efficacy of this technology as a tool for studying the influence of architectural dimensions on emotions.

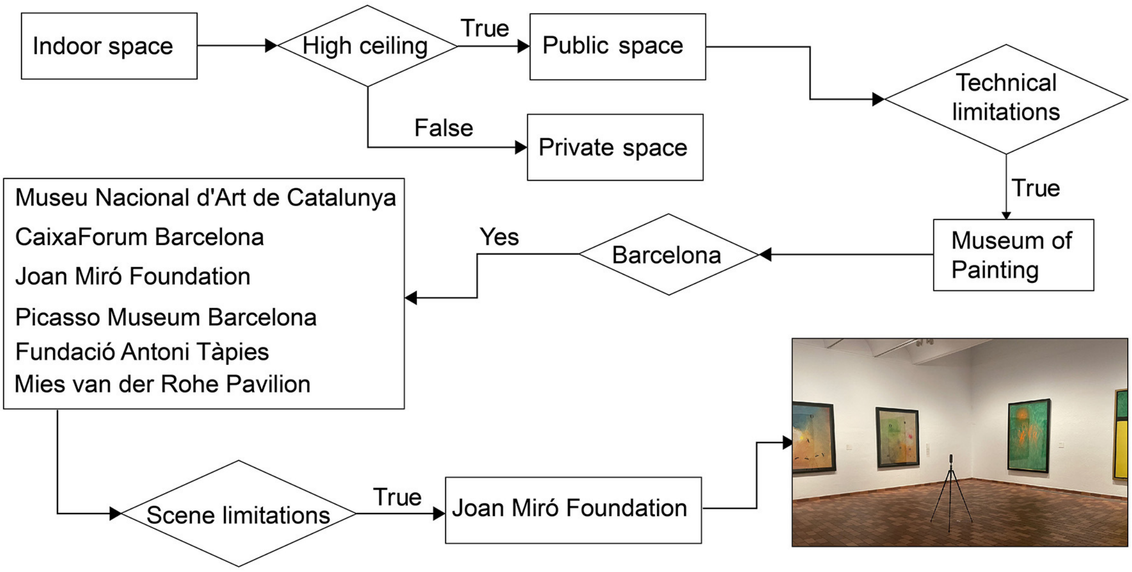

FIGURE 1
Scene selection rationale.

3 Methodology

3.1 Scene selection rationale

In this study, we chose to use panoramic texture mapping technology for operability and realism. Due to the technical limitations of panoramic texture mapping, there are certain requirements for scene selection. First, rooms with isometric shapes, such as rectangular, circular, or hexagonal rooms, are preferred, as these rooms allow for a more even division of wall texture in panoramic photos. Second, spaces without furniture and decorations are selected, as the software's texture projection will cast any furniture or decorations onto the walls, affecting the final result's authenticity. Third, well-lit scenes with sufficient illumination are essential for taking panoramic photos.

Selecting suitable scenes for our research is a crucial aspect of our study, and the following outlines our choice logic (see Figure 1). Given that residential spaces generally have little variation in height (Appolloni and D'alessandro, 2021), we chose to focus on public spaces. Taking into account the technical limitations previously mentioned, museums and galleries were deemed appropriate public spaces for our investigation. We visited various museums in Barcelona, including the Catalan National Art Museum, CaixaForum Barcelona, Joan Miró Foundation Museum, Picasso Museum, Fundació Antoni Tápies Museum, and Mies van der Rohe Pavilion.

In addition to considering technical requirements, we identified several factors to take into account during the scene editing process: (1) enclosed spaces, as the field of view changes when the room's dimensions change in open spaces; although artificial intelligence technology can fill in missing scenes, authenticity is still affected; (2) clear boundaries between walls and ceilings to facilitate software processing when adjusting ceiling heights; (3) single-material wall textures, as multi-material walls pose significant challenges for expanding the simulated texture mapping; (4) the absence of hanging objects, as changing ceiling heights would cause the perspective ratio of hanging objects to differ from reality, affecting authenticity. After filtering through these criteria, we chose a room within the Joan Miró Foundation Museum measuring approximately 8.11 meters by 9.21 meters, resembling a square shape, as our research space and obtained permission from the museum to conduct scene photographs.

3.2 Adopting Le Corbusier's Modulor system for ceiling height

To choose the ceiling heights for our study, we incorporated Le Corbusier's Modulor system, an innovative and human-centered approach to architectural design (Corbusier et al., 1980). This choice was guided by historical and empirical reasons. Notably, Josep Lluís Sert, the designer of the Joan Miró Foundation Museum, who had worked in Le Corbusier's studio, applied his design principles in his works (Bair, 2015). Upon measuring the ceiling heights of the Joan Miró Foundation Museum, we found that they corresponded to Le Corbusier's Modulor system. Similarly, the Tokyo National Museum of Western Art, a collaborative design by Le Corbusier and Kunio Maekawa, also adhered to the Modulor system (Yamana and Fukuda, 2015) (see Figure 2).

The Modulor system is a well-grounded, human-proportion-based approach to architectural design. This system not only ensures the heights chosen align with ergonomic considerations and spatial perception, but it also conforms to broader architectural discourse and practice. Consequently, the findings from our research are more directly applicable to real-world scenarios.

Given the human-centric focus of the Modulor system, we adopted the red and blue series for determining our experimental

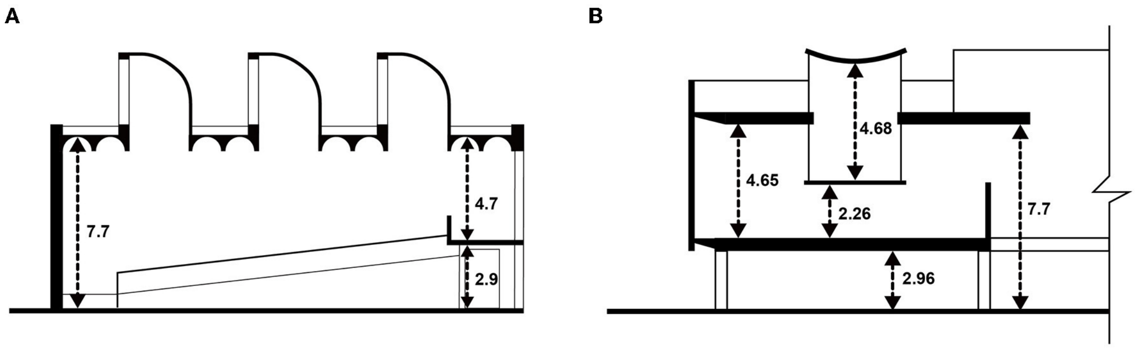

FIGURE 2
(A) Cross-sectional heights of Joan Miró Foundation, **(B)** cross-sectional heights of National Museum of Western Art.

ceiling heights (Steyn, 2012; Itham Mahajan, 2016; Rozhkovskaya, 2020). The heights selected, namely, 2.26, 2.96, 3.66, 4.79, 5.92, 7.74, and 9.57 m, are found in both the Joan Miró Foundation Museum and the Tokyo National Museum of Western Art. For reference purposes, 4.79 m was chosen as it is approximately double the lowest height of 2.26 m and half of the highest height of 9.57 m. It's important to note that our experiment did not include ceiling heights lower than 2.26 m or higher than 9.57 m. In the context of public spaces such as art galleries and museums, we categorize the ceiling heights of 2.26 and 2.96 m as "lower," while 3.66, 4.79, and 5.92 m are considered "common" heights. Conversely, 7.74 and 9.57 m represent "higher" ceiling heights. This categorization is grounded in our examination of ceiling heights in existing museum and gallery spaces, allowing us to present our findings within a relevant architectural context.

These heights, though might seem unconventional in some contemporary architectural projects, hold significant empirical value in that they follow the anthropocentric design principles of the Modulor system.

3.3 Designing environments with diverse ceiling heights

In the production process of our experimental scenes, we started by selecting an enclosed, rectangular exhibition room without exterior windows at the Joan Miró Foundation museum. To capture the 360-degree panoramic images, we positioned a Trisio Lite2 8K camera at the center of the room, ensuring a comprehensive view of the entire space. After acquiring the images, we utilized the Blender PanoCamAdder(+) plugin to intelligently project the captured scene onto the walls, and the arched ceiling, which allowed us to generate texture maps for each surface using the "unwarp" command.

To create the different ceiling heights according to Le Corbusier's Modulor theory, we employed OpenAI's Dall-E2 web application to generate the wall images required for each height (Reviriego and Merino-Gómez, 2022). We input the keyword "blank white walls" and selected the most suitable images from the generated results. We iterated the generation process if an image contained imperfections until the desired outcome was achieved. With the AI-generated images, we used Unity to reassemble the walls and create virtual room models for the seven ceiling heights (2.26, 2.96, 3.66, 4.79, 5.92, 7.74, and 9.57m) (see Figure 3). In preparation for the main study, we conducted pre-tests with a preliminary group of participants to validate the perceptual effectiveness of the virtual environments, particularly in terms of ceiling height variations. Their feedback was instrumental in fine-tuning the virtual spaces to ensure realistic and immersive experiences for the main study participants. This meticulous process allowed us to generate high-quality and accurate models for our experiment, ensuring a realistic and immersive experience for the participants while maintaining consistency across the different ceiling heights.

3.4 Questionnaire development

To ensure that participants were fully immersed in the VR environment and to maintain contextual event continuity, we developed a questionnaire that was embedded within the Unity-based VR experience (Parsons, 2015). This approach allowed participants to complete the questionnaire while remaining in the VR environment, preserving the ecological validity of their emotional responses to the architectural spaces.

In Study 1, the VR-embedded questionnaire consisted of rating scales for each of Ekman's six basic emotions: fear, anger, joy, sadness, disgust, and surprise (Ekman, 1992) (see Figure 4A). Based on our previous research experience, we found that participants often struggled to understand complex emotional scales like the Self-Assessment Manikin (SAM) (Zhang et al., 2022). Additionally, in a VR setting, text-heavy questionnaires such as the Emotion Beliefs Questionnaire (EBQ) (Becerra et al., 2020) are not ideal due to the immersive nature of the environment. Therefore, we opted for a simpler, more direct emotional rating scale complemented by visual aids. Participants were asked to rate their emotional response to the assigned ceiling height on a scale from 0 to 10, with 0 representing "indifferent or neutral" and 10 representing a strong emotional response (e.g., "very fearful" for fear). This rating scale was presented to the participants within the VR environment after they had explored the architectural space for three minutes,

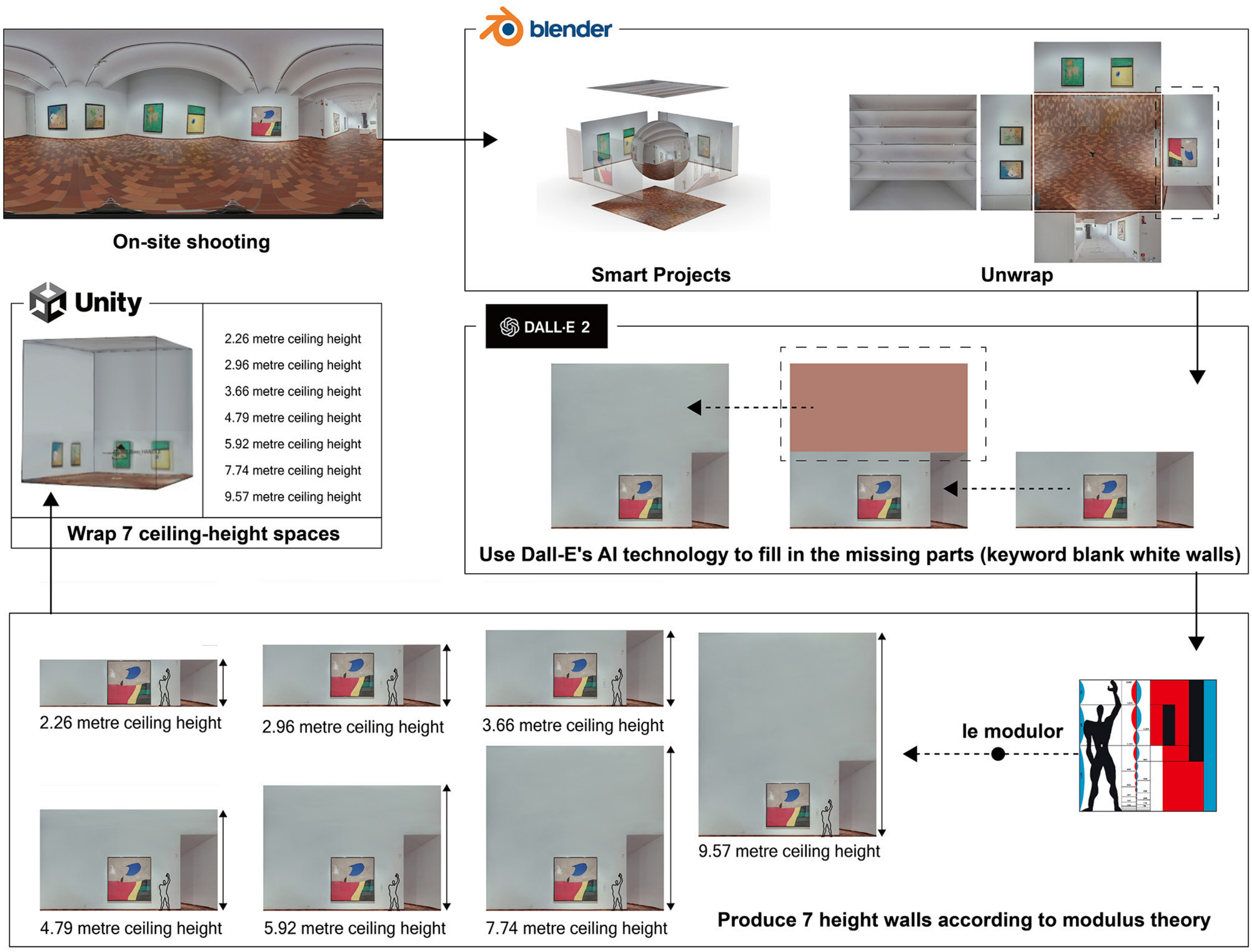

FIGURE 3
Process for designing environments with diverse ceiling heights.

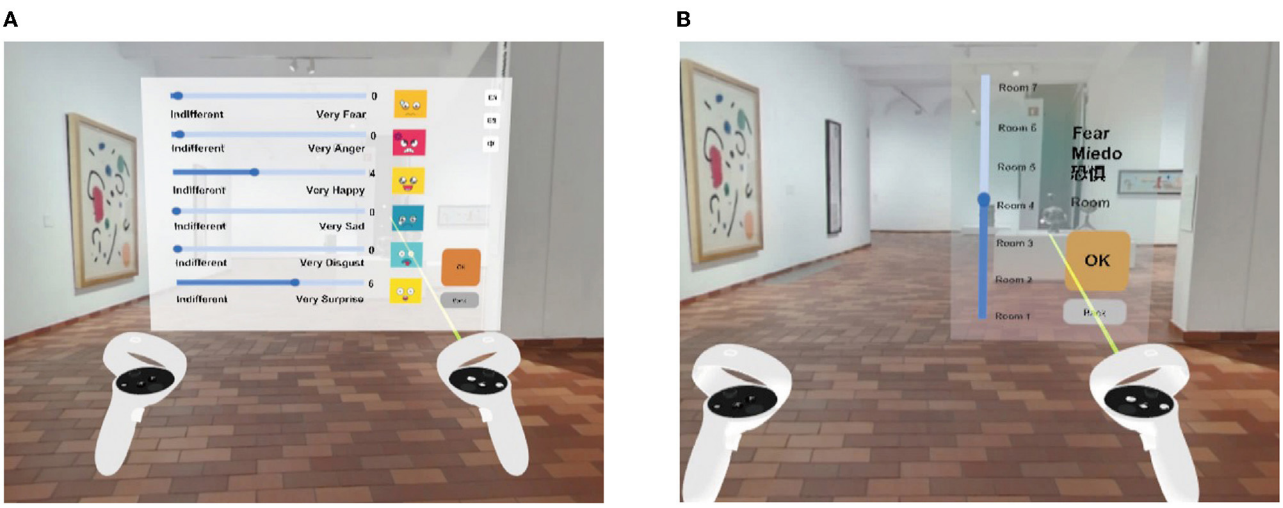

FIGURE 4
(A) VR-embedded questionnaire interface in Study 1, **(B)** the seven-room options with varying ceiling heights for participants to choose from in Study 2.

ensuring that they had sufficient time to experience and react to the space.

In Study 2, participants were assigned an emotion from Ekman's six basic emotions and were asked to select a ceiling height that best resonated with their assigned emotion. They were presented with seven room options, each with a different ceiling height (2.26, 2.96, 3.66, 4.79, 5.92, 7.74, or 9.57m) (see Figure 4B). This task aimed to explore participants' perceptions of the relationship between ceiling heights and emotions.

3.5 Participants

A total of 183 participants from Universitat Politécnica de Catalunya, took part in both Study 1 and Study 2. All participants were architecture students, with a diverse mix of academic levels (i.e., undergraduate, graduate, and doctoral students). The age range of the participants was between 18 and 45 years old. Participants were divided into six groups based on the ceiling height they were assigned to in Study 1: 2.26 m (31 participants), 2.96 m (30 participants), 3.66 m (29 participants), 5.92 m (30 participants), 7.74 m (31 participants), and 9.57 m (32 participants). In Study 2, due to participant errors, only 178 responses were recorded. The groups for Fear, Joy, Sad, Disgust, and Surprise each consisted of 30 participants, while the Anger group had 28 participants.

No demographic information, such as gender, was recorded for this experiment in accordance with the principles outlined in the article "Stop 'controlling' for sex and gender in global health research," ensuring the focus remained on architectural perception (Shapiro et al., 2021). As the experimental spaces were designed with uniformly white walls, we did not exclude participants with color blindness. Participants with myopia were allowed to wear their corrective glasses during the study. Informed consent was obtained from all participants, and the study was conducted in compliance with ethical guidelines and principles.

3.6 Experimental procedures for Study 1 and Study 2

Before the experiment began, the researcher took 5 minutes to explain the procedure and the purpose of the study. Those who agreed to participate in the experiment were asked to sign the informed consent form. The total duration of the experiment was approximately 15 min.

The experiment consisted of two distinct studies, with each participant experiencing both. Initially, participants wore disposable VR eyes masks and VR headsets (Oculus Quest 2) to enter the virtual environment for Study 1. All participants began in a room with a ceiling height of 4.79 m, which served as the reference environment for within-subject comparisons. After exploring the room, they completed the first emotional assessment questionnaire within the VR space. Once the first emotional assessment was completed, participants were divided into six groups, each assigned to a different ceiling height (2.26, 2.96, 3.66, 5.92, 7.74, or 9.57 m), employing a between-subjects design. They were instructed to explore their assigned space and then complete the second emotional assessment using the same questionnaire as before. This approach allowed us to compare the emotional responses across different ceiling heights as well as to examine within-subject changes due to the alteration of ceiling heights.

For Study 2, participants were divided into six new groups corresponding to each of Ekman's six basic emotions. In this study, participants were tasked with selecting a ceiling height (2.26, 2.96, 3.66, 4.79, 5.92, 7.74, or 9.57 m) that they felt best resonated with their assigned emotion. This exercise aimed to explore the participants' perception of the relationship between ceiling heights and emotions (see Figure 5).

The experiment's data was stored on the VR headsets. Upon completion, researchers checked the equipment to ensure participants had followed the instructions correctly. The headsets were then disinfected according to safety protocols, ensuring a clean and safe environment for subsequent participants.

3.7 Statistical analysis

We first preprocessed the collected data, addressing two outliers resulting from participant errors during the experiment, following best practices for data cleaning and preprocessing. Next, we conducted a descriptive statistical analysis using Python to calculate the main features of the data, such as mean, standard deviation, and median, allowing us to better understand the data's distribution and trends.

In our data analysis, we employed different statistical methods depending on the distribution of the data. When the data adhered to a normal distribution, we used the t-test and computed Cohen's d to estimate the effect size (Schmidt and Bohannon, 1988). Conversely, for data that did not conform to a normal distribution, we implemented the Wilcoxon signed-rank test and Cliff's delta (Cliff, 1993). These methods were chosen to ensure a comprehensive and robust statistical analysis, regardless of the data's distribution (Bloice and Holzinger, 2016).

To facilitate our data processing and analysis, we utilized several Python packages. Specifically, we employed NumPy for numerical operations, Pandas for data manipulation and analysis, SciPy for implementing statistical tests, and Matplotlib along with Seaborn for data visualization. The use of these packages ensured rigorous and efficient processing of our experimental data, contributing to the reliability and reproducibility of our results.

4 Result

4.1 Study 1: absolute emotion rating

This section presents a comprehensive analysis of the absolute emotional ratings across various ceiling heights, ranging from 2.26 to 9.57 m. The assessed emotions include fear, anger, joy, sadness, disgust, and surprise, with participants rating their emotions on a scale from 0 to 10. The key findings from the data are as follows (see Figure 6):

1. Negative emotions:

- Fear: Participants generally expressed higher levels of fear in rooms with lower ceiling heights. For instance, in the 2.26 m

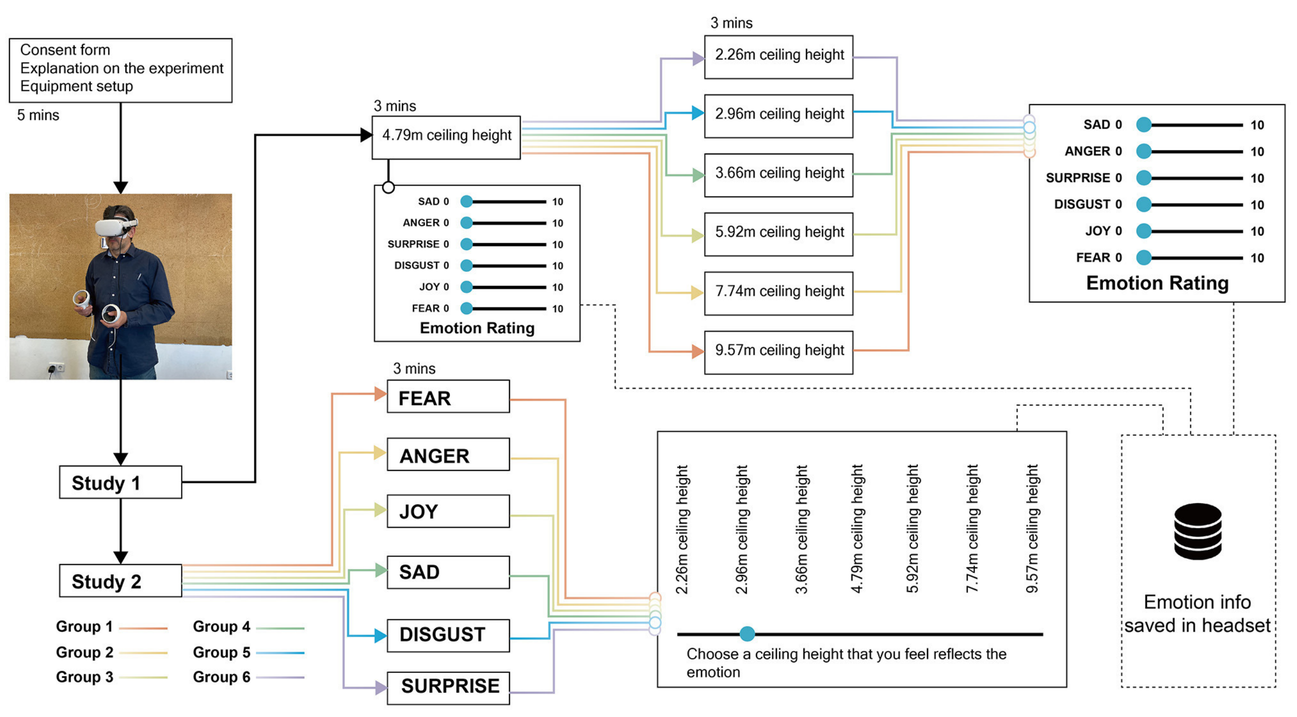

FIGURE 5
Flowchart of experimental procedures for Study 1 and Study 2.

ceiling height, 45.16% of participants gave a rating of 0 for fear, while this proportion increased to 80% in the 2.96 m ceiling height. As the ceiling height increased, the proportion of participants who rated their fear as 0 decreased, reaching a minimum of 62.5% in the 7.74 m ceiling height. However, it rose slightly to 70% in the 9.57 m ceiling height.

- Anger: A similar trend can be observed for anger, where higher proportions of low ratings were observed in rooms with lower ceiling heights. In the 2.26 m ceiling height, 67.74% of participants gave a rating of 0, while this proportion increased to 83.33% in the 2.96 m ceiling height. The proportion of 0 ratings remained relatively high across all the other ceiling heights, with the lowest being 76.67% in the 9.57 m ceiling height.
- Sadness: Participants reported low levels of sadness across all ceiling heights. The proportion of 0 ratings was consistently high, ranging from 70.97% in the 2.26 m ceiling height to 89.66% in the 3.66 m ceiling height. The highest ceiling height, 9.57 m, still had a high proportion of 0 ratings (83.33%).
- Disgust: Disgust ratings were predominantly low across all ceiling heights. In the 2.26 m ceiling height, 48.39% of participants gave a rating of 0, while this proportion increased to 80.65% in the 5.92 m ceiling height. The 9.57m ceiling height had the highest proportion of 0 ratings (80%).

2. Positive emotions:

- Joy: The distribution of joy ratings across different ceiling heights was more varied. The proportion of 0 ratings was highest in the 2.26 m ceiling height (29.03%) and lowest in the 5.92 m ceiling height (3.23%). Interestingly, the 10 rating had the highest proportion in the 9.57 m ceiling height (23.33%), suggesting that participants experienced more joy in ceiling height with higher ceiling heights.
- Surprise: Surprise ratings exhibited a diverse distribution across various ceiling heights. The proportion of 0 ratings was highest in the 2.96 m ceiling height(6.67%) and lowest in the 5.92m ceiling height (12.90%). The 9.57 m ceiling height had a relatively high proportion of 0 ratings (10%) but also had a high proportion of 10 ratings (10%).

4.2 Study 1: relative emotion rating

The importance of relative emotion analysis is evident in our data. For instance, in the emotion "joy," we can observe variations in reported intensity across different groups experiencing the same ceiling height. These variations, indicated by a range of mean values from 3.709 to 5.531, and standard deviations varying from 2.344 to 3.089, highlight the need for an analysis method that better accommodates for this intra-group variation, such as relative emotion analysis. To gain a more objective understanding of the participants' emotional responses, we employed a method that utilized relative emotional values. In this approach, we designated the 4.79-meter ceiling height as the reference height. We then compared the emotional responses from six comparison heights (2.26, 2.96, 3.66, 5.92, 7.74, and 9.57 m) to the responses at the reference height. This analysis aimed to identify differences and correlations between emotional responses in rooms with varying ceiling heights and the reference height.

1. Negative emotions:

- Fear: The fear scores varied among the groups, but no consistent pattern was found in relation to ceiling height. No significant differences existed between the reference height (4.79 m) and

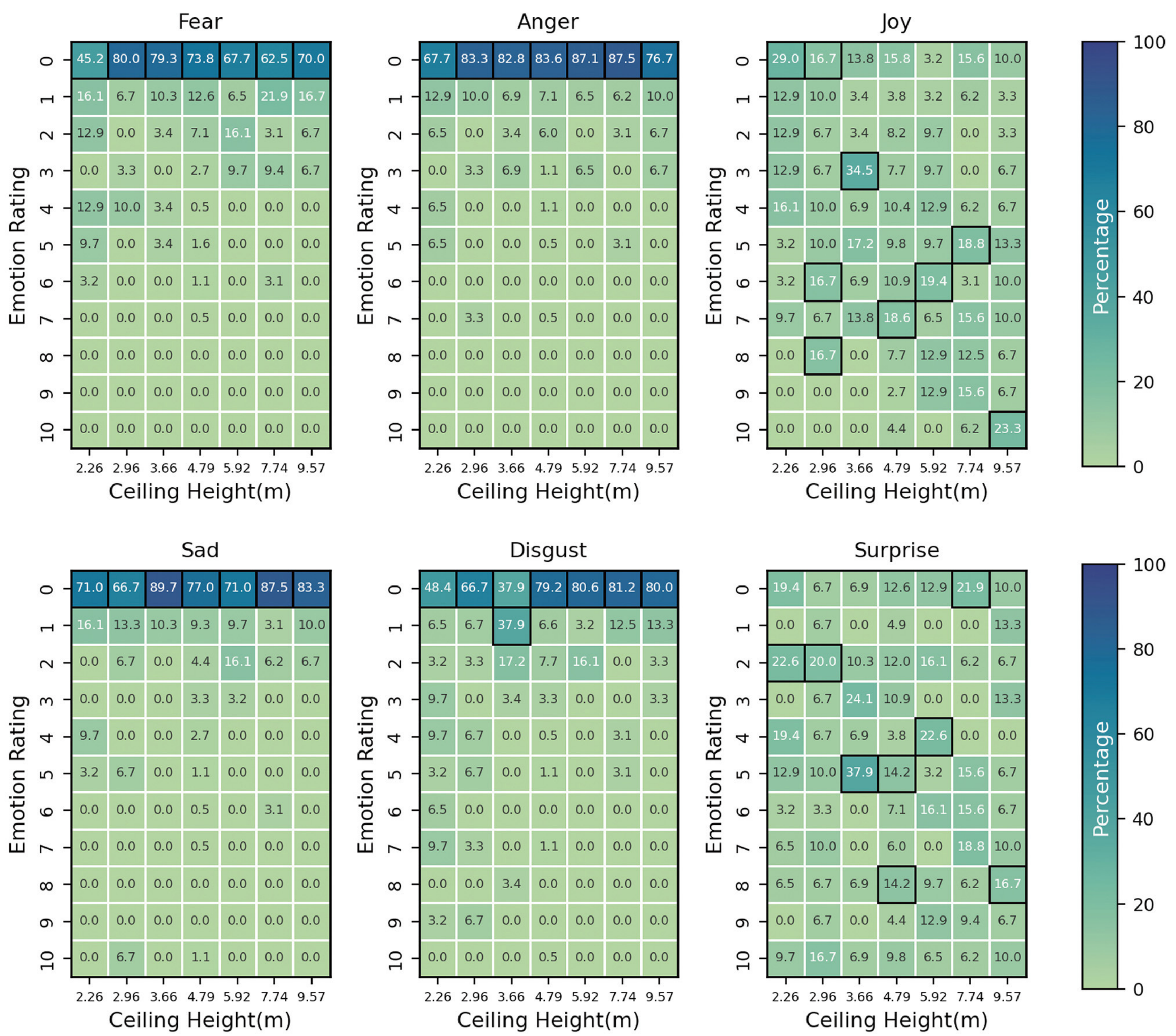

FIGURE 6
Heatmap of absolute emotion values for six basic emotions across ceiling heights.

comparison heights (2.26, 2.96, 3.66, 5.92, 7.74, and 9.57m) in any groups, indicating that ceiling height may not have a substantial impact on fear levels. However, it is worth noting that the differences in the mean and median scores varied across groups, suggesting that other factors may be influencing the fear response in these environments.

- Anger: Similar to the fear category, the anger scores did not show a consistent pattern across ceiling heights. No significant differences were found between the reference height (4.79 m) and comparison heights (2.26, 2.96, 3.66, 5.92, 7.74, and 9.57 m) in any groups, indicating that ceiling height might not play a major role in the experience of anger. However, the variations in mean and median scores across the groups suggest that other contextual factors may have an impact on anger levels.
- Sadness: The results for sadness showed no clear relationship with ceiling height, with varying mean and median scores across the groups. No significant differences were found between the reference height (4.79 m) and comparison heights (2.26, 2.96, 3.66, 5.92, 7.74, and 9.57 m) in any group. This lack of consistency in the results suggests that other factors, besides ceiling height, might be influencing the experience of sadness in these environments.
- Disgust: The experience of disgust varied among groups, with some groups showing significant differences between the reference height (4.79 m) and comparison heights (2.26 m, 2.96 m). In the 2.26m and 2.96 m ceiling height groups, the Wilcoxon signed-rank test revealed significant differences ($p = 0.00624$ and $p = 0.00757$, respectively), with moderate effect sizes (0.2747 and 0.23888). The results indicate that ceiling height may have some influence on the disgust response, but the relationship is not consistent across all groups (see Figure 7).

2. Positive emotions:

- Joy: The relationship between ceiling height and joy demonstrated an interesting pattern. In rooms with ceiling

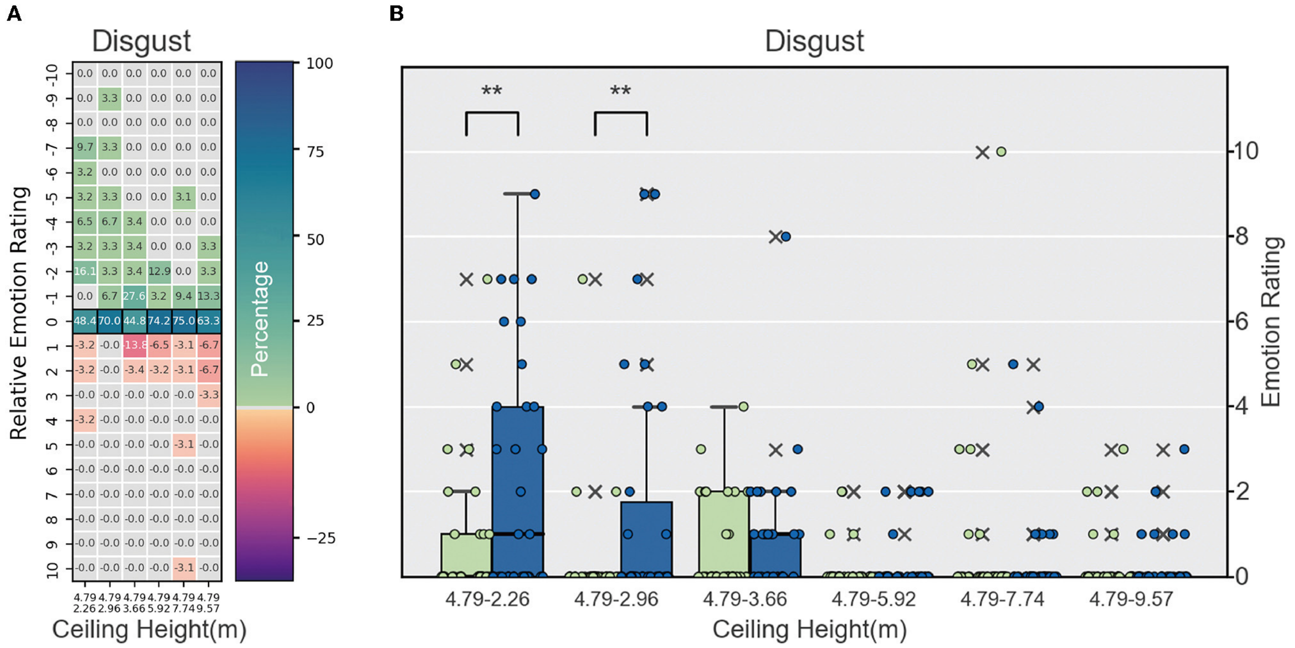

FIGURE 7
(A) Heatmap of relative emotion analysis for disgust across ceiling heights, **(B)** box plot comparing disgust responses at different ceiling heights to reference height, $^{**}p < 0.01$.

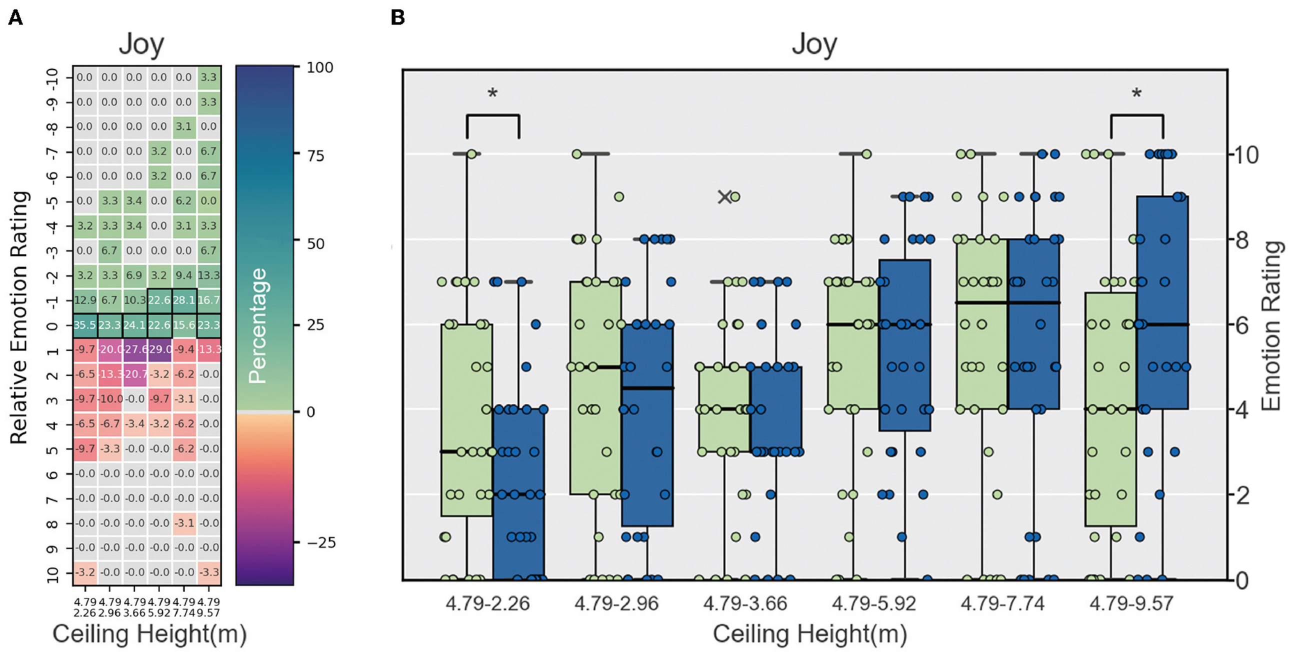

FIGURE 8
(A) Heatmap of relative emotion analysis for joy across ceiling heights, **(B)** box plot comparing joy responses at different ceiling heights to reference height, $^{*}p < 0.05$.

heights of 2.26 and 9.57 m, significant differences were found between the reference height (4.79 m) and comparison heights (2.26 and 9.57 m), indicating that both very low and very high ceiling heights had an impact on the experience of joy. The 2.26 m ceiling height group showed a negative relationship, while the 9.57 m ceiling height group displayed a positive relationship. This suggests that the influence of ceiling height on joy is not linear, and there might be an optimal range where the difference is less pronounced. For the other ceiling heights (2.96, 3.66, 5.92, and 7.74 m), no significant differences were observed between

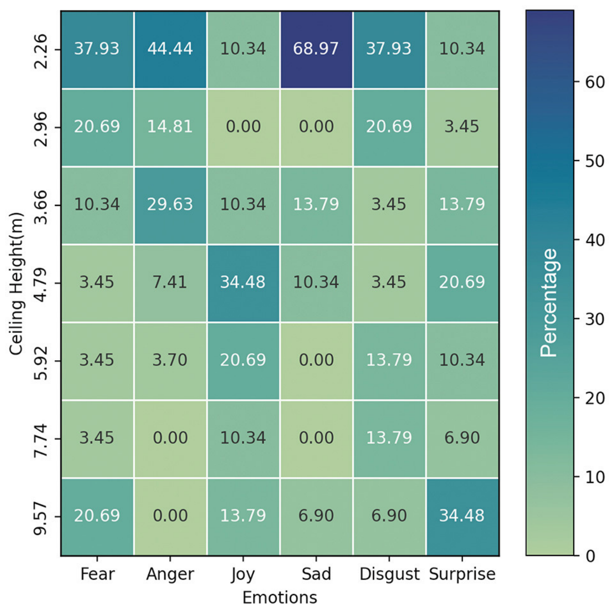

FIGURE 9
Heatmap of emotional associations with different ceiling heights in Study 2.

the reference height (4.79 m) and comparison heights. This indicates that within this range of ceiling heights, the experience of joy is relatively stable and not significantly affected by ceiling height variations. It is worth noting that the impact of ceiling height on joy is more pronounced at the two extremes (2.26 and 9.57 m), suggesting that both very low and very high ceiling heights may have unique effects on the experience of joy in these environments (see Figure 8).

- Surprise: The surprise scores displayed a mixed pattern across the groups. While some groups showed moderate differences between the reference height (4.79 m) and comparison heights (2.26, 2.96, 3.66, 5.92, 7.74, and 9.57 m), no consistent relationship was found with ceiling height. In most groups, no significant differences were detected between the reference height (4.79 m) and comparison heights (2.26, 2.96, 3.66, 5.92, 7.74, and 9.57 m), suggesting that other factors may be contributing to the experience of surprise in these environments. This highlights the complexity of the relationship between ceiling height and emotional responses, as other contextual factors may be at play in shaping the experience of surprise.

4.3 Study 2: choose ceiling height from emotions

In Study 2, the results indicate that participants associated lower ceiling heights (2.26 and 2.96 m) with negative emotions such as fear, anger, sadness, and disgust. For instance, 37.93% of participants chose a 2.26 m ceiling height for fear, while 44.44% selected the same height for anger. On the other hand, a ceiling height of 4.79 m was predominantly chosen for the experience of joy, with 34.48% of participants selecting it. Interestingly, the highest ceiling height (9.57 m) elicited mixed responses, with 20.69% of participants choosing it for fear and 13.79% for joy (see Figure 9). This suggests that extreme ceiling heights may have unique effects on emotional experiences. The results for surprise were also varied, with no clear pattern emerging in relation to ceiling height.

5 Discussion

The findings from this study uncover a complex relationship between ceiling height and emotional responses, as demonstrated in both Study 1 and Study 2. While previous research broadly categorizes lower ceiling heights as fostering negative emotions and higher ceiling heights as promoting positive emotions (Vartanian et al., 2015; Cha et al., 2019), our study delves into more detailed emotional responses. In addition to the structured questionnaire responses, participants provided spontaneous verbal feedback during the main experiment, which indicated a clear perception of changes in ceiling heights. This feedback further validates our findings, demonstrating the effectiveness of our VR simulations in realistically portraying different architectural dimensions.

Specifically, our data indicate that lower ceiling heights correspond to increased feelings of disgust, while higher ceiling heights are linked to enhanced joy. However, the effects on other emotions such as fear, anger, sadness, and surprise are less evident. No consistent patterns emerged for these emotions when comparing participants' responses to the reference height of 4.79 meters.

Upon further analysis, significant differences were observed for disgust between the reference height and the lower comparison heights of 2.26 and 2.96 m. The relationship between ceiling height and joy also presented a distinct pattern, with notable differences identified at the lowest (2.26 m) and highest (9.57 m) ceiling heights. These findings underscore the need for a more detailed understanding of emotional responses to ceiling heights in architectural spaces.

In Study 2, the results indicated that participants associated lower ceiling heights with negative emotions, such as fear, anger, sadness, and disgust, while a ceiling height of 4.79 m was predominantly chosen for experiencing joy. The highest ceiling height (9.57 m) elicited mixed responses, with participants selecting it for both fear and joy, suggesting that extreme ceiling heights may have unique effects on emotional experiences. The results for surprise were varied, with no discernible pattern emerging concerning ceiling height.

Our research differs from the previous studies in several ways, although our findings partially align with theirs. We implemented a wider variety of ceiling heights and provided more precise emotional categorizations. Initially, we considered using a questionnaire format similar to the Self-Assessment Manikin (SAM) (Bradley and Lang, 1994), but such questionnaires can be challenging to translate into clear and straightforward terms, making the results less accessible to non-psychology professionals.

Our second hypothesis, which proposed the use of editable 360-degree panoramic scenes for simulating architectural settings, appears to have successfully provided a more ecologically valid and comprehensive understanding of the relationship between ceiling height and emotional responses. However, to better capture the nuances of real-world architectural experiences, advancements in technology are necessary, such as the integration of Building Information Modeling (BIM) and Augmented Reality (AR) techniques (Chai et al., 2020). The use of BIM-AR technology could potentially enhance the realism of virtual environments and offer a more accurate representation of how individuals interact with and respond to architectural spaces in real-world settings.

Our research offers significant implications for the design of various architectural spaces and contributes to the field of environmental psychology. The nuanced understanding of how ceiling heights affect emotional responses can inform architects and designers in their decision-making process. This is particularly relevant for spaces where emotional ambiance is crucial, such as in healthcare settings, educational environments, and commercial spaces. For instance, higher ceilings in creative spaces could foster an atmosphere of openness and innovation, while lower ceilings in residential settings might create a sense of coziness and security.

Additionally, these findings enrich our understanding within environmental psychology of how physical space influences human emotions. They provide a tangible link between architectural design elements and emotional wellbeing, offering a new perspective on creating spaces that not only meet physical needs but also support emotional health.

Furthermore, the potential of editable 360-degree panoramic scenes in architectural design and virtual reality demonstrates a promising tool for pre-testing the emotional impact of space. This technology could become integral in future architectural planning and design, allowing for a more user-centered approach that prioritizes emotional responses.

6 Limitations

Our study does present several limitations. Firstly, the participant pool consisted solely of architecture students, which may have influenced their perception of the virtual environments and subsequent emotional responses. Moreover, conducting the study within a virtual art gallery setting might not fully replicate the nuanced experiences of real-world architecture. However, it's worth noting that the virtual environment does offer certain advantages, including the ability to maintain consistency and control over experimental conditions.

Secondly, while our study has provided insights into the relationship between ceiling height and emotional responses, it's important to recognize that this relationship might also be influenced by other spatial factors, such as room size and width. Our investigation was confined to a single space, and future research could further explore this dynamic under varied spatial conditions. Regarding the sequence of experimental conditions, we gave this careful consideration during the design phase of the study. The decision to use a medium ceiling height as the reference condition was informed by its common prevalence in many architectural settings, providing a relatable starting point for our participants. During the experiment, several participants even questioned whether they were entering a room of the same height when transitioning to the mid-height conditions, thereby inadvertently validating our decision. We recognize that altering the sequence of experiences could potentially affect the results. For instance, if participants were exposed to the extremes of ceiling height first, it might prime their subsequent responses. As such, future studies might consider manipulating the order of conditions to explore its impact on emotional responses. Nonetheless, for the purposes of the current study, we maintain that our approach allows for a more consistent and controlled exploration of the impact of varying ceiling heights on emotions.

In terms of evaluating emotional responses, our study utilized self-reported measures (Robins et al., 2007). Future studies could consider implementing more objective measurement methods, such as facial expression recognition, which we are currently developing, to provide a more comprehensive assessment of participants' emotional experiences.

These limitations notwithstanding, our findings offer valuable insights into the effects of architectural dimensions on human emotions. This understanding can serve as a foundation for further research in architectural design and environmental psychology, contributing to the creation of more empathetic and emotionally resonant spaces.

7 Conclusion

In this study, we explored the intricate relationship between ceiling height and emotional responses within art gallery settings. Our key findings demonstrate that varying ceiling heights significantly influence emotional experiences, particularly affecting feelings of joy and disgust. The use of editable 360-degree panoramic photo scene modeling technology proved effective in simulating these variations, offering valuable insights into the impact of spatial dimensions on emotional responses.

This research contributes to the broader understanding of how architectural features can shape human emotions, highlighting the importance of considering spatial dimensions in architectural design. The methodology employed in this study opens up new avenues for investigating various architectural aspects and their emotional implications, offering promising prospects for future research in architectural design and environmental psychology.

Our findings provide a foundation for future studies to further explore the complex relationship between architectural spaces and human emotional experiences, ultimately guiding the creation of spaces that enhance wellbeing and emotional comfort.

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 at: doi: 10.6084/m9.figshare.22634017.

Ethics statement

The studies involving humans were approved by Polytechnic University of Catalonia Ethics Committee. 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.

Author contributions

ZZ: Conceptualization, Formal analysis, Methodology, Software, Visualization, Writing – original draft. JF: Conceptualization, Methodology, Supervision, Writing – review & editing. LM: Conceptualization, Data curation, Methodology, Supervision, Writing – review & editing. YC: Investigation, Writing – review & 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.

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Greater usage and positive mood change for users of a dynamic VR app before and after the COVID-19 pandemic onset

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Americans reported an increase in stress during the novel coronavirus disease 2019 (COVID-19). Virtual reality (VR) apps have been shown to distract users from stressors in the environment, but little is known about the efficacy of specific content features to reduce stress or improve mood for consumer users during a pandemic. The present study investigated secondary archival data to explore how mood and usage behavior changed before and after the onset of COVID-19 for consumer users of a VR app with dynamic, interactive content. Study findings indicate that the COVID-19 pandemic had significant effects on user behavior and mood. Users created more accounts and used app content more often during the pandemic, while reporting increased negative mood states. This suggests that users were motivated to use the content to cope with pandemic stressors. Users also experienced a greater positive mood change after using the content during the pandemic than before, which implies that elements related to the VR app content met users' psychological needs. Passive content with less interactivity resulted in a greater positive mood state after the COVID-19 onset, likely related to its capacity to reduce stress, facilitate restoration, and improve persistent affective states in stressful environments. This study offers a vital window into how consumer users respond to psychosocial pandemic stressors outside of a controlled environment as well as the prospective for VR app content to serve as a valuable mental health intervention during similar stressful events.

KEYWORDS

virtual reality, stress, mood, VR, interactivity, presence, pandemic, COVID-19

1 Introduction

As the sense of normalcy from pre-pandemic life returns, significant impacts on mental health remain. U.S. deaths from the virus continue to climb to over 1.1 million deaths (Centers for Disease Control and Prevention, 2023). The need for effective mental health tools has increased as Americans reported prolonged and acute stress during the height of the pandemic. In fact, the American Psychological Association (APA) has warned that we are facing a national mental health crisis that could have serious repercussions for our health and society in the years to come (American Psychological Association, 2020; Centers for Disease Control and Prevention, 2020). The demand for useful interventions to support mental health during psychosocial pandemic-like stressors has advanced the exploration of media content with the capacity to relieve psychological stress, such as virtual reality (VR) software applications, also referred to as VR apps. VR technology involves the use of a headset that allows a user to interact with app content via a simulated three-dimensional (3D) virtual world. One method to investigate whether specific VR app content may improve stress during a pandemic environment is to evaluate trends of usage behavior and reported mood for home users of those apps during COVID-19.

Because stress can have markedly negative long-term health consequences (Segerstrom and Miller, 2004; Leger et al., 2018; Song et al., 2019), determining how Americans have managed this stress at home and what methods have been most effective in the pandemic context can shed light on future interventions. The growth of technology for communication in a post-COVID-19 onset world has contributed to a rising population of consumer users with greater access to devices and apps promoted as stress management tools for use at home. More immersive devices, such as VR headsets and associated apps, are becoming increasingly common as well, along with virtual content designed to promote stress reduction.

While the literature is rich with studies exploring how VR may be an effective method for distraction in and out of the healthcare setting (Hoffman et al., 2014; Small et al., 2015; Burns-Nadera et al., 2017; Boylan et al., 2018; Khadra et al., 2018; Piskorz and Czub, 2018; Soltani et al., 2018; Hoffman et al., 2019; Spiegel et al., 2019), it is more limited on the usage behavior and efficacy of VR apps with unique content features on psychological stress and anxiety reduction, excluding the growing literature on mindfulness and meditative practices (Seabrook et al., 2020; Mazgelyte et al., 2021; Drigas et al., 2022; Kelly et al., 2022; Mitsea et al., 2022, 2023). Moreover, the psychological effects of these content features and user app use have not been adequately investigated in the consumer user population during a pandemic setting.

This study utilized a quasi-experimental repeated measures design with consumer archival data to examine whether the COVID-19 pandemic was associated with an increase in psychological stress, associated behaviors, and affective states for users of different types of VR app content. The study explored whether users increased app usage for certain content when compared to their usage prior to the pandemic. The study also investigated whether usage led to better mood score outcomes reported by these users. Finally, the study examined whether users during the pandemic who experienced additional interactive content features reported more positive mood scores than with the lower levels of interactive content. Consequently, this research provides a unique window into consumer VR app user behavior, motivations, coping mechanisms, interactive content feature effects, and mood outcomes outside of a controlled environment and in the context of a larger psychosocial stressor event. It also provides important implications related to the efficacy of VR app content as an intervention for stress, mood regulation, and wellness for users at home during pandemic or related stressful contexts.

The VR app used for this study is the TRIPP app, a wellness platform with unique, dynamic content designed to reduce anxiety, increase focus, and increase feelings of calm. TRIPP app content experiences include various virtual environments with dynamic visual and audio features that are referred to in this study as worldscapes. When a user engages in a worldscape with the VR app, this is indicated as a run.

This paper will discuss the literature review and theoretical frameworks underlying the psychological impacts of VR content, associated user behavior, and the unique features of VR that may enable stress reduction. Then, the paper will review study methodology and findings before discussing COVID-19 as a predictor for usage behavior and mood as well as interactions with mood and interactivity level. The paper will consider limitations, conclusions, and close with suggestions for future studies.

2 Literature review

2.1 Stress regulation and VR content

Psychological convention on stress regulation implies that consumer users at home during the pandemic are likely to seek out the most effective methods to manage stress available. Coping with stress consists of the "cognitive and behavioral efforts to master, reduce, or tolerate the internal and/or external demands that are created by the stressful transaction" and involves both emotional regulation and problem management (Folkman, 1984, p. 843). Established theories around arousal, mood management, stress and coping, as well as self-regulation all suggest that stress reduction can be facilitated through stimuli or resources in the environment that provide the appropriate level of arousal and/or emotional regulation (Berlyne, 1971; Folkman, 1984; Zillmann, 1988a,b; Bandura, 1991).

Berlyne (1971) implies that individuals will seek out the appropriate stimuli in an effort to obtain a desired state of arousal. Individuals generally prefer an intermediate level of arousal and find this to be a more pleasant experience (Berlyne, 1971). Therefore, those who are bored or under-stimulated and more isolated at home will select media devices and content that increase arousal, while those who are stressed or over-aroused in the same environment will opt for relaxing media stimuli to regulate arousal levels.

VR device content can serve as a feature in the environment which promotes a sense of control and positive distraction, two of the psychological needs that should facilitate a user's ability to cope with stressors (Ulrich et al., 1991; Ulrich, 2001). Perceived control can be influenced via interaction, while VR content with dynamic, naturalistic elements is expected to enhance this effect because of the inherently pleasing properties of nature and its restorative effects (Gerber et al., 2017; Tanja-Dijkstra et al., 2018). The ability to experience content evocative of nature is likely to be especially important when supportive outdoor recreational activities are limited.

Positive distractions, such as VR app content, accessible in the home environment may influence the experience of positive feelings and distraction from negative stimuli. The level of interactivity the user has with the virtual environment as well as the level of control the user has over conducting tasks and manipulating objects in that environment should influence perceived control, which can be expected to increase the sense of presence (Witmer and Singer, 1998). Users are encouraged to choose content that produces the greatest sense of presence and distraction from outside environmental stressors, including content features with the highest level of interactivity.

The uses and gratifications (U&G) theory (Katz et al., 1973; Rubin, 2002), along with the compensatory internet use theory (Kardefelt-Winther, 2014), suggest that users will continue to be motivated to choose and use devices and features of those devices if certain psychological needs are met. Needs motivate behavioral outcomes when users select media content that is expected to offer gratifications or expected gains (Rauschnabel, 2018). These needs include cognitive, informational, tension-release, diversion, affective or aesthetic experience needs, and/or to regulate negative emotion (Katz et al., 1974; Kardefelt-Winther, 2014; Rauschnabel, 2018).

Many resources and coping options were limited during some of the most stressful months of the pandemic. However, when users have access to a resource in the environment that facilitates positive distraction from stressors, reduces arousal in high stimulation environments, influences an intermediate level of arousal, provides a coping resource in the environment that helps to promote emotional regulation, and meets certain psychological needs, a reduction in stress can reasonably be expected. Users should choose to engage in VR app content when environmental stress increases in order to regulate this stress.

Therefore, for users of an app delivered by a VR headset with dynamic content, we predict:

> *H1*: Users will use content more frequently during the Pandemic than Pre-Pandemic.

2.2 Mood and usage behavior

The relationship between stress and mood is complex. Research shows that stress hormones, such as cortisol and norepinephrine, have associations with low mood as well as anxiety (Drigas and Mitsea, 2020). In contrast, serotonin and oxytocin are linked with positive mood states (Drigas and Mitsea, 2020). Furthermore, psychosocial stressors can modify sensitivity to oxytocin through alterations in brain region connectivity (Fan et al., 2015). Mood is of great interest for investigating whether usage of specific content on VR devices can influence a more persistent affective state than initial, short-lived emotional responses to stimuli.

Affective responses to pandemic stress may best be measured by mood because it reflects a user's appraisal of his or her relationship with the environment and the larger overarching factors in life (Lazarus, 1991; Morris, 1992; Russell, 2003, 2005; Ekkekakis, 2013). While there is some argument that mood lacks a direct object, other research supports the notion that moods often reflect a more generalized or overview outlook on the greater issues in one's life rather than an adaptation to a particular stimulus (Lazarus, 1991; Morris, 1992; Russell, 2003, 2005; Ekkekakis, 2013). For these reasons, user mood changes in response to usage of VR content are expected to be the most representative of how a user is feeling, not just about the situation in the immediate environment, but also the overarching domain. Lower mood levels reported before using an app may accurately reflect the longer-term effect that COVID-19 has had on a user's life outlook, while higher mood scores after using an app would then suggest that the app content positively influenced this overarching mood state.

Mood management theory posits that a user's current emotional state will influence, either directly or indirectly, what media content that user assesses will optimize mood (Zillmann, 2000). This includes efforts to promote emotional regulation, such as reducing negative mood and maintaining positive mood (Zillmann, 2000). Users are likely to choose content designed to reduce stress and boost mood, since users may be motivated, in part, to satisfy affective or aesthetic needs and improve negative affect (Kardefelt-Winther, 2014; Rauschnabel, 2018). Because emotions and mood are associated with self-regulation, engaging in behavior with VR app content that induces positive affect will likely encourage continued engagement with this feature of the environment (Fredrickson, 2001). In this view, users would be innately motivated to engage in VR content that meets their affective goals based on their feelings related to the pandemic when they are likely to feel stressed and experience low mood.

Because mood is expected to be sensitive to longer term psychosocial stressors present in a user's environment, and users are innately motivated to choose media content that will potentially reduce stress and boost negative mood, we predict that for users of an app delivered by a VR headset with dynamic content:

> *H2*: Users will report lower mood scores at the start of content runs during the Pandemic than Pre-Pandemic.

2.3 Immersive VR: presence and interactivity

Characteristics associated with VR app content, such as presence, immersion, and interactivity play a role in relieving user stress through various mechanisms and interrelationships. The experience of presence is important for distracting from unpleasant stimuli and may mediate the restorative effects of VR nature-based content (De Kort et al., 2006). Presence may mirror similar components as that of restoration (Lessiter et al., 2001; Schubert et al., 2001; Freeman, 2004; De Kort et al., 2006). According to Mitsea et al. (2023), VR content minimizes cognitive load, mental fatigue, and increases processing capacity. Several studies have shown that fun ratings for VR positively correlate with sense of presence and pain reduction (Hoffman et al., 2006, 2008; Maani et al., 2011). Immersive factors, such as interactivity may also influence a greater experience of presence, as will increased control over the VR environment, particularly with greater ability to manipulate elements in that environment.

Previous studies have shown that interactivity plays a critical role in how effective device content may be as a distraction from stressors and unpleasant stimuli in the greater environment (Sil et al., 2014; Boylan et al., 2018). For example, one study showed that pain tolerance was improved with engagement in more active media, such as a video game or VR world, than simply watching video clips (Boylan et al., 2018). Another study found that the interactivity of a video game itself on a Nintendo Wii console was enough to effectively distract children from pain and improve pain tolerance (Sil et al., 2014). Furthermore, complexity that requires greater task interaction and additional challenges may be an even more effective distractor (Piskorz and Czub, 2018).

VR content may not only distract a user's attention but also direct the user's attention toward targeted goals or behaviors (Mitsea et al., 2023). Digital game-based tasks that challenge the user to overcome obstacles through attention or observation offer intrinsic or external rewards and reinforcement. They can improve self-efficacy, mental and emotional well-being as well as self-regulation (Mitsea et al., 2023). These games can also enhance positive emotions, satisfy psychological needs, and contribute to feelings of control (Mitsea et al., 2023). Presence, interaction, and immersion are thought to further enhance the VR gaming experience so that it is less stressful, more enjoyable, and meaningful (Mitsea et al., 2023). For example, VR games can positively impact feelings of autonomy, competence, need satisfaction, and greater positive feelings than traditional game displays (Mitsea et al., 2023). VR app content with gaming elements also contributes to self-motivation and drives performance improvement (Mitsea et al., 2023).

The passive content in this study more likely utilizes positive distraction and restoration as a means of improving stress and mood. While this VR content also includes high levels of presence and immersion, it requires less interactivity than the active content. The active content involves a basic VR game, which entails task challenges and, based on past literature, should result in superior stress reduction during increased pandemic stress. Principles around coping, perceived control, arousal optimization, gratification, and mood regulation merged with a high interactivity level for the active content reinforce this assumption. Furthermore, if the pandemic causes a greater mood decrement overall, then a greater change in mood from before a user engages in the active content vs. after can be anticipated.

Consequently, for users of an app delivered by a VR headset with dynamic content, we predict:

> *H3*: Interactivity level (active vs. passive) will interact with Time (Pre-Pandemic vs. Pandemic) such that mood score change will be higher for active content during but not before the Pandemic.

3 Methods

3.1 Participants

Participants for this study were taken from anonymous user archival data via the TRIPP app for users that met specific criteria, such as geographic location, completed (pre post) survey data, and data presence across the full time series. The number of U.S.-based users meeting criteria for the study included 14,653 accounts. The gender composition of these users was approximately 53.7% male, 38.2% female, and another 7.3% had no answer. Exclusion criteria included any users that did not provide complete survey data, those who reported as users outside of the U.S., or those who did not have data available for the time period needed for the assessed dates.

3.2 Measures

3.2.1 Mood

The Mood score was measured via a quantitative mood survey that appeared at the beginning and end of each worldscape run. Users could select a number from 1 to 10 (1 = Poor, 10 = Excellent) to represent their perceived mood, resulting in a Mood Scale score. The mood scale used by TRIPP was developed by a team at the National Mental Health Innovation Center and appears to have good face validity because it is expected to provide an appropriate measure of subjective mood scores from the individual user perspective across time. Because data was collected via archival data, time-related and carryover effects could not be controlled for. However, to ensure high levels of internal reliability, individual variation was controlled for with the within-subjects design and repeated measures.

3.2.2 Usage

Usage behavior was measured across time by exploring several variables derived from the data that indicated when account users accessed specific TRIPP content. This included the number and frequency of worldscape runs by week and month. The number of accounts and whether an account had active users who had used the content within a certain time frame were also examined to determine usage behavior.

3.2.3 Time frame

Pre-Pandemic was defined as between 7/24/2019 to 3/9/2020, while Pandemic was defined as a period of time between 3/15/2020 to 9/1/2020. The dates for the Pre-Pandemic and Pandemic event for all hypotheses were separated by an interval of 5 days from March 10–14, which included the March 11 date when COVID-19 was declared a pandemic by the WHO and the March 13, 2020 date when COVID-19 was declared a national emergency in the U.S. This time frame was selected to allow for a one-day period before COVID-19 was declared a pandemic by the WHO and 1 day after COVID-19 was declared a national emergency in the U.S. to account for variations in when users may have become aware of pandemic status. Therefore, data from these interval dates were generally not included in hypotheses analysis.

3.3 VR experience

The user experience with the TRIPP app involved the use of a head-mounted display to fully immerse the user into a simulated environment with visual and sound elements. The headset utilized a head-tracking system that allowed natural movement for the user within the VR world. The TRIPP app content in this study also had interactive capabilities as well, so that the user could take action to affect the VR environment. The user could choose to interact with the environment by fixating one's gaze on an interactive object in the worldscape. At the beginning of the worldscape run, the user is asked to rate their mood. After they complete the VR experience, the user is asked to rate their mood again.

3.3.1 Active vs. passive

The interactivity level of the content was defined as either active or passive. Passive content has a lower level of interactive content designed to promote relaxation, reduce psychological stress, and improve mood. Active content has a higher level of interactivity designed to promote focus, reduce psychological stress, and improve mood. It also includes an interactive arcade-style game with tasks that must be completed to move forward with the experience in the TRIPP app.

For this study, the VR app passive content consisted of content with a lower level of interactivity designed to promote relaxation, reduce psychological stress, and improve mood. This VR experience featured natural and organic scenes with movement, color and shape changes, interest points, and gentle music. TRIPP reports that average run time for these passive worldscapes is 13.77 min.

The active content is defined as content with a higher level of interactivity designed to promote focus, reduce psychological stress, and improve mood, featuring similar content as the passive worldscapes but with the addition of psychedelic visuals and an interactive arcade-style game with tasks that must be completed to move forward with the experience in the app. The tasks may include using a randomly colored disc shooter to clear a row of three discs of the same color before the remaining discs reach the end of a line or making contact with coins between obstacles. Average run time for these worldscapes is reported by TRIPP to be 8.08 min.

Screen shots of the dynamic, nature-based visuals in the TRIPP app are depicted in Figures 1A–D, while the active vs. passive screen shots are shown in Figures 2A,B.

3.4 Procedure

The study involved the analysis of existing archival data from the consumer VR app TRIPP. Data was composed of de-identified account information, session information, and run information as well as various data associated with each run as allowed by company privacy policy. Users were limited to those accounts reporting as U.S.-based, which TRIPP noted represented about 64% of the accounts available in the dataset. We selected only those worldscape runs with a disposition categorized as either "aborted" or "completed." An aborted run is indicated when a user engages in worldscape content but does not finish either the entire worldscape experience and/or the mood rating questionnaire at the end. A completed run means the user finished the worldscape experience and also filled out the survey at the end of the run.

3.5 Analysis

The method for H1 and H2 was a within-subjects pretest-posttest design comparing reported mood scores as well as usage behavior based on frequency of runs Pre-Pandemic and Pandemic for users of the TRIPP app. Mood Scale scores and frequency of user worldscape runs were analyzed via archival data from 7/24/2019 to 9/1/2020 for US users on the TRIPP VR app. Scores during the COVID-19 event transition period (from and to dates) were discarded from the analysis.

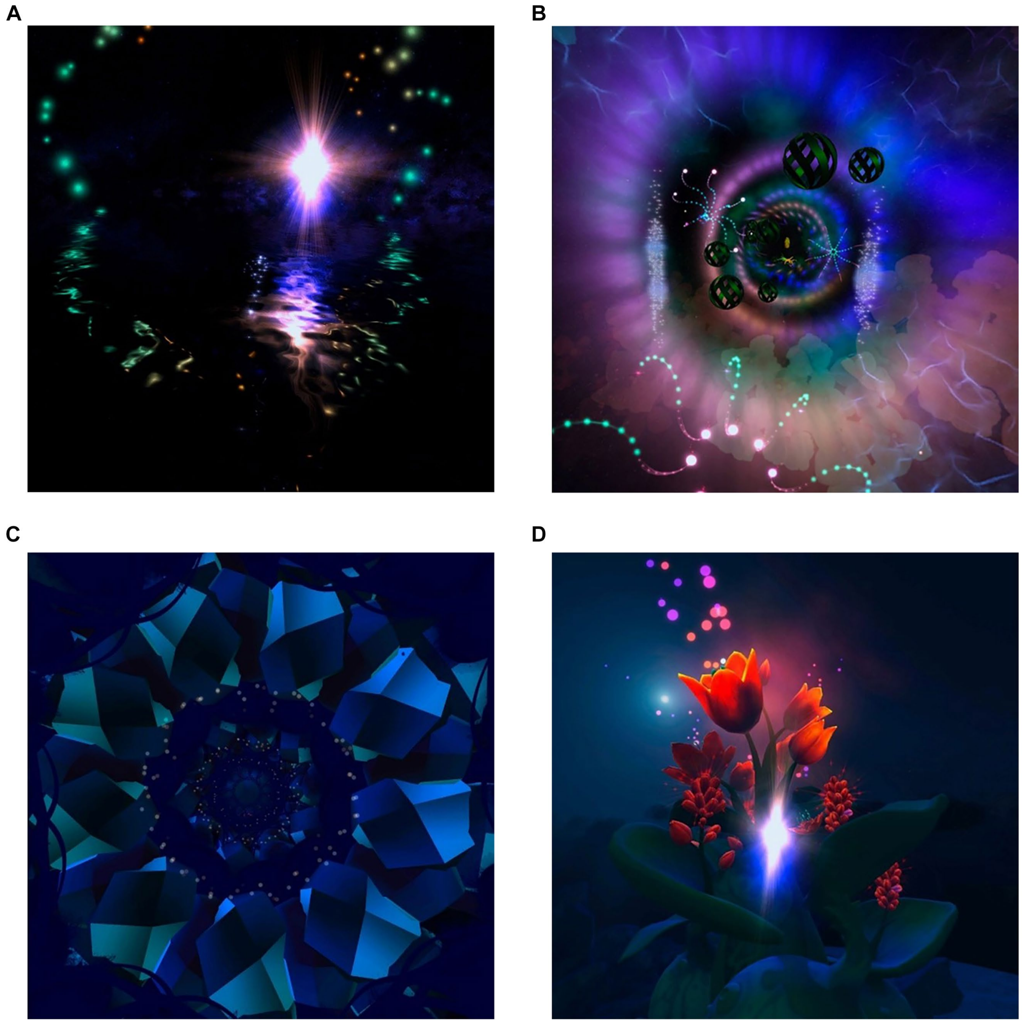

FIGURE 1
Dynamic, nature-based TRIPP content **(A–D)**. Reproduced with permission from TRIPP, Inc, www.tripp.com.

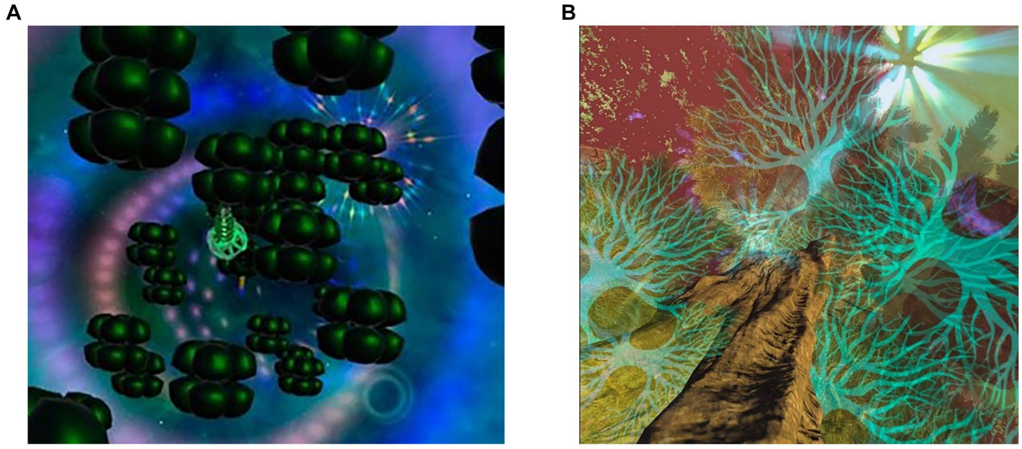

FIGURE 2
TRIPP active and passive content scenes **(A)** Active, **(B)** Passive. Reproduced with permission from TRIPP, Inc, www.tripp.com.

Mood Scale score before and after app use was also analyzed to examine mood score change.

The method for H3 was a within-subjects design comparing the Mood Scale score before and after app use to explore mood score change from the active vs. the passive content conditions for both Pre-Pandemic and Pandemic.

4 Results

For H1 and H2, data included 181,496 U.S. worldscape runs within 14,653 user accounts. For H3, a smaller sample of 121,140 U.S. worldscape runs categorized as either passive or active was analyzed. Other content outside of these categories was not analyzed.

The natural consumer behavior for users of this particular VR app appeared to be sporadic, decreasing dramatically from the first week of use to later weeks. Therefore, usage behavior for the app content often varied within different time frames, making date and certain time comparisons impractical.

Several variables were extracted and created from the raw data to address the hypotheses.

4.1 H1 users will use content more frequently during the pandemic than pre-pandemic

To compare the number of runs Pre-Pandemic and Pandemic, the number of runs per month from November 2019 to June 2020 was examined. This time frame was chosen to give good representation of frequency of use before COVID-19 and after COVID-19, which was defined as before March 9, 2020 and after March 15, 2020, respectively. Additional variables were created that indicated the number of "completed" and "aborted" runs each month from November to June, the number of accounts with a first run each month from November to June, and how many runs were initiated in the first week of use. Preliminary analyses indicated a dramatic drop-off in use for the second week of use, so the first week was chosen as an indication of use Pre-Pandemic and during the Pandemic.

TABLE 1 Number of runs per month.

Month	Aborted runs	Completed runs	Total runs	Accounts with first run
November	88	523	611	50
December	442	2,821	3,263	754
January	2,744	8,752	11,496	1,280
February	2,896	9,545	12,441	874
March	2,500	8,695	11,195	727
April	5,254	11,980	17,234	1,502
May	6,987	11,787	18,774	1,556
June	5,709	10,436	16,145	1,146

Analyses consisted of frequency counts and is shown in Table 1 by number of runs per month (total, completed, and aborted) as well as the number of accounts with a first run each month. This was illustrated by bar graphs in Figure 3 depicting the number of runs (total, completed, and aborted) each month.

The analysis showed a fairly steady number of runs January through March of 2020, and then a sharp increase for April through June after COVID-19. Of additional note is the dramatic increase from December to January, which we speculate is due to holiday-related sales of the TRIPP application. There were more runs of the app during the 3 months after COVID-19 than the 3 months before COVID-19.

Figure 4 displays the number of accounts that had a first run each month. As is shown, the number of user accounts with first worldscape runs nearly doubled from March to April. Therefore, the jump in number of runs is likely due to the increase in the number of these first time runs after COVID-19.

To see whether there was a change in the number of runs within the first week of use for each account before and after COVID-19, 14,423 accounts were examined. This is slightly less than from the initial dataset, as there were accounts that had an initial session

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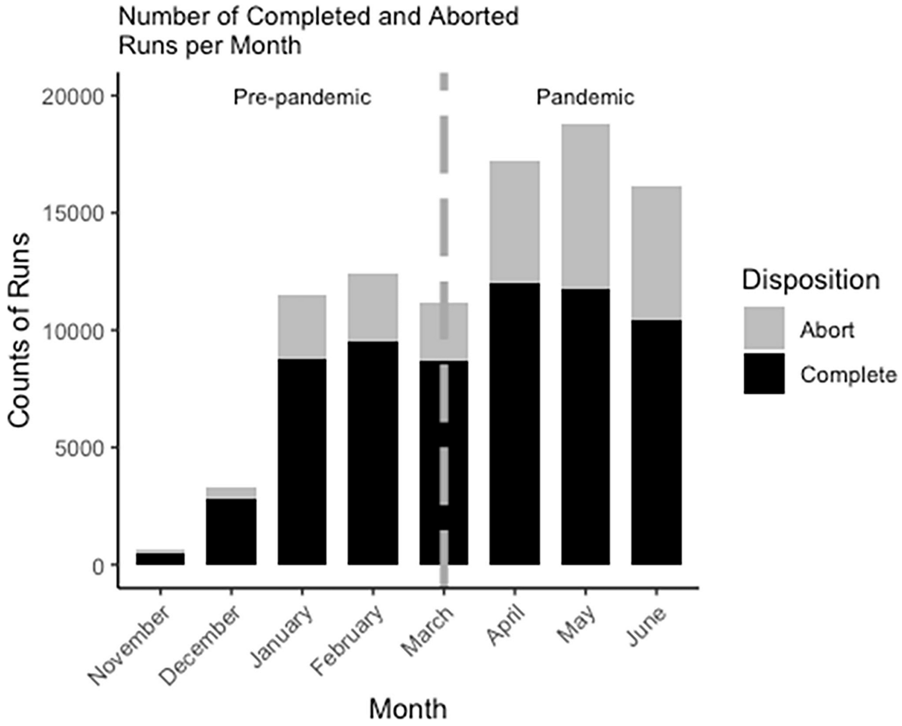

FIGURE 3
Stacked bar chart of runs per month November to June.

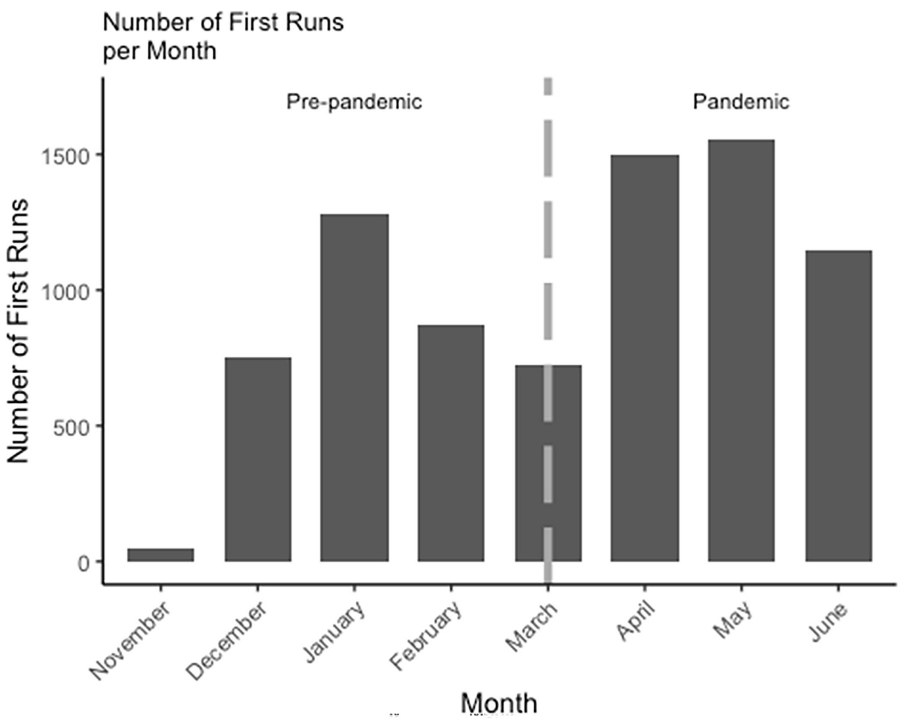

FIGURE 4
Number of accounts that had a first run each month.

between the COVID-19 dates defined (between 3/9/2020 and 3/15/2020) that were not included.

As Table 2 depicts, *T*-tests of Pre-Pandemic and Pandemic showed that the number of runs the first week of use increased significantly if the first session was after COVID-19.

In order to investigate if aborted or completed status of runs interacted with the number of first week runs Pre-Pandemic and Pandemic, a 2×2 ANOVA was used to compare the number of runs in the first week of use for both Pre-Pandemic and Pandemic. Findings showed that the average number of first week runs per account that were aborted were 2.71 (SD = 2.44) Pre-Pandemic and 3.81 (SD = 3.45) during Pandemic. The average number of first week runs per account that were completed were 4.56 (SD = 4.19) Pre-Pandemic and 3.62 (SD = 3.53) during the Pandemic. The interaction of the 2 × 2 ANOVA was significant $F(1, 23, 620) = 299.34$, $p < 0.001$, partial $\eta^2 = 0.01$. The interaction plot below in Figure 5 depicts that the number of aborted runs increased after COVID-19, and the number of completed runs decreased. All simple effects comparisons between groups were significant.

Next, we calculated and compared the number of user worldscape runs for the week prior and the week after COVID-19 as well as the number of active accounts that had at least one run the week prior and the week after COVID-19. This would provide additional information on usage trends. For the week prior to COVID-19, there were 2,584 worldscape runs and 648 active accounts. For the week right after the start of COVID-19, there were 4,727 worldscape runs and 914 active accounts. This data added to the general trend of more active accounts and more runs after the COVID-19 pandemic.

Finally, we examined changes in use after the COVID-19 onset for 648 accounts that had an active account showing at least one worldscape run before the start of the COVID-19 pandemic. A paired sample t-test indicated the number of runs decreased somewhat in these accounts after COVID-19 as displayed in Table 3.

4.2 H2 users will report lower mood scores at the start of content runs during the pandemic than pre-pandemic

To compare opening mood Pre-Pandemic and Pandemic, a variable was created for the average mood per week within an account. Average mood per week per account provided a more accurate index of mood and eliminated the necessity of equal time periods Pre-Pandemic and Pandemic. A change in mood score was calculated subtracting opening score from the closing score for the mood questionnaires for each run, averaged per week per account.

A paired samples analysis compared opening mood and change in mood scores for those accounts that had at least one run for both Pre-Pandemic and Pandemic. This is shown in Table 4.

The paired samples *t*-test analysis indicates that mean opening mood significantly decreased from Pre-Pandemic to Pandemic and change of mood had a slight but significant increase. Users reported lower opening mood after the COVID-19 pandemic became a national emergency than before, and the change in mood after engaging in worldscape runs on the app was greater after the pandemic than before. However, it is worth noting that the effect sizes are small for mean mood ($d = 0.14$) and mood score change ($d = 0.06$), and the sample on which the statistical significance is based is large (>1,000).

4.3 H3 interactivity level (active vs. passive) will interact with time (pre-pandemic vs. pandemic) such that mood score change will be higher for active content during but not before the pandemic

Worldscape runs were identified as either active with a high level of interaction or passive with a low level of interaction based on the worldscape experience content name and whether it involved an interactive game or not. To see whether content type affected mood score change, intraindividual effects were not examined due to limited available repeated data within accounts, and instead each run, whether active or passive, was treated as an independent event. Mood change variables were created to evaluate change in mood before and after using the VR app content, along with variables to identify whether the worldscape run was Pre-Pandemic (before 03/09/2020) or Pandemic (after 03/15/2020).

Two analyses were conducted to examine the question of how mood change varied between passive and active runs and whether this change varied from Pre-Pandemic and Pandemic. A preliminary independent *t*-test analysis was conducted to see if there was a significant difference in mood change when comparing passive and active runs. The second analysis used a 2×2 ANOVA to examine if this change varied Pre-Pandemic and Pandemic.

There were fewer passive runs (n = 55,730) than active runs (n = 68,410) in this data set. Mean mood change for before and after runs is displayed below in Table 5.

For the total sample, the passive runs had a greater mood change than the active runs, but this change was quite small (Cohen's $d = 0.03$). In addition, there was a significant interaction between type of run (passive or active) and when the run occurred, Pre-Pandemic or Pandemic, when examining mood change, as illustrated in the graph below (Figure 6).

Before COVID-19, there was no difference in effect between passive and active runs in this dataset. After COVID, the passive runs had an effect roughly 1/10 point greater than the active runs. As indicated in the figure above (Figure 6), the difference between active and passive is significant for after COVID-19, but not before COVID-19. The difference between before COVID-19 and after COVID-19 was significant for the passive runs but not for the active runs. It is important to note that while these results are significant, the differences are small.

TABLE 2 *T*-test comparison of number of runs in first week pre-pandemic and pandemic.

	Pre-pandemic	Pandemic	Mean difference	*t*-value	Cohen's *d*
First week runs	5.78 (5.39)	6.28 (5.60)	0.50 [0.29, 0.72]	4.64***	0.09 [0.05, 0.13]

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

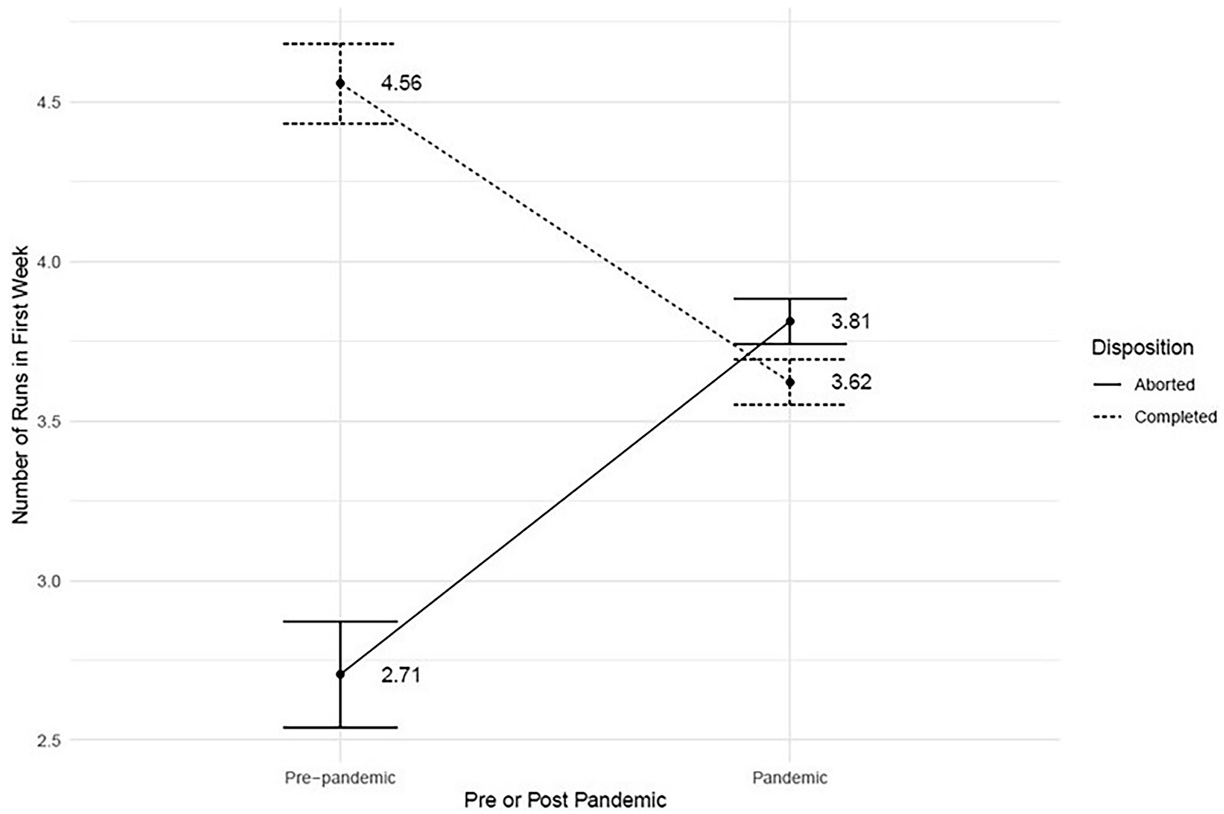

FIGURE 5
Number of runs by disposition pre-pandemic and pandemic.

TABLE 3 Number of runs week prior and week after COVID-19 within accounts.

	Week prior to COVID-19	Week after COVID-19	Mean difference	*t*-value	Cohen's *d*
Number of runs	3.99 (3.86)	3.20 (5.89)	.-0.79 [−0.38, −1.19]	3.08***	0.15 [0.07, 0.23]

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

5 Discussion

This study explored how COVID-19 affected behavior and mood for consumer users of a VR app with dynamic content and various levels of interactivity. Analyses addressed three primary questions. First, how did the frequency of use for a VR app with dynamic, interactive content change Pre-Pandemic to Pandemic? How did the reported opening mood and change in mood when using this VR app content vary Pre-Pandemic to Pandemic? Finally, did mood change differ between passive and active worldscape runs and did this change vary from Pre-Pandemic and Pandemic?

5.1 COVID-19 onset as predictor for frequency of app content use

A pattern of app use emerged from the analysis findings, which showed increases in use during the COVID-19 pandemic. The total number of worldscape runs per month spiked from April to May as did the total number of accounts with a first run in the data, likely explaining the increase in the number of worldscape runs as new users chose to use the app content to a greater degree shortly after the effects of the COVID-19 pandemic manifested. Likewise, the number of runs for a user's first week of use increased after COVID-19 became a national emergency. New users in the data used the app more than they did before. Furthermore, the number of runs for the immediate week prior and after COVID-19 increased, coinciding with the start of the pandemic, and active accounts with at least one worldscape run prior and after the pandemic increased as well. The trend in this frequency data all suggest that users created more accounts and used this app content more often after the start of COVID-19.

However, two other relevant findings were discovered during the analysis. To further examine usage of these worldscape runs, such as whether the runs were partially or completely finished from beginning mood survey to closing mood survey, data were examined to compare the frequency of completed or aborted runs. The results showed that there were a greater average number of aborted disposition runs in the first week of use after COVID-19 compared to before COVID, with the opposite pattern for completed runs. It is important to note that a disposition of aborted simply means the user did not complete the

TABLE 4 Paired samples *T*-test pre-pandemic pandemic for opening mood and mood change.

	Pre-pandemic	Pandemic	Mean difference	*t*-value	Cohen's *d*
Opening mood ($n = 1,187$)	5.97 (1.30)	5.76 (1.60)	−0.21 (1.51)	−4.75***	−0.14 [−0.08, −0.19]
Mood change ($n = 1,103$)	1.48 (0.98)	1.56 (1.32)	0.08	2.09*	0.06 [0.004, 0.12]

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

TABLE 5 Mean mood change pre-pandemic and pandemic.

	Total sample	Pre-pandemic	Pandemic	Mean difference
Passive	1.49 (1.52)	1.45 (1.48)	1.51 (1.53)	0.06 [0.02, 0.10]***
Active	1.45 (1.47)	1.46 (1.53)	1.44 (1.45)	−0.02 [−0.05, 0.01]
Difference	0.05*** [0.03, 0.07]	0.01 [0.03, −0.05]	−0.07*** [−0.09, −0.05]	

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

entire worldscape run experience and fill out the survey at the end. This implies that first time users tended to not finish the worldscape experiences and/or surveys more often during the week after the pandemic than the week before.

The other finding of interest is that within active accounts, the number of worldscape runs actually decreased significantly when an analysis was conducted looking at the week prior and the week after COVID-19. Users who used the app at least once in the week before the COVID-19 pandemic used it less the week following the COVID-19 pandemic being declared. This indicates that the majority of the increases in accounts and runs were not from active users. However, it is important to consider these results in the context of the trend in the data for each user to generally drop usage from Week 1 to 2. An analysis of whether this decline was to a greater or lesser degree than before the COVID-19 pandemic was not feasible. It is also worth noting that additional weeks for these users were not analyzed to indicate whether this pattern continued as the pandemic progressed.

The findings in this study add to the prior research, in that new or less active users seemed to be more motivated to use the app content more frequently and to complete the worldscape runs, perhaps as a coping mechanism to deal with the added stressors of COVID-19 as suggested by the trends in the data after the start of COVID-19. This appears to be consistent with theories of supportive design, arousal, mood management, stress and coping, as well as self-regulation in the choice of content (Berlyne, 1971; Folkman, 1984; Zillmann, 1988a,b; Bandura, 1991; Ulrich et al., 1991; Ulrich, 2001).

However, users appeared to abort runs more frequently and users who used the app in the week before COVID-19 did not appear to use it as much in the week after COVID-19. Based on the literature, there could be various reasons for this. The uses and gratifications (U&G) theory, along with the compensatory internet use theory, suggest that users are motivated to use devices and features of those devices in order to satisfy an array of psychological needs, including tension-release, diversion, affective or aesthetic experience needs, and emotional regulation (Kardefelt-Winther, 2014; Rauschnabel, 2018). This suggests that users may have been able to achieve self-regulation and the appropriate level of arousal during COVID-19 with less runs, thus relieving stress and improving mood prior to completing the experience. Users were motivated to use the app only for the duration of time it took to achieve the desired psychological benefits, including distraction from outside stressors related to the pandemic.

Of course, another possibility along these lines is that users who were initially motivated to use the app content lost motivation to start and continue runs because the content was not meeting these increased demands during the COVID-19 pandemic. Interestingly, if this is the case, then this could actually be good news for app developers because it indicates that during "normal" everyday life outside of a pandemic, users were more motivated to use the app content to meet their psychological needs.

Finally, because there was a general trend for users to drop off usage from the first week of use in the data to the second week, it is possible that lack of interest with the worldscape experiences and/or surveys may have influenced users to abort or stop using the app before the run or the survey was completed over time. It is also possible that the app content did not adequately meet some user's needs and that these users would have chosen to engage in the content for less time on Week 2 regardless of COVID-19.

Features of the VR device itself might also play a role in this as well because immersion in VR requires disengaging from the external environment, which may be difficult to maintain repeatedly, particularly for those who are very busy or require frequent awareness of their surroundings. This would have been particularly relevant with users at home during the pandemic, potentially with children, pets, or other people around.

It is possible that interest in use for new users was initially very high as COVID-19 pandemic accounts skyrocketed with users seeking new ways to cope with the increased stressors but that interest tapered out over time as users were unable to get the long-term stress relief they were seeking. Additional longitudinal studies would be informative.

5.2 COVID-19 as predictor for mood scores

This study compared mood scores and mood change before and after COVID-19, with findings indicating that users reported lower opening mood scores after COVID-19 started than before it was

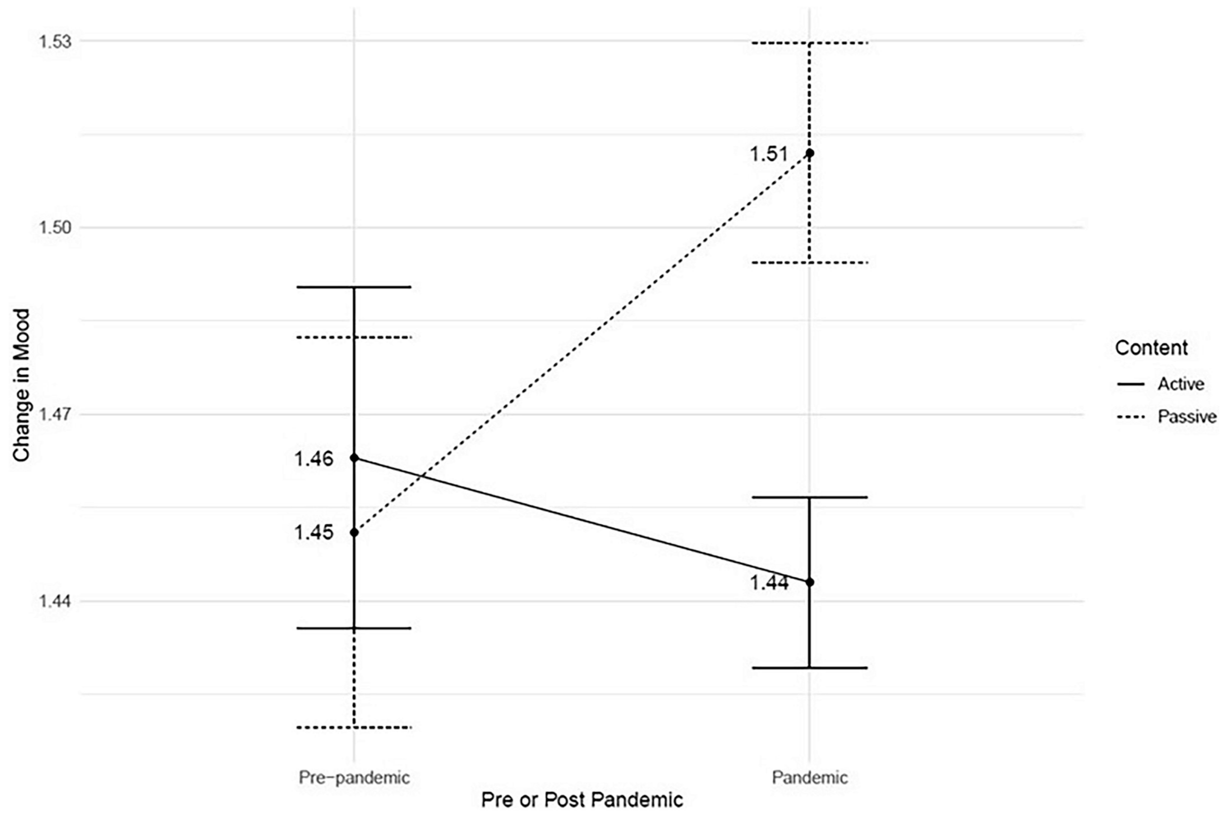

FIGURE 6
Mood Change and Type of Run Pre- and Post-Pandemic.

declared a national emergency in the US and greater positive changes in mood after engaging in worldscape runs on the app as well. When individual user mood scores were compared, there was a slight decrease in opening mood as well as a slight positive increase of change in mood from Pre-Pandemic to Pandemic. This appears to agree with the literature that suggests reported mood may be reflective of a more generalized outlook and persistent affective state than other briefer emotional states (Lazarus, 1991; Morris, 1992; Russell, 2003, 2005; Ekkekakis, 2013). These findings, along with the spike in accounts, runs, and frequency of use for H1, indicates that users may have chosen to enter the worldscape experiences in order to self-regulate these increased negative mood states. Indeed, device content that is able to create positive emotions and improve mood is expected to motivate user behavior (Fredrickson, 2001).

Additionally, this analysis shows that the change in mood scores from opening to closing was higher after these users engaged in worldscape runs than it was before the pandemic, despite overall mood being lower prior to using the app. This demonstrates that the VR app content may function as a feature of the environment to meet users' psychological needs during increased stress and successfully distract users from negative stimuli, even improving mood states during the pandemic. Immersive elements, sense of presence, interactivity, and aesthetic content features of a VR app may all influence the level of stress relief as well as user perceptions of control and positive distraction (Ulrich et al., 1991; Lessiter et al., 2001; Schubert et al., 2001; Ulrich, 2001; Freeman, 2004; De Kort et al., 2006; Gerber et al., 2017; Tanja-Dijkstra et al., 2018). Unfortunately, measures of these factors were not available to better elucidate which contributed to a greater extent to improve mood, but some interplay between them is very likely based on the prior literature.

5.3 COVID-19 as predictor for interactivity level usage and mood

Because of the unique properties of highly interactive content, it was predicted that a more active level of interactive content would result in higher mood score change than a more passive level of interactive content during COVID-19. If users feel that needs for control, positive distraction, tension-release, diversion, affective or aesthetic are met, or if mood is improved, users should continue to be motivated to use that content, while experiencing stress reduction (Ulrich et al., 1991; Fredrickson, 2001; Ulrich, 2001; Kardefelt-Winther, 2014; Rauschnabel, 2018). Content that produces the greatest sense of presence and distraction from outside environmental stressors, such as those that offer high levels of interactivity, should be exceptionally effective (Witmer and Singer, 1998).

Surprisingly, the opposite pattern emerged than that which was predicted based on the literature. Specifically, users chose to use more interactive content in general, but the less interactive content was slightly more effective for enhancing reported mood following these worldscape experiences during COVID-19. Both levels of interactivity appeared to improve mood, but the less interactive, more calming content led to slightly higher positive mood score changes only after the start of the COVID-19 pandemic. Because users still preferred to use the more interactive content with higher levels of complexity across the studied time frame, despite its lower mood score effects after COVID-19 onset, this suggests that the stress-reducing and psychological effects of content with more interactivity may be better measured via some other short-term affective state, while less interactive content designed to be more restorative may have a stronger effect on overall mood during stressful events.

While interactivity influences presence, other factors such as positive distraction may have a more important role for reducing stress, creating a sense of restoration, and improving mood. The increased technological strain and overstimulation from working and going to school virtually with regular interaction requirements during the pandemic may have also partly influenced these findings. A more passive experience could be more effective at restoration and mood improvement by reducing cognitive and performance demands. However, because interactive content has been shown to be more fun and create a greater sense of presence and perceived control, users may have chosen to use it more and derive benefits from it that were not measured in this study. It may have influenced a more temporal affective state or perhaps the mechanism by which active levels of interactivity effects stress is more related to pleasant levels of arousal within the rewards circuit that alleviates boredom or intrusive thoughts. The challenges of higher levels of interactivity may be more motivating and the rewards greater when the user achieves some goal. Other measures of emotional states, arousal levels, escapism, and experiences of pleasure, tension-release, or hedonic value may better elucidate this relationship.

It is important to note that some of the effect sizes were small in this study (e.g., for H3, mood change between active and passive run was Cohen's $d = 0.03$). However, the results seem to follow a general trend for these hypotheses that reveals COVID-19 had an effect on user behavior and mood states and that specific content may have had more influence than others for this effect.

6 Limitations

Consumer archival data may present unique challenges for the researcher in that the collection, analysis, and interpretation for findings to research questions may have to adapt to accommodate the available data that were collected. Certain method modifications may be needed to address unexpected data, the appearance of inconsistencies, and/or limitations discovered during analysis. In this study, for example, we had to be creative in how to approach measuring sporadic data values that did not nicely match up with one another on a timeline. In these situations, open communication between those involved in development with the app and the researcher is imperative.

Another issue is the accuracy of collected data and researcher interpretation. Consumer data may involve an abundance of unknowns for the researcher since it is not possible to observe users at home inputting the data or control for the multitude of factors and variables that may play a role in any analysis results. It is not known, for example, whether an account in this study was actually used only by one individual or by multiple individuals. Along the same lines, is the question of how representative survey responses reported on a consumer app may actually be for any particular user. Reporting reliable demographic data for this study was particularly challenging since users may choose not to provide voluntary information or may input incorrect data. For example, user age could not be ascertained on any analysis due to reliability concerns since a number of users reported an unreasonably high age in years (>100).

Researchers should be cautious when using large consumer data sets to support interpretations for significant findings. Although a large *N* provides higher external validity due to generalization, and reduces selection bias, significant results may be discovered due to the high number of participants in the sample. Since *p*-values depend upon both the magnitude of association and the sample size, *p*-values can be considered significant at $p < 0.05$, even if the magnitude of effect is small. Therefore, significant findings, which may be interesting, may not be as helpful for predicting the effects of an intervention. Looking at data trends may be a more informative approach with large sample sizes, particularly to compare research questions around data that extend over a period of time as well as before and after an event or intervention. It is also possible that although a large sample can provide some generalizability, the fact that an entire consumer dataset that met certain criteria for one specific app was analyzed without randomization may make these results difficult to apply to users of any other VR app, let alone users of technology in general, or the general population during a pandemic.

While the single mood score measure appears to have good face validity as a subjective measure for mood within subjects, other measures of validity were not conducted. Additionally, reliability of the measure has not been established. Further research would be useful in exploring whether a one question numerical mood measure correlates with more established mood measures.

It is also worth noting that our selection for the time frame of the COVID-19 intervention revolved around the March 11 date when COVID-19 was declared a pandemic by the WHO and the March 13, 2020 date when COVID-19 was declared a national emergency in the US with a few days cushion in-between. Certainly, users may have been aware of the issue prior to these dates or may have been slower to get an understanding of the evolving situation and its direct effect on them. Therefore, usage behavior or mood may have been impacted earlier or later than the dates we used to describe the COVID-19 intervention.

We look forward to future research to begin to untangle the threads.

7 Conclusion

This study sought to show whether a relationship appeared to exist between COVID-19, behavior, and mood for users of a VR app with dynamic, interactive content as well as promote additional research that may build upon this topic. After examining archival user data for a VR app with dynamic, interactive content before and after the COVID-19 crisis, our statistical analysis concluded that the COVID-19 pandemic had significant effects on user behavior and mood.

The majority of users in the dataset used content more frequently during COVID-19 than before. Users did report lower mood scores at the start of using app content during COVID-19 than before, suggesting that the pandemic had a negative effect on mood. Additionally, mood appears to have positively increased to a greater degree when users engaged in the VR app after the pandemic started, making this app an effective mood booster, even with the increasing stressors related to COVID-19. Other study findings contradict the prior literature around interactivity and expected findings of superior stress reduction and mood improvement. Results of this study show that a more passive level of interactive content improved mood to a greater degree after the start of the COVID-19 pandemic, although users did choose to engage in more active forms of interactive content regardless of COVID-19 pandemic status. This indicates that the passive content was likely more restorative for users, positively increasing mood, but that the more active content also likely provided some psychological effect that motivated users to continue to engage in it.

The implications of these findings indicate that users outside of a controlled environment are likely to seek out VR apps with the potential to regulate stress in their everyday lives during increased psychosocial stressors, such as a pandemic. Additionally, measures of mood collected from consumer archival data may adequately capture related increases in stress and negative affect, while VR apps with dynamic, interactive content can improve wellbeing measures, such as mood, even with reported declines. Furthermore, the benefit of the content type used by consumers may vary for differing psychological needs. In this case, passive content may improve overall mood more effectively during increasingly stressful events, and thus be the most useful intervention to employ during pandemic-like contexts. However, the relationship between pandemic stressors, usage behavior, mood, and the existing research is not yet definitive.

While we conclude that brief mood measures such as that used in this study may be an appropriate measure for users experiencing pandemic stress, additional measures of stress and affective states may better indicate this relationship. Additionally, it is possible that other types of VR app content, which users continue to find engaging over time, could produce stronger effects. Future research should build on our understanding of longitudinal pandemic stress, its effects on users, and what consumer devices and content may be most useful to reduce that stress in the home environment. A better understanding of features related to certain content and devices that contribute to stress reduction and improved mood is paramount in order to develop effective resources for those with restrictions or limited access to normal coping mechanisms.

Data availability statement

The data analyzed in this study is subject to the following licenses/restrictions: the data analyzed in this study was obtained from TRIPP. TRIPP will not authorize the public release of this data because it is proprietary and trade secret. Other researches who wish to use this data to validate or build upon our findings can contact research@trippinc.com to obtain a copy of this anonymous dataset. Requests to access these datasets should be directed to research@trippinc.com.

Ethics statement

The studies involving humans were approved by Fielding Graduate University IRB. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required from the participants or the participants' legal guardians/next of kin in accordance with the national legislation and institutional requirements.

Author contributions

JH: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. AC: Formal analysis, Methodology, Supervision, Writing – review & editing. KS: Supervision, Writing – review & 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/fpsyg.2024.1278207/full#supplementary-material

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How do differences in native language affect out-of-body experiences?

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Out-of-body experiences are scientifically inducible cognitive phenomena attracting global attention due to their application in the Metaverse and medical care. Despite previous studies suggesting that one's native language influences one's cognition, the out-of-body experiences of humans with different native languages have not been investigated separately. This study replicated an experiment from a 2007 study to investigate whether differences in native language affect the ability to have scientifically induced out-of-body experiences. A total of 19 age-matched native English and Japanese speakers completed the experiment in two blocks. Thereafter, their experiences were evaluated using questionnaires, and their responses were compared. Importantly, no significant differences between the English and Japanese native-speaker conditions were found. The results showed that out-of-body experiences were induced similarly in both groups, suggesting that people can have out-of-body experiences as a response to similar stimuli, regardless of their native language. However, differences in participants' introspective reports suggested that their experiences may differ qualitatively, possibly, due to the different linguistic backgrounds. The elucidation of the mechanisms of science-assisted out-of-body experiences that consider different cultural and cognitive characteristics, such as native language, could lead to the investigation of their applications in the borderless Metaverse and medicine.

KEYWORDS
out-of-body experiences, OBE, native language, cognitive phenomena, Japanese, English, sense of embodiment

1 Introduction

Out-of-body experiences (OBEs) are scientifically inducible cognitive phenomena that have recently attracted global attention due to their application in the Metaverse (Moon and Han, 2022) and medical care (Szczotka and Wierzchoń, 2023). In the Metaverse, individuals can embody avatars, computer-generated representations of themselves, and interact with others using avatars that resemble real individuals (Petrigna and Musumeci, 2022). The Metaverse is often connected with immersive experiences in virtual worlds, resulting in a growing interest in virtual reality (VR) and augmented reality systems and applications that provide lifelike multimodal sensory experiences. Regardless of native language or national borders, plans to utilize these technologies for various social implementations and applications is becoming widespread.

An OBE is defined as a cognitive experience in which the awake person views their physical body from outside (Brugger et al., 1997; Blanke et al., 2004). OBEs were originally reported in clinical conditions that interfere with normal brain functioning, such as strokes, partial-onset seizures (epilepsy), and drug abuse (Grüsser and Landis, 1991; Brugger et al., 1997; Brugger, 2002; Blanke et al., 2004). However, this psychological phenomenon can occur just as well in the normal population (Blackmore, 1982, 1984), suggesting the possibility that our self-body perceptions are not always with our actual bodies themselves. Moreover, OBEs can occur during wakefulness and sleep, including in persons initiated from sleep paralysis (Cheyne and Girard, 2009). Surprisingly, it has become possible to induce OBEs scientifically in recent years. Ehrsson (2007) reported that this illusory experience can also be induced in healthy participants. In such instances, individuals experience the perceptual illusion of their center of consciousness, or "self," being outside their body and see it from another person's perspective. This illusion is an effect of having the sensation of localization in the body realized through a perceptual process, that is, by combining a visual perspective with multisensory stimulation. Moreover, this OBE has been reported to be a highly reproducible cognitive phenomenon in follow-up studies (Guterstam and Ehrsson, 2012), and brain functions related to OBE have been elucidated using fMRI (Guterstam et al., 2015). However, the OBEs of persons with different native languages have not been investigated sufficiently.

Previous studies have reported on the relationship between native language and human cognitive phenomena. One previous study (Flecken et al., 2014) used eye-tracking to investigate how language influences attention to motion event recognitions. It compared the speakers of two different native languages in non-verbal tasks. Their results contributed to the language-and-thought debate by examining grammatical concepts. Another previous study (Athanasopoulos et al., 2015) focused on the extent to which language affects the process that people use to make sense of objects and events around them by classifying them into identifiable categories. Their findings suggested that different languages caused their speakers to behave differently. However, the relationship between OBEs as cognitive phenomena and the native language of the persons experiencing these phenomena has not been clarified.

Therefore, this study aimed to examine and report whether differences in native language affect OBEs. From the above background, our working hypothesis is that OBEs are perceptual illusions based on a combination of multisensory stimuli; consequently, regardless of differences in people's native languages, OBEs are elicited in the same way based on human being cognitive functions related to illusions. However, we also hypothesize that people with different native languages report different verbal content when interpreting OBEs verbally. To test this, we followed the methodology reported by Ehrsson (2007) for his Experiments #1 and #2, with age-matched native English speakers and native Japanese speakers as the participants. Self-evaluations of OBEs were collected using the same questionnaire methods as those used by Ehrsson (2007); thereafter, we compared the results.

2 Materials and methods

To investigate the effect of different native languages on OBEs, age-matched native English speakers (number: 13, age: 27.4 ± 3.2, height: 169.1 cm ± 10.1, weight: 67.2 kg ± 10.3) and native Japanese speakers (number: 9, age: 21.2 ± 1.1, height: 168.0 cm ± 7.2, height: 168.0 cm ± 7.2, weight: 57.0 kg ± 9.4) were recruited to participate in this study (see Table 1 for the sample's demographic information). There were no differences in height, weight, or sitting height between the two populations.

The study was conducted in conformity with the Declaration of Helsinki and was approved by the Ethics Committee of the Tokyo Institute of Technology (Permit No.: 2021217). Written informed consent was obtained from all participants. Three native English speakers were excluded from the analyses: one who experienced a system error during the experiment and two who had had extensive experience with VR games, which could have led to decreased relevance of the illusion and thus less responsiveness (Fribourg et al., 2021).

The experimental setup was arranged as shown in Figure 1. Each subject sat on a chair and wore a head-mounted display (HMD) connected to a stereo camera and positioned 2 m behind their back at the same height as their eyes. The stereo camera consisted of two monocular red-green-blue cameras (left and right) and was wired to a PC, which transmitted the images to the HMD using the Unity programming language (Unity Software Inc.) and an experimental software developed using C#; the image from the left video camera was displayed on the left-eye display, and the image from the right camera was displayed on the right-eye display. Thus, the person saw their own back from the perspective of the person sitting behind them in the stereoscopic view. The experimental software had two modes: the synchronous mode, in which the stereo camera images were displayed on the HMD in real-time, and the asynchronous mode, in which the stereo camera images were displayed on the HMD with a 0.5-s delay. Experimental Block #1 used only the synchronous mode, whereas experimental Block #2 used both the synchronous and asynchronous modes.

The stimulation method of the experiment was applied according to the hypothesis of Ehrsson's (2007) study, in which

TABLE 1 Participants' demographic characteristics.

Item	Native English speakers	Native Japanese speakers
Number of participants (male, female)	13 [M:7, F:6]	9 [M:7, F:2]
Age (years)	27.4 (±3.2)	21.2 (±1.1)
Height (m)	169.1 (±10.1)	168.0 (±7.2)
Sitting height (m)	118.5 (±3.2)	118.3 (±2.7)
Body weight (kg)	67.2 (±10.3)	57.0 (±9.4)
History of residence in Japan (foreigners only)	2.6 (±1.3)	–
Common European Framework of Reference for Languages (CEFR) [Level: A1-C2]	(Native language)	A2 level: 2 people B1 level: 5 people B2 level: 2 people
Japanese Language Proficiency Test (JLPT) [Level: N1-N5]	N1 level: 2 people N3 level: 4 people N4 level: 1 people N5 level: 6 people	(Native language)

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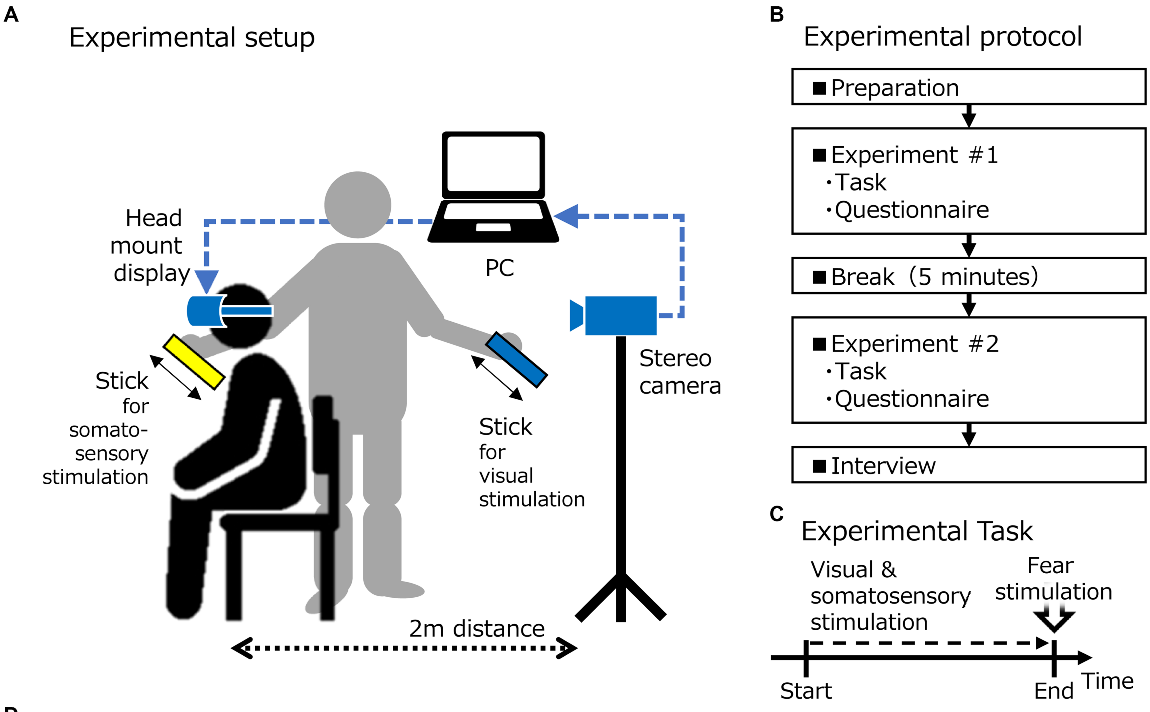


D

Questionnaire items for Experiment #1 in English and Japanese

7-point visual analogue scale (for #xperiment #1).
-3: 'absolutely certain that it did not apply', 0: 'uncertain whether or not it applied', +3: 'absolutely certain that it applied'.

No.	Questionnaire item (English version)
1	I experienced that I was located at some distance behind the visual image of myself, almost as if I was looking at someone else.
2	I felt as if my head and eyes were located at the same place as the cameras, and my body just below the cameras.
3	I experienced that the hand I was seeing approaching the cameras was directly touching my chest (with the rod).
4	I felt that I had two bodies.
5	I experienced that my (felt) body was located at two locations at the same time.
6	I experienced a movement-sensation that I was floating from my real body to the location of the cameras.
7	I felt as if my head and body was at different locations, almost as if I had been 'decapitated'.
8	I did not feel the touch on my body but at some distance in space in front of me.
9	I could no longer feel my body, it was almost as if it had disappeared.
10	The visual image of me started to change appearance so that I became (partly) transparent.

No.	Questionnaire item (Japanese version)
1	私は映像内の自分の体よりも後ろに位置しているような体験をし、まるで他の誰かを見ているようでした。
2	自分の頭や目がカメラと同じ位置にあり、カメラのすぐ下に自分の体があるような感覚でした。
3	カメラへ向け近付いてきた実験者の手は、直接自分の胸を棒で触れているような体験をしました。
4	体が二つあるように感じました。
5	私の(感覚的な)体が同時に二つの場所にあるように感じられました。
6	自分の体からカメラのある場所まで浮いていくような移動感覚を味わいました。
7	頭と体の位置が違うような、まるで「首を切られた」ような感覚に陥りました。
8	触覚刺激を私の体で感じたのではなく、目の前の空間の中で少し離れたところで感じました。
9	自分の体の感覚がなくなり、まるで消えてしまったかのようでした。
10	映像内の自分の姿が変化していき、私が(部分的に)透過できるように感じ始めた。

E

Questionnaire items for Experiment #2 in English and Japanese

10-point visual analogue scale (for Experiment #2).
1: 'no anxiety at all', 10: 'strongest possible anxiety imaginable'.

No.	Questionnaire item (English version)
1	Rate the anxiety you had experienced when you saw the hitting hammer (synchronous condition)
2	Rate the anxiety you had experienced when you saw the hitting hammer (asynchronous condition)

No.	Questionnaire item (Japanese version)
1	向かってくるハンマーを見たときに感じた不安を評価してください（同期条件）
2	向かってくるハンマーを見たときに感じた不安を評価してください（非同期条件）

FIGURE 1
Organization of Blocks #1 and #2. **(A)** The experimental system, setup, and task used to induce the out-of-body experience illusion. **(B)** The experimental protocol of Block #1 and Block #2, including preparation, breaks, and an interview. **(C)** The experimental task with timeline.

(Continued)

FIGURE 1 (Continued)
(D) Questionnaire items for Block #1 in English and Japanese scored on a 7-point visual analog scale (−3: "absolutely certain that it did not apply"; 0: "uncertain whether or not it applied"; +3: "absolutely certain that it applied"); **(E)** Questionnaire items for Block #2 in English and Japanese scored on a 10-point visual analog scale (1: 'no anxiety at all;' 10: 'strongest possible anxiety imaginable').

illusions were induced from a first-person perspective, combining visual and tactile information. Sticks for visual and somatosensory stimulation were used in both blocks. Additionally, to examine the participants' emotional responses to their illusory body being "injured," a visual fear stimulus was provided by having the experimenter swing a hammer at the stereo camera as if he would hit it; the participants saw the hammer swinging down toward their faces via the HMD.

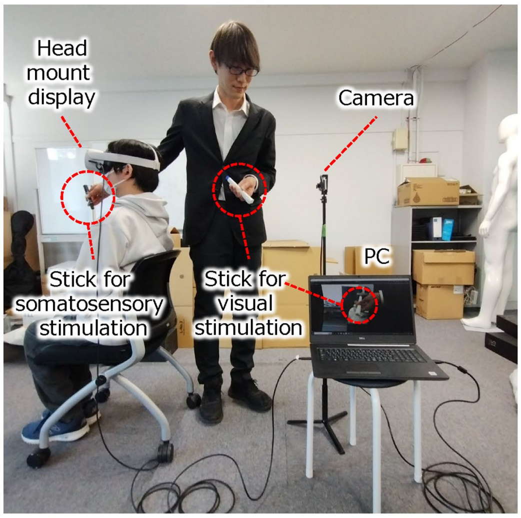
In this study, both Blocks #1 and #2 consisted of a task and a structured questionnaire. There was a 5-min break between the two blocks, after the completion of which, unstructured interviews were conducted with participants. The experimental protocol, setup, and questionnaire items are illustrated in Figure 1.

2.1 Experimental block #1

Block #1 consisted of simultaneous stimuli of a visual and somatosensory kind, as shown in Figure 1. The experimental task started with the participant sitting on the chair and observing the stereo camera images using the HMD. The experimental software was set to synchronous mode, and stereo camera images were presented to the participants in real-time. The experimenter stood right next to the participants (in their view) and used two plastic sticks to simultaneously touch the chest of the invisible person and the chest of the "illusory body" as shown in Figure 2 (written informed consent was obtained from the participants in the figures for the publication of identifying information/images in an online open-access publication), moving the visual-stimulation stick downward from the center of the stereo camera in front of it. To the participants wearing the HMD, it appeared as if the stick was tapping their chest. Thus, the participants synchronously felt the visual and somatosensory stimuli, and this simultaneous stimulation was administered continuously for 2 min. It should be noted that Block #1 included only this experimental condition of applying synchronized simultaneous stimuli of visual and somatosensory kind to participants.

Afterward, a visual fear stimulus was applied. The experimenter swung a hammer at the stereo camera as if he would hit it. The participants saw the hammer swinging down toward their faces via the HMD. This stimulus was only applied once to each participant.

After completing the experimental task, participants were asked to answer a structured questionnaire, presented in Figure 1, in which they either affirmed or denied cognitive effects. This questionnaire consisted of 10 items (Q1-Q10), each scored on a visual analog scale from −3 to +3, where −3 meant "absolutely certain that it did not apply," 0 meant "uncertain whether or not it applied," and +3 meant "absolutely certain that it applied." Items Q1-Q3 were designed to capture the experience of the illusion, while Q4-Q10 were unrelated to OBEs and served as controls. The native English speakers answered the English questionnaire and the native Japanese speakers answered the Japanese questionnaire.

A


B


FIGURE 2
Experiment scenery of the illusion of out-of-body experience and the experimental result of Block #2. **(A)**. The experimental setup used to induce the illusion of an out-of-body experience. **(B)** The synchronized visual and somatosensory stimuli are given to the experimental participants. (Written informed consent was obtained from the participants in the figures for the publication of identifying information/images in an online open-access publication).

The questionnaire results for the first block were analyzed in two ways: first, the average scores of Q1-Q3 and Q4-Q10 were calculated for each participant. These were then compared between native English and Japanese speakers using a significance test for linear regression with a generalized linear model (GLM). This GLM consisted of the gamma distribution and the invers link function. The objective variable was the average score, and the explanatory variables were NATIVE-LANGUAGE Factor (NL-Factor) and QUESTIONNAIRE-SCORE Factor (QS-Factor). NL-Factor was related to the native language {"native English speaker," "native Japanese speaker"}, and QS-Factor was related to the questionnaire items about cognitive effects {"Q1, 2, 3," "Q4, 5, 6, 7, 8, 9, 10"}. This significance test was conducted by converting the scores from −3 to +3 into scores from 1 to 7 because of the GLM with the gamma distribution. In this way, we analyzed whether OBEs were induced among both linguistic groups. If an OBE was induced, the scores for "Q1, 2, 3" would have been significantly higher than those for "Q4, 5, 6, 7, 8, 9, 10." If there was a difference in the induction of OBEs between native English and Japanese speakers, there would have been a significant difference between the two groups in the ratings of all the questionnaire items. Second, we compared the mean scores of the questionnaire results for each item from Q1 to Q10 between the two groups. Mann–Whitney's U test was used for comparison.

2.2 Experimental block #2

Block # 2, just like Block # 1, included simultaneous visual and somatosensory stimuli and the same visual fear stimulus. However, the difference was the implementation of the asynchronous condition as a control condition. In this condition, the somatosensory and visual stimuli were no longer synchronized.

The duration of the visual and somatosensory stimuli in the experimental task was set randomly between 40 and 80 s. The task was performed six times for each participant: three times in the synchronous condition and three times in the asynchronous one. The order of the experimental tasks in both conditions was pseudo-randomized, and either (1,2,2,1,1,1,2) or (2,1,1,1,2,2,2,1) was used, where 1 indicates the synchronous condition, and 2 indicates the asynchronous one.

After completing all six experimental tasks, we administered a structured questionnaire (see Figure 1), which asked the participants to rate the anxiety they experienced when they saw the hammer swinging down toward their faces via the HMD, on a visual analog of a 10-point Likert scale. The items were numbered Q11 and Q12 for the synchronous and asynchronous conditions, respectively. On this scale, "1" meant "no anxiety at all," and "10" meant "the worst possible anxiety imaginable." Native English speakers rated the English questionnaire items, and native Japanese speakers rated the Japanese questionnaire items.

The questionnaire results for the second block were analyzed as follows: averages were calculated per participant for Q11 and Q12, and comparisons were made between the synchronous and asynchronous conditions in STIMULI-PATTERN Factor (SP-Factor). In addition, comparisons were made between synchronous and asynchronous conditions for native English and Japanese speakers in NL-Factor. A significance test for GLM was used for the comparisons. This GLM consisted of the poison distribution and the log link function. The objective variable was the score, and the explanatory variables were NL-Factor and SP-Factor, as defined above. Thus, we analyzed whether OBEs were induced among both groups. If an OBE was induced, the Q11 evaluation value for the synchronous condition would be significantly higher than the Q12 evaluation value for the asynchronous condition. If the groups differed in their ability to have OBEs, a significant difference was expected to be observed between Q11 and Q12 for the respective conditions.

2.3 Unstructured interviews

Unstructured interviews were conducted after the completion of all the blocks. The participants were asked, "Please describe, in as much detail as possible, what you experienced and felt during the experiment." They were also given the following main points to discuss: "visual body versus actual body," "how you felt when being tapped," and "how you felt when you saw the hammer." Instructions were given in English to native English speakers and in Japanese to native Japanese speakers. All participants responded freely in their native language.

Two video cameras and two integrated-chip recorders were used to record the interviews. All utterances in the interviews were transcribed and used for analysis.

3 Results

3.1 Result in block #1

The experimental results in Block #1, presented in Figure 3 and Tables 2, 3, showed a significant main effect for the QS-Factor, related to the cognitive-effects questionnaire items ($p < 0.0001$). Concurrently, the main effect of the NL-Factor was not significant ($p = 0.9$), neither was there an interaction between the QS-Factor and NL-Factor ($p = 0.5$). These results indicate that OBEs were induced similarly in both groups. Importantly, no significant differences were found between English and Japanese native speakers in the NL-Factor.

As an additional detailed examination of the experimental results, we analyzed whether there were differences between the native English and Japanese speakers for each of the 10 questionnaire items used in Block #1. The results are presented in Figure 4 and Table 4. Interestingly, among the questionnaire items, Q4–10 were unrelated to OBEs, and native English speakers scored significantly higher in Q6 than native Japanese speakers ($p < 0.01$). Q6 read: "I experienced a movement-sensation that I was floating from my real body to the location of the cameras." Furthermore, native Japanese speakers had significantly higher scores in Q8 than native English speakers ($p < 0.05$). Q8 read: "I did not feel the touch on my body but at some distance in space in front of me." These differences in introspective reports might be related to qualitative differences in OBEs between native English and Japanese speakers.

There were no significant differences in the responses given by the two groups to any of the other questionnaire items ($p > 0.1$).

3.2 Result in block #2

The results in Block #2 are presented in Figure 5 and Tables 5, 6. The experimental results displayed in Figure 5 showed a significant main effect for the SP-Factor ($p < 0.01$). Subsequently, the NL-Factor's main effect was found to be insignificant ($p = 0.4$). There was also no interaction between the SP-Factor and NL-Factor ($p = 0.5$). These results indicated that the OBEs were induced similarly in both groups. Moreover, no significant differences were

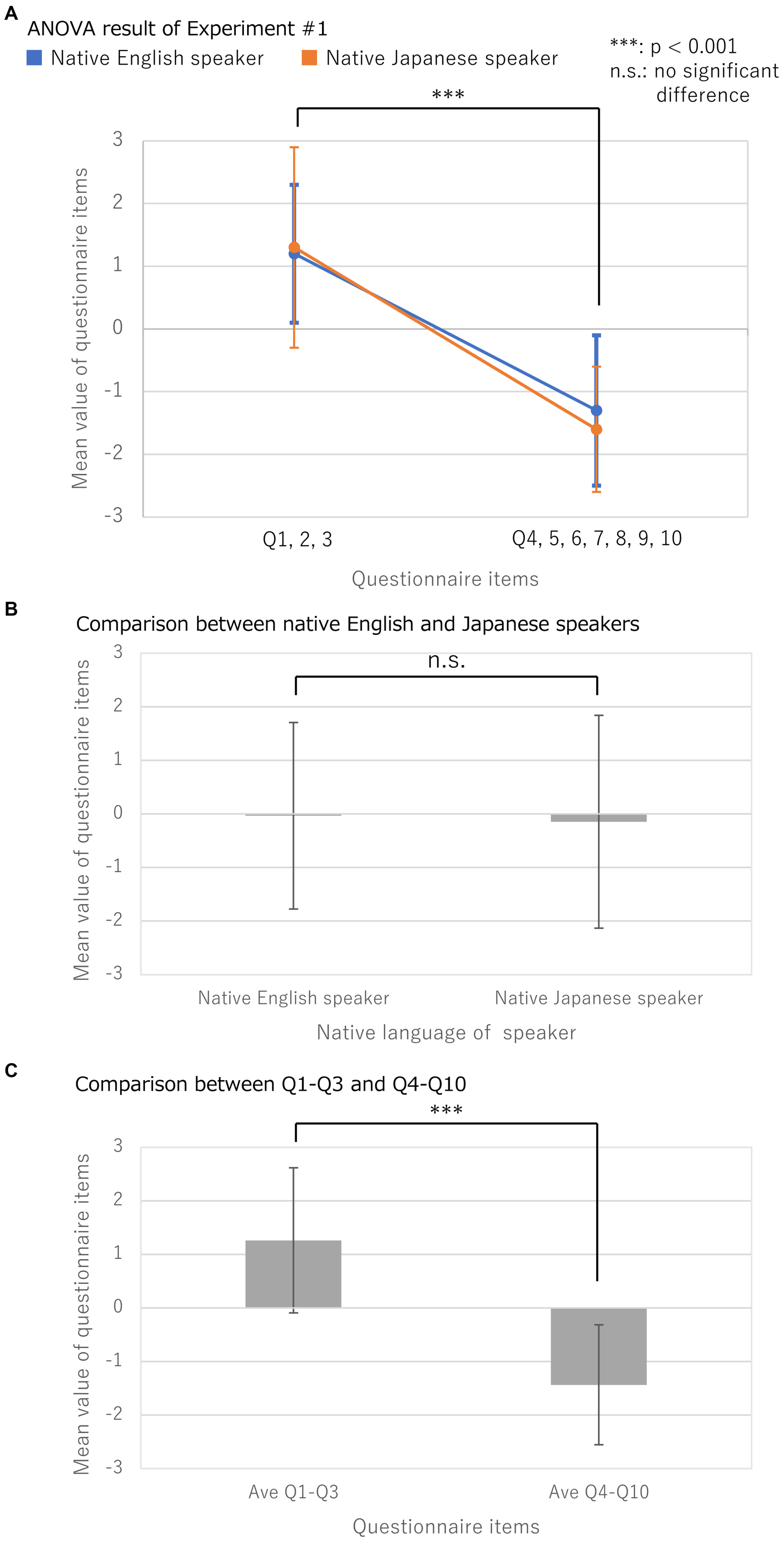


FIGURE 3
Experimental result of Block #1. **(A)** Mean values and standard deviations for questionnaire items after Block #1 a two-factor Mixed-Design Analysis of Variance (ANOVA) with and without correspondence, was used to analyze NL-Factor for native language {"native English speaker," "native Japanese

(Continued)

FIGURE 3 (Continued)
speaker"} and QS-Factor for the cognitive-effects questionnaire items {"Q1, 2, 3," "Q4, 5, 6, 7, 8, 9, 10"} were compared; **(B)** Results of the comparison between native English and Japanese speakers; **(C)** Results of the comparison between Q1-Q3 and Q4-Q10.

TABLE 2 Mean values and standard deviations for the questionnaire items after Block #1.

NL-Factor	QS-Factor	Mean (±SD)
Native English speakers	Q1, 2, 3	1.23 (±1.13)
	Q4, 5, 6, 7, 8, 9, 10	−1.30 (±1.25)
Native Japanese speakers	Q1, 2, 3	1.30 (±1.64)
	Q4, 5, 6, 7, 8, 9, 10	−1.59 (±1.01)
Native English speakers	–	−0.03 (±1.74)
Native Japanese speakers	–	−0.16 (±1.99)
–	Q1,2,3	1.26 (±1.35)
–	Q4,5,6,7,8,9,10	−1.44 (±1.12)

TABLE 3 Result of the significance test for linear regression with a generalized linear model (GLM) in Experimental Block #1.

	Dependent variable			
Predictors	Estimates	Confidence interval (CI)	*p*	
(Intercept)	1.21	1.16–1.27	<0.001	***
NL-Factor	1	0.94–1.06	0.943	n.s.
QS-Factor	1.2	1.09–1.32	<0.001	***
NL-Factor × QS-Factor	1.05	0.91–1.21	0.526	n.s.

NATIVE-LANGUAGE Factor (NL-Factor): {"native English speaker," "native Japanese speaker"}. QUETIONNAIRE SCORE Factor (QS-Factor): {"Q1,2,3," "Q4,5,6,7,8,9,10"}. This GLM consisted of the gamma distribution and the inverse link function. The objective variable was the average score, and the explanatory variables were NATIVE-LANGUAGE Factor (NL-Factor) and QUESTIONNAIRE-SCORE Factor (QS-Factor). NL-Factor was related to the native language {"native English speaker," "native Japanese speaker"}, and SP-Factor was related to the questionnaire items about cognitive effects {"Q1, 2, 3," "Q4, 5, 6, 7, 8, 9, 10"}. "***" means significant difference with $p < 0.001$; "n.s." means non-significant difference.

found between English and Japanese native speakers in the NL-Factor.

3.3 Result in unstructured interviews

English native speakers were characterized by talking in detail about (1) the sensation of perspective and the body shifting toward the camera and (2) the sensation of the body floating or receding. The detailed results of these unstructured interviews are presented in the Supplementary data S1 and Supplementary Figure S2. Six of the 10 native English speakers mentioned at least one sensation. This may be taken as support for the result that native English speakers scored considerably higher than the Japanese native speakers on Q6 ("I experienced a movement-sensation that I was floating from my real body to the location of the cameras").

The differences in the introspective reports from the interviews may be related to qualitative differences in the OBEs experienced by English and Japanese native speakers. In other words, when experiencing OBEs, the former is more likely than the latter to experience the perception that their viewpoint and bodily sensations move backward to where the camera is or that their bodies float.

4 Discussion

The results of Blocks #1 and #2 indicate that OBEs were induced in both native English and Japanese speakers similarly. These findings are consistent with a previous study by Ehrsson (2007), whose experimental results they replicate. Importantly, no significant differences were found between the English and Japanese native-speaker conditions in NL-Factor. Therefore, the results suggest that people can experience OBEs as a response to similar stimuli, regardless of their native language. Significantly, this is in line with the notion that the OBE is a perceptual-spatial illusion (Ehrsson, 2007; Guterstam and Ehrsson, 2012) and that basic perceptual experiences of the self in space can be reported similarly across native languages. Moreover, our findings have potentially broader implications in the understanding of body ownership.

Several independent studies in Japan, Europe, and the United States have investigated OBEs from the first-person perspective and found similar results on questionnaire ratings (Petkova and Ehrsson, 2008; Kondo et al., 2020). Their results suggest that the reports of full-body ownership have the potential to be similar across native speakers of Japanese and English. Moreover, based on discussions in previous studies (Kilteni et al., 2012; Guy et al., 2023), the sense of embodiment, which refers to the sensations of being inside, having, and controlling a body, arises when the attributes of the virtual body are processed as if they were those of one's own biological body. This sense of embodiment consists of three subcomponents with sense of self-location, sense of agency, and sense of body ownership. Sense of self-location means the sensation of occupying a specific volume in space; sense of agency means the feeling of possessing overarching motor control; and sense of body ownership means the feeling of ownership of one's body. Since OBEs are thought to be closely related to these sensations, it is possible that native English speakers and native Japanese speakers perceive these sensations similarly, without significant differences.

As a supplementary discussion of the control questionnaire items in experimental Block #1, a further detailed analysis of the responses might reveal differences between the introspective reports of the two groups. For instance, in experimental Block #1, there was a significant difference in questionnaire item Q6, even

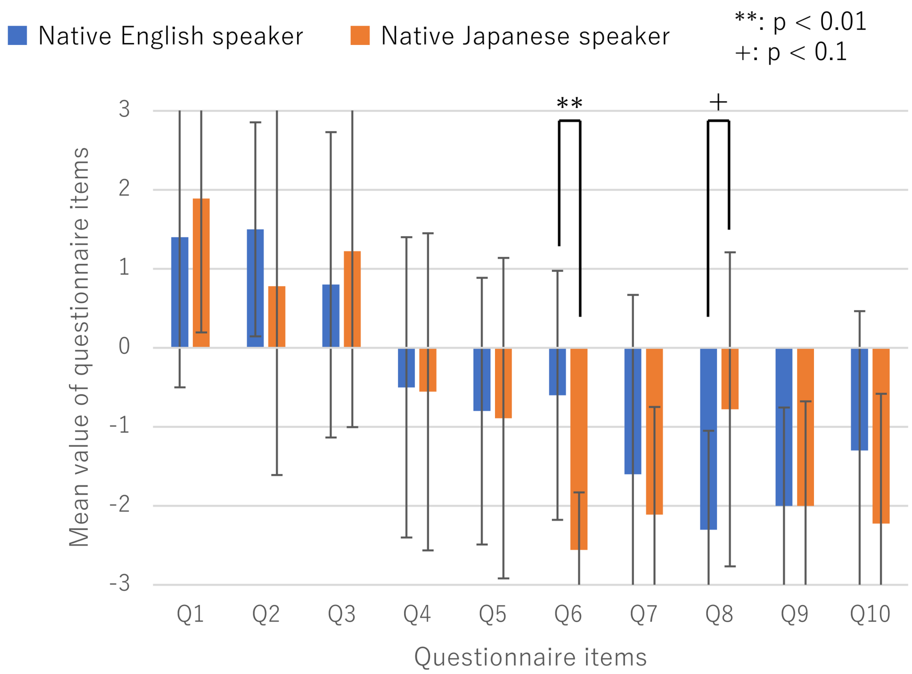


FIGURE 4
Mean values and standard deviations for each of the 10 questionnaire items regarding participants' introspection of their OBEs to determine if there were differences between native English and Japanese speakers.

TABLE 4 The results of the statistical analyses on the differences between native English and native Japanese speakers for each question item after Block #1.

Questionnaire item no.	Native English speakers	Native Japanese speakers	*p*-value	
Q1	1.4 (1.9)	1.9 (1.7)	0.563	n.s.
Q2	1.5 (1.4)	0.8 (2.4)	0.422	n.s.
Q3	0.8 (1.9)	1.2 (2.2)	0.663	n.s.
Q4	−0.5 (1.9)	−0.6 (2.0)	0.951	n.s.
Q5	−0.8 (1.7)	−0.9 (2.0)	0.918	n.s.
Q6	−0.6 (1.6)	−2.6 (0.7)	0.003	**
Q7	−1.6 (2.3)	−2.1 (1.4)	0.566	n.s.
Q8	−2.3 (1.3)	−0.8 (2.0)	0.059	+
Q9	−2.0 (1.2)	−2.0 (1.3)	1.000	n.s.
Q10	−1.3 (1.8)	−2.2 (1.6)	0.256	n.s.

"**" means significant difference with $p < 0.01$; "+" means marginally significant difference with $p < 0.1$; "n.s." means non-significant difference.

though Q6 was only a control questionnaire item. Specifically, native English speakers reported significantly higher scores on the visually related item (Q6). This suggests that they tended to perceive "visual" sensorial changes strongly. These reports were consistent with those recorded only among native English speakers during the unstructured interviews conducted after the completion of all the blocks, wherein all participants were asked: "Please describe, in as much detail as possible, what you experienced and felt during the experiment." These differences in introspective reports might be related to the qualitative differences in OBEs between native English and Japanese speakers. While it has been reported that cultural differences, including native language, affect human perceptions of the external world (Flecken et al., 2014; Athanasopoulos et al., 2015), our results further suggest that they also affect perceptions of one's self-body. Although this study used structured questionnaire items previously used by Ehrsson (2007), there may been evaluation limitations in clarifying the effects of cultural differences, including native language, on the perception of the self-body and the relationship between oneself and the world. Further development of the evaluation method, including improvement of the questionnaire items, is required in the future.

The experiment used in this study induced a first-person perspective OBE, but third-person perspective OBEs have also been reported (Lenggenhager et al., 2007). Since bodily sensations change in both cases of first-and third-person OBEs (Moon and Han, 2022), qualitative differences between native English and Japanese speakers may also occur in third-person perspective OBEs. Moreover, previous studies have suggested that full-body illusions are much stronger from the first-person perspective compared to the third-person perspective (Petkova et al., 2011; Maselli and Slater, 2013, 2014; Gorisse et al., 2017). It was a strength that our present study has studied OBE illusion from the first-person perspective. However, further research targeting third-person full-body illusions may need to consider additional items not considered in this study.

This study's limitations were as follows. First, although this study represents a further step in this field of research, it is

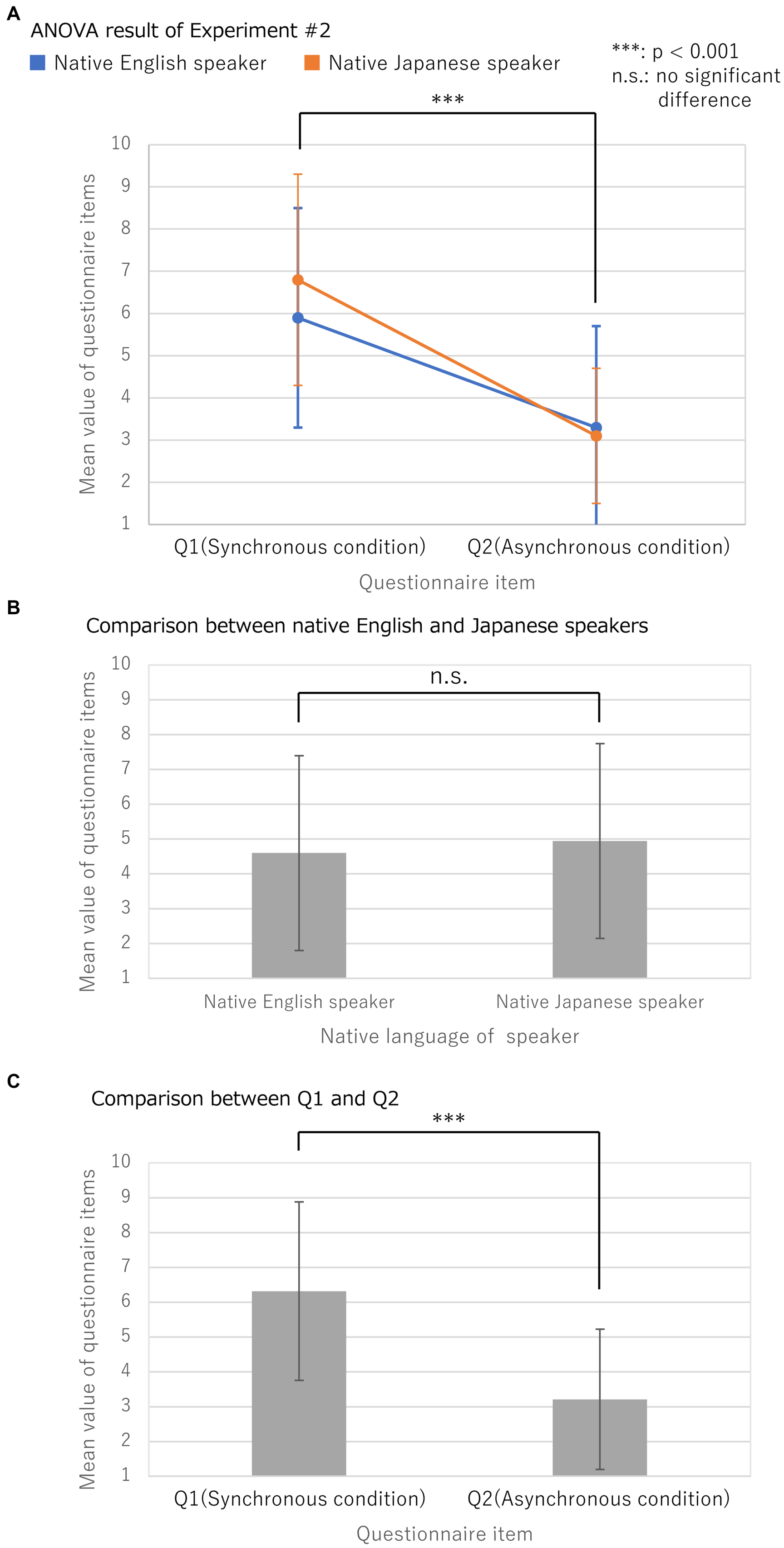


FIGURE 5
Experimental result of Block #2. **(A)** Mean values and standard deviations for questionnaire items after Block #2, a two-factor Mixed-Design Analysis of Variance (ANOVA) with and without correspondence, was used to analyze NL-Factor for native language {"native English speakers," "native Japanese
(Continued)

FIGURE 5 (Continued)
speakers"} and SP-Factor for the cognitive-effects questionnaire items {"Q1(Synchronous condition)," "Q2(Asynchronous condition)"} were compared; **(B)** Results of the comparison between native English and native Japanese speakers; **(C)** Results of the comparison between questionnaire items Q1 (synchronous condition) and Q2 (asynchronous condition) in Block #2.

TABLE 5 Mean values and standard deviations for questionnaire items after Block #2.

NL-Factor	SP-Factor	Mean (±SD)
Native English speakers	Q1 (Synchronous condition)	5.90 (±2.64)
	Q2 (Asynchronous condition)	3.30 (±2.41)
Native Japanese speakers	Q1 (Synchronous condition)	6.78 (±2.54)
	Q2 (Asynchronous condition)	3.11 (±1.62)
Native English speakers	–	4.60 (±2.80)
Native Japanese speakers	–	4.94 (±2.80)
–	Q1 (Synchronous condition)	6.32 (±2.56)
–	Q2 (Asynchronous condition)	3.21 (±2.02)

TABLE 6 Result of the significance test for linear regression with a generalized linear model (GLM) in Experimental Block #2.

	Dependent variable			
Predictors	Incidence rate ratios	Confidence interval (CI)	*p*	
(Intercept)	5.9	4.52–7.54	<0.001	***
NL-Factor	1.15	0.80–1.65	0.448	n.s.
SP-Factor	0.56	0.36–0.85	0.008	***
NL-Factor × SP-Factor	0.82	0.44–1.52	0.531	n.s.

NATIVE-LANGUAGE Factor (NL-Factor): {"native English speaker," "native Japanese speaker"}. STIMULI-PATTERN Factor (SP-Factor): {"Q11" "Q12"}. This GLM consisted of the poison distribution and the log link function. The objective variable was the score, and the explanatory variables were NATIVE-LANGUAGE Factor (NL-Factor) and STIMULI-PATTERN Factor (SP-Factor). NL-Factor was related to the native language {"native English speaker," "native Japanese speaker"}, and SP- Factor was related to the questionnaire items about cognitive effects {"Q11" "Q12"}. "***" means significant difference with $p < 0.001$; "n.s." means non-significant difference.

necessary to conduct further analyses using larger sample sizes in the future. In Block 2, the experimenter knew the participants' condition. This could be problematic since the experimenter could inadvertently induce the participant to experience the OBEs or not (e.g., by doing slightly different movements). Therefore, verification through double-blind comparative trials is a necessary future avenue to further this research. Due to constraints in recruiting participants for the experiment, there were differences in the ages of the respective populations of native English and Japanese speakers. The dependence of the results on such age differences will need to be investigated in the future.

In interpreting the results of this study, it is important to note that the participants had some knowledge of the other language, although their proficiency was not perfect. In addition, cultural differences may be more relevant in the interpretation of observed results. Therefore, further experiments are needed in this area, wherein, it will be important to distinguish between the effects of linguistic differences and cultural differences. However, it was apparent in this study that by at least controlling for differences in native language in the experimental conditions, differences could be observed in the verbalization of OBEs.

This study reported that there were no differences in height, weight, or sitting height between the populations of English and Japanese speakers, and did not focus on the influence of physical characteristics of the individuals. On the other hand, previous studies suggested that our perception of body shape influences our body embodiment perception (Warren, 1984; Mark and Vogele, 1987; Warren and Whang, 1987; Proffitt and Linkenauger, 2013). Moreover, modifying morphological aspects of our bodies can consequently impact our perception of the environment's scale (Stefanucci and Geuss, 2009; Stefanucci and Geuss, 2010; van der Hoort et al., 2011). From the viewpoint of relationships between the perception of body shape and OBEs, further investigation is expected in the future.

As a supplementary argument, we considered the significant difference observed in the control questionnaire items. However, the statements in the control questionnaire items were "weird" and included to control for task compliance, suggestibility and unspecific cognitive bias. Therefore, further detailed analysis of the content of the interview results will be required in the future.

5 Conclusion

To investigate whether differences in native language affect people's ability to undergo scientifically induced OBEs, this study followed the methodology of Experiments #1 and #2 reported by Ehrsson (2007) and invited age-matched native English and Japanese speakers to participate. Thereafter, their OBEs were evaluated using a structured questionnaire based on a visual analog scale. The comparison of the results showed that OBEs were induced in similar ways in both groups, suggesting that people can have OBEs as a response to similar stimuli, regardless of their native language. However, differences in introspective reports between participants suggested that their experiences may differ qualitatively, and this may be due to the different linguistic backgrounds.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by the Ethics Committee of the Tokyo Institute of Technology. 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. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

HU: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. YY: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – review & editing. KU: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Validation, Visualization, Writing – review & editing. YN: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Resources, Validation, Visualization, Writing – review & editing. YM: Conceptualization, Funding acquisition, Methodology, Resources, Supervision, Validation, Writing – review & 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.

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Supplementary material

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A theoretical review of the Proteus effect: understanding the underlying processes

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Humans' inherent fascination for stories can be observed throughout most of our documented history. If, for a long time, narratives were told through paintings, songs, or literature, recent technological advances such as immersive virtual reality have made it possible for us to interact with storylines and characters in a completely new manner. With these new technologies came the need to study how people interact with them and how they affect their users. Notably, research in this area has revealed that users of virtual environments tend to display behaviors/attitudes that are congruent with the appearance of the avatars they embody; a phenomenon termed the Proteus effect. Since its introduction in the literature, many studies have demonstrated the Proteus effect in various contexts, attesting to the robustness of the effect. However, beyond the first articles on the subject, very few studies have sought to investigate the social, affective, and cognitive mechanisms underlying the effect. Furthermore, the current literature appears somewhat disjointed with different schools of thought, using different methodologies, contributing to this research topic. Therefore, this work aims to give an overview of the current state of the literature and its shortcomings. It also presents a critical analysis of multiple theoretical frameworks that may help explain the Proteus effect. Notably, this work challenges the use of self-perception theory to explain the Proteus effect and considers other approaches from social psychology. Finally, we present new perspectives for upcoming research that seeks to investigate the effect of avatars on user behavior. All in all, this work aims to bring more clarity to an increasingly popular research subject and, more generally, to contribute to a better understanding of the interactions between humans and virtual environments.

KEYWORDS

Proteus effect, avatar embodiment, virtual reality, self-perception theory, deindividuation, priming, virtual environments

1 Introduction

For most of our recent history, it seems that humans have had a fascination for stories. This inclination can be observed across cultures and millennia alike. From Paleolithic cave paintings to centuries of literature or today's immense media landscape, stories seem to be ever-present around us. Even more fascinating is our ability to be transported into a narrative in such a way that we forget, for a moment, its fictitious nature (i.e., narrative transportation, Green et al., 2004). Some scholars have theorized that this inclination could stem from our deeply social nature as humans (Oatley, 1999). Our appeal for storytelling, characters, and plotlines could therefore stem from how important understanding social dynamics around us is since it is a key component of our survival as a social species.

Thus, stories can be thought of as a way to simulate or recount critical scenarios without suffering the possible consequences of these situations. In many ways, this disposition could represent an evolutionary advantage as it trains our social and emotional intelligence and helps to communicate societal norms.

If books, songs, or paintings have been a way to tell stories for centuries, today's technologies offer new revolutionary ways to interact with narratives and characters. Notably, immersive virtual reality (IVR) is a particularly interesting way to do so. Through this new technology, we are able, for the first time, to look through the eyes of an avatar completely different from us. Even more remarkable is the way our brains seem to adopt the new virtual reality while consciously knowing that what is shown is simulated by a computer. For example, a study has been able to demonstrate that people show genuine fear when their virtual body might be in physical danger (Argelaguet et al., 2016). Another one showed that people seem to adapt their behavior when extra limbs are added to their virtual bodies (Arai et al., 2022).

These phenomena illustrate humans' inherent tendency to accept and engage in realities we know to be fictitious. Faced with the democratization of immersive technologies and the resulting new forms of interaction, researchers have sought to investigate the effects that embodying different virtual bodies would have on the users of virtual environments. Specifically, embodying avatars with physical characteristics that may evoke strong stereotypical behaviors or attitudes has been the subject of multiple studies. So, could embodying a Nobel prizewinner, an elderly person or even God change how people behave? If so, through which mechanisms? These questions are at the center of what researchers have termed the Proteus effect, and the subject of this review.

The goal of this article is to provide a critical review of the theoretical frameworks that could explain the Proteus effect. To our knowledge, no other review about the Proteus effect has addressed this question as extensively. The review is organized as follows. In Section 2, we summarize the current state of literature surrounding the Proteus effect, which brings us to question which processes could be responsible for this phenomenon. In Section 3, we review the hypotheses that have already been addressed in previous research, and thereafter, in Section 4 we address new or insufficiently researched hypotheses. In Section 5, we will present which hypotheses we find to be the most relevant to explain the Proteus effect. We conclude in Section 6 and give recommendations for future research on the Proteus effect.

2 Proteus effect

In Greek mythology, the sea God Proteus is believed to be the first son of the Olympian God of the sea, Poseidon. Proteus is described by Homer in the Odyssey as "the old man of the sea" and the herdsman of sea monsters and animals (Homer, 1919). Alongside knowing everything past, present, and future, Proteus also had the ability to change his shape at will. This last feature is thought to reflect the ever-changing quality of the sea from which the God originated. It was noted, however, that Proteus did not wish to share his extraordinary knowledge with others. Notably, he was known to change his shape to escape from the humans who wished to use his prophetic abilities. Since, the Greek God has given its name to several concepts, notably the English adjective "protean" that describes one's tendency to change frequently.

2.1 Princeps publication

In 2007, two researchers at Stanford University published a paper detailing two experiments in which participants embodied an avatar within an immersive virtual environment (Yee and Bailenson, 2007). Through those experiments, the researchers sought to investigate how the physical characteristics of the avatars could change the way users behave while embodying them. In their first experiment, participants were assigned avatars that could be either attractive, neutral, or unattractive. They then started the task by observing their avatar in a virtual mirror for about a minute. After that, participants were asked to interact with a confederate inside the virtual environment. The results of this first experiment showed that, compared to participants using less attractive avatars, users embodying an attractive avatar tended to come physically closer to the confederate, but also reveal more information about themselves (self-disclosure).

In the second experiment, the researchers manipulated the height of the avatars so that participants would either be shorter, taller, or the same height as the confederate. In this experiment, participants took part in a negotiation task in which they took turns splitting a sum of money with the confederate. The other person could then accept the split and take the money or refuse, in which case none of them would receive any money. The results of the negotiation task showed that users embodying a taller avatar tended to propose more unfair splits (to their advantage) compared to those using a shorter avatar. On the other hand, participants embodying shorter avatars were more likely to accept offers that did not benefit them.

Importantly, in both experiments, the confederates were blind to attractiveness and height manipulations (i.e., for all experimental conditions, they perceived avatars as either neutrally attractive or the same height as them). Thus, the observed effects on the participants cannot be explained by a change in the behavior of the confederate in response to those manipulations (i.e., behavioral confirmation). From these results, the authors concluded that participants' behavior changed in response to the appearance of their avatars. Specifically, it seemed that participants tended to display behaviors that were congruent with the features of their virtual representations. Indeed, we know from the literature that people commonly believe attractive individuals to be more confident (Dion et al., 1972), and taller people to be more likely to be leaders (Hamstra, 2014). These commonly held stereotypes could explain why participants with attractive and tall avatars acted more self-confident and self-serving in the tasks.

Based on these results, Yee and Bailenson (2007) defined the Proteus effect as the process by which users conform their behavior to the expectations evoked by the physical appearance of their avatars. In other words, users embodying an avatar seem to exhibit behaviors that an outside observer would consider consistent with the appearance of their avatars.

2.2 Further demonstrations

Since this first publication, many studies have replicated the Proteus effect using a wide variety of avatars and contexts. Within this literature, the avatar features manipulated by the researchers vary greatly. In this Section, we describe the main characteristics that have been used to show the Proteus effect in past research. These will be presented in two different categories: bodily features, which encompass traits such as gender, race, or attractiveness, and characters, which include the reference or use of famous individuals, uniforms, or even non-human figures.

Within the bodily features category, one of the aspects that is often manipulated is the gender of the embodied avatar (Yee et al., 2011; Ratan and Dawson, 2016). In one study, this manipulation was used to demonstrate stereotype threat (i.e., conforming to a negative stereotype about oneself) among participants completing a mathematics test while embodying customized avatars (Ratan and Sah, 2015). Results showed that participants embodying a female avatar had worse scores on the test compared to the participants embodying male avatars. The authors concluded that participants conformed to the negative sexist stereotype associated with the gender of their avatar (i.e., women are bad at mathematics). Other studies manipulating gender have shown differences in pro-social behaviors within online games depending on the gender of the avatar used (Yee et al., 2011). However, several studies have also failed to show behavioral differences using avatars of different genders (Chang, 2014; Kaye et al., 2018). These shortcomings could be explained by the fact that individuals tend to have quite complex attitudes toward gender and the associated stereotypes. These attitudes may interact with many other factors that are not accounted for in these experimental protocols. This could, therefore, prevent participants from displaying the stereotypical behaviors expected from them.

Physical features of the avatars manipulated in other experiments include height (Yee and Bailenson, 2007; Yee et al., 2009), attractiveness (Yee and Bailenson, 2009; Yulong et al., 2015), age (Reinhard et al., 2020), ethnicity (Ash, 2016), or weight (Pea et al., 2016; Joo and Kim, 2017; Ferrer-García et al., 2018). For example, researchers showed that, after having cycled for a period of time, participants embodying avatars considered to be less athletic tended to report higher levels of perceived exertion compared to participants embodying more athletic avatars. Moreover, these avatars also influenced users' heart rate such that less athletic looking avatars were associated to higher heart rate during cycling compared to athletic avatars. Another study showed a decrease in participants' walking speed post-VR use when embodying an elderly avatar compared to those using a younger avatar (Reinhard et al., 2020). Finally, the category of bodily features also includes studies testing the effect of structural changes to the avatar's body (Won et al., 2015). This has been done using avatars with an abnormal number of limbs such as six fingers (Hoyet et al., 2016), or avatars with tails (Steptoe et al., 2013).

It should be noted that using negative stereotypes relating to race, gender, or body size has been criticized for its lack of consideration of the sensitive nature of these topics (Clark, 2020). Using avatars to highlight the existence of harmful stereotypes is not inconsiderate in itself. Rather, the criticism can stem from a lack of acknowledgment that these stereotypes have very detrimental consequences for a very large part of the population and that the ultimate goal should be to find ways to minimize them.

The second category of features manipulated within the Proteus effect literature, termed "characters", includes studies in which participants embody well-known characters or figures that evoke strong attributes. One way this is done is through the embodiment of famous individuals associated with extraordinary qualities. For example, one such study showed an increase in performance on a cognitive task when using an avatar resembling Albert Einstein (Banakou et al., 2018). Another experiment has shown increased divergent thinking abilities, a component of creative thinking, when embodying an avatar of Leonardo da Vinci (Gorisse et al., 2023).

Another way in which researchers have used characters to study the Proteus effect is through the use of uniforms (Guegan et al., 2016, 2017). Peña et al. (2009) for example showed a link between the use of avatars dressed in either black cloaks or Ku Klux Klan (KKK) uniform and aggression. In another study, Buisine et al. (2016) used two different types of avatars in their experiment: either ones representing typical users of public transport or ones that were reminiscent of the stereotypical image of an inventor. The distinction between the two groups was communicated through the avatars' clothes (e.g., jeans and tee-shits vs a laboratory coat). In this experiment, engineers were asked to come up with innovative applications of a new technology in public transport. Results showed that the ones embodying the inventor avatars found more technological-centered ideas whereas the ones embodying user avatars were more likely to propose user-centered ideas. These results showed how the appearance of the avatars, and more specifically their clothing, shaped the creative thinking of engineers.

The last mention in this category concerns the embodiment of non-human figures, which may convey traits that humans cannot possess (Ahn et al., 2016). One experiment found a decrease in physiological responses to danger when participants embodied an avatar resembling the Christian God (Frisanco et al., 2022). In another study, participants were found to be more efficient during a task in which they had to block incoming projectiles when they used alien-like avatars, compared to human-like avatars (Christou and Michael-Grigoriou, 2014). These results indicate a tendency for users to feel less physically vulnerable and more confident when embodying figures with supernatural attributes.

Nonetheless, if avatar appearance has been shown to impact users of virtual environments it is also important to note that other elements surrounding such experiences can also affect how avatars are perceived. Indeed, factors such as avatar-environment congruence (Mal et al., 2023), from which point of view the user sees the avatar (i.e., first or third) (Gorisse et al., 2017), or the type of displays being used (Hepperle et al., 2022) have been found to affect the users' perception of avatars. Beyond avatars, other core aspects of virtual environments such as the level of detail of the graphics or the context cues provided to the users also impact user behavior (for a review see Neo et al., 2021). Even if these elements are not the subject of this review, it is important to consider them when trying to understand avatar and user interactions, especially in the context of novel social virtual environments such as the Metaverse.

2.3 Current state of the literature

All these demonstrations are a testimony to the robustness of the effect and its applicability to a wide variety of contexts. Through these examples, it was shown that the Proteus effect could affect the user's cognitive performance (Banakou et al., 2018), affective state (Peña et al., 2009), motor behavior (Reinhard et al., 2020), physiological responses (Frisanco et al., 2022), or psychological dimensions such as confidence (Yee and Bailenson, 2007) or creativity (Guegan et al., 2016; Gorisse et al., 2023). Two recent meta-analyses corroborated the validity of the effect by finding a small to medium mean effect size (r = 0.24) for the Proteus effect (Ratan et al., 2020; Beyea et al., 2023), an effect size comparable to similar media-related effects. Thus, based on this growing body of literature, it seems reasonable to assume that avatar appearance can indeed affect the behavior, cognition, or emotional state of the users embodying them.

However, if a significant number of studies have been able to replicate the effect, the social, affective, and cognitive processes underlying such a phenomenon do not seem as clear. Indeed, most publications on the subject have focused on demonstrating the effect but very few have sought to explore the theoretical explanations of this effect beyond those given by the first publications about the Proteus effect. Although a few recent reviews of the Proteus effect have highlighted this gap in the literature, and sought to address parts of it (Praetorius and Grlich, 2021; Szolin et al., 2022), these publications did not discuss some of the fundamental shortcomings of the current explanations of the Proteus effect. Indeed, in their systematic review, Szolin et al. (2022) chose to focus on the Proteus effect in the context of video games. They did so in order to study the phenomenon from a more ecologically valid perspective compared to studies using avatars and virtual environments specifically designed for experimental purposes. In that context, the researchers reviewed which avatar characteristics has been found to affect users' behaviors and attitudes while playing video games (e.g., avatar gender, attractiveness or weight) but also how avatars could influence the players' post-game beliefs. This review provided a clear overview of how the Proteus effect can affect players of video games but did not address nor challenge the theoretical understanding of the effect. The review by Praetorius and Grlich (2021) did however discuss this point. The authors conducted a qualitative analysis of the Proteus effect literature in order to classify the selected studies according to a model of identification processes (Looy et al., 2012). This analysis is based on a previous meta-analysis on the Proteus effect (Ratan et al., 2020) that links the Proteus effect to processes of self-identification between the user and the avatar. Although studying the link between identification and the Proteus effect has offered new insights into the mechanisms underlying the effect, Praetorius and Grlich (2021) still believe that the Proteus effect is best explained by the two most widely cited hypotheses on the subject: self-perception theory and priming. Indeed, in their review, both identification and embodiment processes are presented as moderating factors of the Proteus effect, and priming and self-perception processes as the potential underlying causes of the effect. Therefore our review aims to go beyond these previous publications by challenging the widely accepted explanations of the effect as well as proposing new theoretical frameworks to better understand it.

Thus, to inform the theoretical framework of the Proteus effect and avatar embodiment we will confront six different theoretical hypotheses within this review. We will start by addressing the three hypotheses that have already been cited in the Proteus effect literature and their limitations, including self-perception theory, priming, and deindividuation. In the following Section, we will introduce three new hypotheses that may be relevant to better understanding the processes underlying the Proteus effect: cognitive dissonance, embodiment, and perspective-taking. Finally, we will compare all six hypotheses to determine which ones provide a better explanation of the phenomenon.

3 Current theoretical hypotheses behind the Proteus effect

In Yee and Bailenson (2007)'s first article on the Proteus effect, the authors cited two existing theoretical frameworks to explain the phenomenon: Self-Perception Theory (SPT, Bem, 1972) and the Social Identity model of Deindividuation Effects (SIDE, Spears and Lea, 1992, 1994; Reicher et al., 1995).

3.1 H1: self-perception theory

As the first theoretical hypothesis to have been used to explain the Proteus effect, SPT remains the most cited explanation of the phenomenon to date. SPT states that, in situations where one's internal states (attitudes, emotions, cognition, etc.) are unclear, one might infer them from the external cues they exhibit (i.e., behaviors, circumstances in which a behavior occurs, etc.) (Bem, 1972). More specifically, SPT relies on two main propositions:

1. "Individuals come to 'know' their own attitudes, emotions, and other internal states partially by inferring them from observations of their own overt behavior and/or the circumstances in which this behavior occurs."
2. "Thus, to the extent that internal cues are weak, ambiguous, or uninterpretable, the individual is functionally in the same position as an outside observer, an observer who must necessarily rely upon those same external cues to infer the individual's inner states." (Bem, 1972, p. 2).

According to SPT, if attitude A and behavior/external cue B are commonly associated with each other, when a person exhibits B, they might infer that they must also hold attitude A, in the same way that an outside observer would. Therefore, in the context of the Proteus effect, the theory would suggest that, since the appearance of the embodied avatar is associated with certain attitudes (e.g., aggression, confidence), the user assumes that they must also hold those attitudes.

In Yee and Bailenson (2007) experiment, SPT would posit that, because people tend to perceive taller individuals as more likely to be leaders and competent (Hamstra, 2014), a participant embodying a taller avatar would adopt attitudes commonly associated with these traits (confidence, dominance, etc.). This would cause the participants to be more self-serving during the negotiation task, as it would be congruent with the expectations placed on tall individuals. Likewise, in the case of Banakou et al. (2018), SPT would consider that users perceive Albert Einstein as a figure of intelligence. Therefore, when they see themselves embodying the famous physicist, they must put more effort into the cognitive task to perform well. This allows users to maintain a coherent image of the smart scientist.

3.2 H2: deindividuation

Yee and Bailenson (2007) also theorized that the use of immersive virtual reality and avatars could amplify the effect of SPT through the process of deindividuation. According to the most recent model on the subject, deindividuation refers to a psychological state in which a person's behavior is driven by situational norms instead of personal ones (Reicher et al., 1995). Such a state can lead a person to display anti-normative behaviors they would ordinarily never engage in. It has been used to explain extreme behaviors within crowds such as the ones seen in groups of football hooligans for example. It is theorized that deindividuation can be induced by a combination of circumstances such as anonymity, lack of accountability, or group immersion (Vilanova et al., 2017). According to Yee and Bailenson (2007), immersive virtual reality and avatar embodiment could also lead to a similar state.

The study of deindividuation dates back to Le Bon (1895) and his book "The Crowd: A Study of the Popular Mind" where he describes the way people's behavior changes when they are part of a group. Already at that time, Le Bon described how being in a crowd led people to ignore their personal judgment in favor of the group's dynamics. The term deindividuation was later coined by Festinger et al. (1952) and has been extensively researched since in the field of social psychology (for a review see Vilanova et al., 2017). One particular study by Johnson and Downing (1979) demonstrated that when participants were wearing either a nurse's outfit or a Ku Klux Klan robe while administrating fake electrical shocks to a confederate, the participants in the nurse outfit would administer less intense shocks compared to subjects in the KKK robes. Interestingly, they found this effect to be amplified when the participants were deindividuated, resulting in an increase in prosocial behavior when situational cues (i.e., the nurse's outfit) prompted participants to behave that way.

This focus on situational norms was the basis for the most recent theory of deindividuation, the Social Identity Model of deindividuation Effect (SIDE) (Spears and Lea, 1994; Reicher et al., 1995). This model argues that when individuals find themselves deindividuated (e.g., anonymity, group immersion, etc.), they will tend to conform to the norms evoked by the situation even if those norms contradict their personal beliefs. It is believed that this happens as individuals' attention is taken away from their personal characteristics, toward situational norms.

Interestingly, this model has been used to explain some anti-normative behaviors observed in online spaces. Indeed, computer-mediated communication might be prone to induce deindividuation because of factors such as anonymity, distance, or a lack of accountability. For instance, one study found that anonymous players of an online game were more likely to cheat (Chen and Wu, 2015). This link between deindividuation and technologies has led (Yee and Bailenson, 2007) to hypothesize that deindividuation could also occur when individuals are immersed within a virtual environment and embody an avatar. According to this view, this happens when users' attention is diverted away from their personal characteristics and toward the avatar's identity cues. The users then adhere to the social identity evoked by the avatar and conform their behavior and attitudes to it. They hypothesized that deindividuated users would be more likely to follow the norms evoked by their avatar in the same way that the participants in the nurse's outfit did when administering electric shocks (Johnson and Downing, 1979). More specifically, they stated, "Users who are deindividuated in online environments may adhere to a new identity that is inferred from their avatars" (Yee and Bailenson, 2007, p. 274). Overall, the authors concluded that, combined, both deindividuation and self-perception are responsible for the Proteus effect.

3.3 H3: priming

Following the introduction of the Proteus effect, Peña et al. (2009) published a study in which they challenged Yee and Bailenson (2007)'s theoretical explanation of the phenomenon. According to them, the Proteus effect could be explained, not through SPT and deindividuation, but simply through priming mechanisms. More specifically, the authors base their claims on the automaticity of social interactions model (Bargh et al., 1996; Bargh, 2006), which argues that there exist automatic perception-behavior links such that perceiving certain stereotypes or associations primes the observer to display matching behaviors or cognitive responses. The authors claimed that, in the context of the Proteus effect, the avatar merely acts as a prime that activates related concepts (e.g., tall avatar activates confidence, leadership, assertiveness, etc.) and inhibits conflicting concepts (e.g., shyness). The activation and inhibition of these concepts then make it more likely for individuals to display behaviors congruent with the prime.

To support their hypothesis, the authors designed two experiments in which they investigated the effects of avatar uniforms on the user, using a desktop computer to display the virtual environment. The first experiment demonstrated that, compared to participants embodying avatars wearing white cloaks, those using avatars wearing black cloaks among a small group of players had more aggressive intentions toward other players and lower group cohesion. In the second experiment, when asked to interpret ambiguous images, participants using avatars with Ku Klux Klan robes were more likely to write stories with higher levels of aggression compared to a control avatar, and showed lower affiliation compared to a doctor avatar.

From these results, the authors concluded that the negatively connoted avatars (i.e., black cloaks and KKK robes) unconsciously primed negative beliefs within the users, which resulted in antisocial intentions and aggressive thoughts. Although these results do not directly contradict the self-perception and deindividuation hypotheses of Yee and Bailenson (2007), the authors argue that priming mechanisms represent a more parsimonious explanation of the Proteus effect. Furthermore, they claim that SPT does not explain the inhibition of conflicting concepts shown in these experiments (e.g., reduced group cohesion and affiliation).

In response to these claims, Yee and Bailenson (2009) published a follow-up experiment arguing that there is a difference between perceiving a concept and embodying an avatar relating to that same concept. Their experiment sought to differentiate possible priming mechanisms from self-perception ones by showing that observing vs. embodying an attractive person did not have the same effects on users. Similarly to their original study, participants either embodied an attractive or unattractive avatar inside the immersive virtual environment. However, at the start of this experiment, people could either observe their avatar in a virtual mirror (i.e., mirror condition) or watch a video of their avatar moving, (i.e., playback condition). Afterward, when asked to choose potential dating partners from a pool of pictures, participants using attractive avatars tended to select more attractive partners than those using unattractive avatars. However, this was only the case for participants in the mirror condition; no difference was observed for the playback condition.

These results demonstrate the importance of avatar embodiment for the Proteus effect to occur and differentiate it from the hypothesized priming mechanisms. The main difference between priming and SPT to explain the Proteus effect is that priming does not distinguish the appearance of the avatar from any other external visual stimulus that might have a priming effect on the user. From the perspective of SPT, however, the avatar is perceived as the physical representation of the user, therefore differentiating it from other visual elements perceived and increasing its relevance to the user. This is what, in their view, made the behavioral change observed in their experiment more powerful.

Finally, a few years later, Ratan and Dawson (2016) proposed an alternative view of the issue that combined both self-perception and priming. In their view, the perception of the avatar triggers the activation of concepts related to the avatar (i.e., stereotypes) in a similar way that priming mechanisms would. Through avatar embodiment, these concepts may become associated with concepts relating to the self. If that is the case, a person's own behavior starts to be influenced by these avatar-related concepts, as seen through the Proteus effect.

3.4 Limitations of the current theoretical frameworks

Since the self-perception vs. priming debate, very few studies about the Proteus effect have sought to refine or provide alternative theoretical explanations. Instead, most have focused on demonstrating the effect in a novel experimental context.

In today's literature, most research stands behind hypothesis H1 of self-perception theory as the explanation of the phenomenon based on the original article from Yee and Bailenson (2007). However, SPT also raises a few issues. The first one is that what is considered as "external cues," from which attitudes are derived, remains rather vague. Indeed, Bem defines these cues as "their own overt behavior and/or the circumstances in which this behavior occurs" (Bem, 1972, p. 2). This explanation applies rather well to situations in which bodily reactions are experimentally manipulated to cause a change in attitude. For instance, hearing a fake accelerated heartbeat while viewing a picture of a woman made men believe they were more attracted to the woman in the picture (Valins, 1966). However, in the case of the Proteus effect, the external cue in question is the appearance of the avatar the user embodies. From Bem's own wording, it can seem farfetched to consider avatar appearance as such an external cue since being tall or attractive, for example, is not an overt behavior. Even by considering the second description of external cues as "the circumstances in which this behavior occurs," it is hard to describe what "behavior" it could refer to in the context of the Proteus effect. Indeed, in most of the literature, it is simply the sight of the avatar that induces a change in attitude or behavior, not the sight of the avatar displaying a specific behavior.

The second issue with considering SPT to explain the Proteus effect is that it seems quite difficult to falsify experimentally. Indeed, if we do consider avatar appearance to be a valid "external cue" for self-perception, it becomes challenging to test whether self-perception truly explains the behavior change and not an alternative cognitive process. The theory simply tells us that the perception of the avatar's appearance would cause individuals to display an attitude that would be considered congruent with the avatar's image. As highlighted by the priming vs. self-perception debate, self-perception does imply that the avatar has to be perceived as part of the "self," separated from other cues present in the environment. This subtlety does distinguish possible self-perception processes from priming within the Proteus effect, which was demonstrated experimentally. However, experimentally distinguishing self-perception from other alternative explanations is more challenging.

Perhaps, one of the results that might indicate whether self-perception processes are involved in the Proteus effect comes from a study in which participants embodied either creative-looking avatars or control avatars (Buisine and Guegan, 2019). This experiment found, among other results, that using creative-looking avatars increased participants' creativity during a brainstorming task. In addition, researchers also measured participants' perception of the creative identity of the avatars. They tested whether that variable would mediate the relationship between the type of avatar and their creativity during the task. They found that the creative-looking avatars were indeed perceived as more creative than the control avatars. However, that perception did not mediate the relationship between avatar appearance and creativity. This result indicates that consciously identifying the avatar as more or less creative did not influence the fact that the avatar could affect the participant's creativity. In the context of self-perception, it can be argued that one would have to perceive their avatar as creative for the effect to work, which is not the case here. This example does not constitute an actual demonstration that self-perception processes cannot explain the Proteus effect (e.g., the perception of the avatar's creative image could happen unconsciously); however, investigating these subtleties will bring more clarity to this question.

Another aspect of SPT that could be tested comes from the notion that, according to the theory, the person's internal states must be somewhat "weak, ambiguous, or uninterpretable" for self-perception to occur. This then results in the person having to rely on external cues to deduce their attitudes. Thus, investigating whether individuals' internal states really are inaccessible in the context of a Proteus effect protocol would provide more evidence to understand if self-perception might explain the effect.

Overall, beyond its shortcomings, SPT remains a solid theory to explain the Proteus effect. For instance, compared to other frameworks, it highlights the importance of the self and avatar embodiment within this effect as highlighted by Yee and Bailenson (2009).

The second hypothesis (H2) that was brought up was the role of a potential deindividuated state within the users of virtual environments that may explain why they adhere to the identity of their virtual representation. Even though Yee and Bailenson (2007) only considered deindividuation in combination with self-perception processes to explain the effect, deindividuation could also be considered as an explanation of the effect on its own. Indeed, in the same way that a deindividuated person immersed in an aggressive crowd may become aggressive, the user embodying an avatar inside a virtual environment could also be inclined to match their attitude and behavior to the identity of the avatar. This hypothesis would also explain why virtual reality and avatars have successfully shaped behavior in a way that behavioral priming has not, as demonstrated by the failed attempts at reproducing Bargh et al. (1996)'s experiment (Doyen et al., 2012) which was later successfully reproduced using the Proteus effect (Reinhard et al., 2020). In addition, deindividuation potentially emphasizing the Proteus effect could also partly explain why a recent meta-analysis has found that immersive virtual reality setups seem to drive a stronger Proteus effect compared to PC screen displays (Beyea et al., 2023). Indeed, the virtual reality setup would provide a higher level of deindividuation as the user's body is replaced by the avatar's, concealing crucial identity cues. However, no experiments so far have explicitly tested the hypothesized role of deindividuation in the Proteus effect. To do so, future studies could aim to experimentally shift the user's focus away from the situational norms evoked by the avatar to instead redirect it toward their own personal norms. This could be achieved by increasing the salience of the user's identity within the virtual environment, as was done in past deindividuation protocols (Festinger et al., 1952).

Finally, regarding the priming hypothesis (H3), its flaw was well expressed in the title of Yee and Bailenson (2009)'s paper "The Difference Between Being and Seeing." However, this does not mean that the cognitive mechanisms ascribed to priming are completely unrelated to the mechanisms underlying the Proteus effect. Indeed, some priming processes could explain how the visual perception of the avatar can activate a semantic network of concepts relating to the appearance of the avatar (i.e., spreading activation, Anderson, 1983). These mechanisms have been used to explain the results of classical priming experiments such as word completion tasks. Furthermore, in the context of the Proteus effect, it is difficult to explain how the perception of an avatar could lead to the activation of related concepts without a process such as spreading action. However, the fact that concepts become more salient in memory does not explain why participants would go as far as changing their behavior or attitudes after this activation of semantic networks.

A specific sub-field of priming research actually relates to the Proteus effect: behavioral priming. This type of priming was mostly investigated between 1990 and 2010 and provided some very well-known results. For example, one of these studies infamously showed that simply priming participants with words related to intelligence led them to have higher scores on a general knowledge test (Dijksterhuis and van Knippenberg, 1998). Another similar paper related that priming participants with words associated with elderly people made them walk slower when exiting the experiment (Bargh et al., 1996). The theory behind these papers was that priming individuals with a specific concept could unconsciously elicit behaviors related to that concept. Unfortunately, this specific field has suffered from the replication crisis, as many subsequent studies were unable to replicate the results of both experiments cited above. Specifically, a recent study was only able to replicate the results of Bargh et al. (1996) when the experimenter charged with measuring the pace of the participants was prompted to believe participants would indeed walk slower (Doyen et al., 2012). This indicates that the original results were probably simply caused by confirmation bias since the experiment was most likely not a double-blind protocol. Those results do not indicate that behavioral priming is entirely false as a whole, but it shows that the effect, if it exists, is probably smaller and less common than originally assumed.

If today this framework lacks credibility, it is interesting to note that the Proteus effect has been used successfully to demonstrate very similar results with avatar embodiment. Indeed, as cited earlier, Reinhard et al. (2020) showed that embodying an elderly avatar led participants to walk slower after exiting the virtual environment. Unlike the original experiment, this one followed a strict double-blind protocol, adding to the credibility of the results.

Therefore, it seems that trying to evoke a certain behavior through a word prime has a less robust effect than inducing said behavior through the embodiment of a specific avatar. The main identifiable difference between those two protocols seems to reside in how the primed concept relates to the subject. Indeed, relating a concept to the self by way of avatar embodiment seems to be more efficient at evoking a congruent behavior in the user than the mere presentation of words referencing that same meaning. This idea actually echoes previous findings that showed that the effects of a prime could be amplified when self-relevance to the prime was higher. For example, a study on stereotype threat showed that black participants performed worse on a cognitive test after reading a text about a black person from a first-person perspective than they did when reading it from a third-person perspective (Marx and Stapel, 2006). Overall, hypothesis H3 cannot explain the Proteus effect on its own. However, processes relating to priming such as spreading activation might still be involved in the effect.

4 Further theoretical hypotheses

In this Section, we will present three additional hypotheses that may provide more insight into the theoretical understanding of the Proteus effect: cognitive dissonance, avatar embodiment, and perspective-taking.

4.1 H4: cognitive dissonance

Interestingly, SPT was originally developed as an alternative explanation to the theory of cognitive dissonance (Festinger, 1957). Cognitive dissonance is thought to be a state of psychological stress people experience when their actions contradict their beliefs (e.g., being concerned for animal welfare but eating meat) (Festinger, 1957). It is theorized that people try to minimize this dissonance when it occurs by either changing their behavior or their beliefs (e.g., stopping eating meat or rationalizing animal suffering).

The difference between SPT and cognitive dissonance is that in SPT, people do not experience this state of psychological distress in response to contradictions. Instead, people's attitudes are simply shaped to be congruent with their own behavior. Even though these two frameworks were introduced as competing theories, it was later accepted that each explained slightly different phenomena (Fazio et al., 1977). It is thought that SPT is better suited to describe situations in which people's internal states are relatively ambiguous or vague whereas cognitive dissonance applies to situations in which people clearly display a strong contradiction between their beliefs and actions. Today, SPT is mainly cited within areas such as marketing and persuasion (e.g., the foot-in-the-door technique, Burger, 1999) whereas cognitive dissonance remains a highly influential theory across many domains of psychology (Harmon-Jones et al., 2015; Kaaronen, 2018).

More generally, however, one could argue that, at its core, what SPT and cognitive dissonance try to describe is a deeper intrinsic need for humans to try to remain coherent. Both theories illustrate people's drive to have congruent attitudes/internal states and behaviors/external cues and vice versa.

Interestingly, this description of the phenomenon echoes recent work on predictive processing to explain brain functioning and behavior (Friston, 2009). Put simply, the theory of predictive processing (or predictive coding) posits that the brain constructs a generative model of its environment based on prior knowledge (Clark, 2013; Millidge et al., 2021). This representation is then used to make predictions about upcoming sensory events, which, in turn, are compared to the actual upcoming sensory information. Any prediction errors are then used to update the generative model of the environment to minimize future errors. In a recent article, Kaaronen (2018) proposed a new model of cognitive dissonance based on predictive processing: the theory of predictive dissonance. As the author explains, both frameworks fundamentally rely on the idea that individuals aim to reduce surprise (i.e., dissonance or prediction errors). Furthermore, bringing elements of predictive coding within cognitive dissonance theory allows us to explain certain issues related to the cognitive dissonance theory.

This new account of cognitive dissonance shows how this theory originally drafted in Festinger (1957) remains highly relevant in today's literature and even relates to some of today's most influential theories of brain functioning. All of this highlights how fundamental this drive for consistency is for individuals, which is also illustrated in SPT. Interestingly, some findings attributed to SPT could also be included within this wider framework such as the fact that inducing specific facial expressions can shape people's subsequent attitudes (Laird, 1974; Ito et al., 2006). This could very well be explained in terms of prediction errors of upcoming sensory information causing, down the line, a change in attitude.

Thus, we could try to understand the Proteus effect in terms of minimizing the dissonance created by an attitude that would be incongruent with the perceived appearance of the avatar. In other words, the user embodying a tall avatar takes on an assertive attitude to avoid being incoherent regarding the image they have of tall individuals. This account could provide an alternative explanation to SPT that still addresses this drive for coherence between internal and external states without the shortcomings associated to SPT's definition. Furthermore, this theoretical framework is linked to a large and contemporary body of literature within the cognitive sciences, giving the phenomenon more context.

4.2 H5: embodiment

As mentioned in previous hypotheses, avatar embodiment plays an important role in the Proteus effect. However, while most definitions of the effect will mention "avatar embodiment," not all studies actually define the notion of embodiment and what role it could play in the behavioral change observed.

The sense of embodiment in virtual reality is defined by Kilteni et al. (2012) as a combination of three different factors: a sense of agency (SoA), a sense of self-location (SoSL), and a sense of body ownership (SoBO). The SoA describes the feeling of having motor control over the body and being aware of its movements. In virtual reality, visuomotor synchronicity between the user's and the virtual body's movements is crucial to instill a SoA within the user. SoSL refers to the feeling of being located in a space, which is typically our own physical body but can also apply to an avatar in a virtual environment. This can change even more in out-of-body experiences where individuals report feeling located outside their own bodies (Ehrsson, 2007; Lenggenhager et al., 2012). Finally, SoBO is defined as recognizing a body as our own. This is the sense that is manipulated in the famous rubber hand illusion in which participants felt ownership over a plastic hand located close to their real hand (Botvinick and Cohen, 1998). This was done by visually hiding the participant's real hand under a sheet and the use of synchronous tactile stimulation of both the real and the fake hand. Each of these three factors have been experimentally manipulated within virtual environments to understand how an optimal level of embodiment could be felt by users. Fribourg et al. (2020) did so by using the user's level of control over the avatar to influence the SoA, the avatar's appearance (i.e., minimal or realistic) to change the SoBO and the user's point of view (i.e., first or third person) to alter the SoBL.

Regarding the Proteus effect, multiple studies have sought to understand how these different aspects of embodiment may shape the effect. Several of these studies have found that a higher sense of embodiment was linked to a stronger Proteus effect (Kilteni et al., 2013; Beaudoin et al., 2020; Frisanco et al., 2022). More specifically, two of these studies (Kilteni et al., 2013; Beaudoin et al., 2020), found the SoBO to be associated with a higher Proteus effect. This last finding is coherent with literature about the SoBO as it has been shown that multiple aspects of avatar appearance such as realism or similarity can modulate SoBO (Argelaguet et al., 2016; Lin and Jörg, 2016). These results seem to indicate a possible moderating effect of embodiment on the Proteus effect and even point to SoBO as the underlying process. However, several other studies did not find such a link between embodiment and the Proteus effect (Ratan and Sah, 2015; Verhulst et al., 2018; Reinhard et al., 2020), thus contradicting the previously cited results.

Based on these conflicting accounts, a recent study aimed to test whether the sense of embodiment does in fact moderate the Proteus effect (Dupraz et al., 2024). Interestingly, their results revealed that participants' embodiment levels did not impact the Proteus effect, therefore refuting the notion of a moderating effect. Based on these results, the authors hypothesized that despite lower embodiment levels in certain experimental conditions, the participants still established a link between the avatar and themselves, allowing for the Proteus effect to occur regardless. It could be theorized that this hypothesized link between the self and the avatar could be explained by identification processes also mentioned in this article. Indeed, such processes are defined as the experience of assimilating some of the avatar's characteristics into the user's self-perception (Klimmt et al., 2009). These have previously been presented as potential influences of the Proteus effect (Ratan et al., 2020; Praetorius and Grlich, 2021), however, to our knowledge, no study has currently tested the influence of identification processes within the Proteus effect.

Future studies could therefore aim to test such a hypothesis. If identification processes do indeed play a role within the Proteus effect, they could potentially explain why previous studies have found conflicting results when testing the moderating effect of embodiment on the Proteus effect (Dupraz et al., 2024). Indeed, it could be theorized that high levels of identification could compensate for lower levels of embodiment and still facilitate the Proteus effect. The interaction between these two processes should therefore be tested in future studies.

All in all, current research about the role of embodiment within the Proteus seems inconsistent. The disparity in the literature could potentially be explained by additional underlying processes at play during avatar embodiment that are not being measured as of now. Therefore, broadening our understanding of the processes involved in the Proteus effect could help clarify how embodiment fits within this framework.

4.3 H6: perspective-taking

The final hypothesis surrounding the effects of avatar embodiment that will be addressed comes from a slightly different side of the literature than the Proteus effect. Some researchers have used immersive virtual reality and avatars to induce perspective-taking experiences that aim to reduce negative biases among users. Within this literature, researchers hypothesize that embodying an avatar representing a person from a marginalized group (e.g., the elderly, women, certain ethnicities, etc.) will increase the user's empathy for the group in question (Loon et al., 2018). This then prompts the users to display behaviors that go against the negative stereotypes associated with the avatar.

Interestingly, based on this description, the framework generally makes opposite predictions to the Proteus effect (Clark, 2020). Indeed, the Proteus effect assumes that embodying an avatar will cause the user to adopt behaviors that would be coherent with any stereotypes associated with the avatar's appearance. On the contrary, virtual reality perspective-taking predicts that users will not display stereotypical behaviors, as their empathy toward the avatar has increased through the embodiment.

Both sides of the literature include experiments supporting each opposing view. Some studies using virtual reality perspective-taking have shown that embodying black avatars led participants to show a decrease in implicit racial bias (Peck et al., 2013). Another showed similar results on implicit ageism using elderly avatars (Oh et al., 2016). On the other hand, Proteus effect research has shown that embodying the avatar of an individual from a stereotyped group has led participants to display behaviors and attitudes in line with the stereotypes. For instance, Pea et al. (2016) demonstrated that participants using avatars with a larger body showed a decrease in physical activity compared to people using thinner avatars. In this experiment, participants displayed behaviors that were coherent with negative stereotypes associated with larger individuals (i.e., being lazy). Similar results were found regarding negative racial stereotypes (Ash, 2016).

This nuance between increasing empathy toward a stigmatized group and accentuating negative stereotypes toward said group through avatar embodiment highlights the need for a better understanding of the Proteus effect. The distinction between these two views may lie in the framing of the embodiment experience. For instance, in their experiment assessing how perspective-taking could impact negative biases toward elderly people, Oh et al. (2016) specifically asked the participants to "Imagine a day in the life of this individual, looking at the world through her/his eyes and walking through the world in her/his shoes" (p.402) while embodying an elderly avatar. This emphasis on placing oneself in the avatar's perspective is not common in Proteus effect studies and would be more likely to promote empathy. In addition, the perspective-taking approach only applies to experiments using avatars of marginalized groups (e.g., gender, race, sexuality, etc.). Even though it can be argued that the Proteus effect does rely on having more or less accurate preexisting stereotypes about whom the avatar represents (e.g., engineers are creative), those are not necessarily negative and would not foster empathy in the user embodying them. Thus, this framework does not apply to a large part of the Proteus effect literature that uses avatars unrelated to those social issues (e.g., alien avatars, engineers, Einstein, tall individuals, etc.). Overall, the perspective-taking hypothesis cannot account for many of the results found within the Proteus effect literature and seems to account for a different phenomenon associated with avatar embodiment.

TABLE 1 Summary of the six hypotheses aiming to explain the underlying processes of the Proteus effect, their mechanisms, and examples.

Hypotheses	Mechanisms	Example
H1: Self-Perception Theory	Attitudes of the user are derived from observing external cues (avatar appearance) and match what an outside observer would find coherent.	The user embodies Albert Einstein. An external observer would expect Einstein to perform well in a cognitive task. Therefore, the user puts more effort into the task to perform well.
H2: Deindividuation	The use of virtual environments and avatar embodiment deindividuates the user. They then conform to the situational norms evoked by the avatar's appearance.	The user embodies Albert Einstein. This experience shifts the user's attention from their personal norms toward the norms evoked by Einstein. They then conform to those norms and perform better on the cognitive task.
H3: Priming	The sight of the avatar activates networks of concepts associated with the avatar's appearance. This prompts the user to display behaviors related to these concepts.	The user embodies Albert Einstein. Viewing the avatar activates concepts related to intelligence within the user, which prompts them to act accordingly and perform well on the cognitive task.
H4: Cognitive dissonance	The user aims to keep their behavior and attitudes coherent with what the appearance of their avatar suggests to avoid feeling dissonance.	The user embodies Albert Einstein. Since embodying a figure related to intelligence and performing poorly on a cognitive task would be incoherent and create dissonance, the user puts in more effort to perform well.
H5: Embodiment	The user's subjective experience of embodying the virtual body of the avatar and processing it as it was their own body.	The user embodies Albert Einstein. Through a high sense of agency of over the movements of the avatar, ownership over the virtual body and feeling located inside the avatar, the user processes the virtual body as its own which facilitates the emergence of the Proteus effect.
H6: Perspective- taking	The experience of embodying an avatar of a different individual prompts the user to feel empathy toward them. The user then adopts attitudes that oppose any negative stereotypes associated with that individual.	The user embodies the avatar of a woman. This experience increases the user's empathy toward women. Therefore, when confronted with a mathematics test, the user puts more effort into the task to contradict negative stereotypes about women.

5 Discussion

This review aimed to provide a critical analysis of different theoretical frameworks that may explain the underlying processes of the Proteus effect. A total of six different hypotheses were assessed through this review. As of now, there does not seem to be a unique hypothesis that can explain the effect all by itself, but rather a combination of a few hypotheses that may explain different aspects of the phenomenon. All six hypotheses are summarized in Table 1. For each hypothesis, its mechanisms are described along with how this framework would apply to a specific example of the Proteus effect. Whenever applicable, we used the protocol of Banakou et al. (2018) as an example.

Thus, to summarize, the self-perception hypothesis (H1) conveys that the Proteus effect relies on a need for coherence between external cues and attitudes. In addition, it also emphasizes the importance of embodying the avatar for the Proteus effect to occur (Yee and Bailenson, 2009), however, this hypothesis has a few limitations. As discussed previously, whether this theory can be applied to the Proteus effect remains unclear and should be further tested in upcoming research. Furthermore, beyond its limitations, the strong points of the theory cited earlier can be found in alternative hypotheses such as cognitive dissonance or avatar embodiment. Therefore, even if we do not claim that it is impossible for SPT to explain the Proteus effect, we propose an alternative view of the processes responsible for the effect, described at the end of this Section, that does not include SPT and reject H1.

On the other hand, deindividuation (H2) could represent an interesting explanation of the phenomenon and more specifically, why virtual reality and avatar embodiment are powerful means of inducing specific behaviors within users. Furthermore, this framework is linked to previous research that provides additional context to the Proteus effect, notably the effect of certain uniforms or costumes on behavior (Diener et al., 1976; Johnson and Downing, 1979; Greco, 2019). This hypothesis remains to be tested but provides a strong explanation of the effects of avatar embodiment on behavior from a social psychology point of view. Based on this we choose to include H2 in our framework.

As for the priming hypothesis (H3), as explained, it does not account for the importance of avatar embodiment. However, the cognitive mechanisms associated with priming (i.e., spreading activation) could explain how networks of related concepts are activated after the perception of an avatar and thus, how individuals can go from concepts such as "tall" to "confidence." Nonetheless, we reject H3 since priming mechanisms as a whole do not seem to explain the Proteus effect.

H4 brought forward the idea of cognitive dissonance as an alternative explanation to SPT. This allows us to understand the Proteus effect through the lens of trying to minimize dissonance potentially caused by a discrepancy between one's appearance (the avatar) and one's behavior or attitude. This hypothesis also fits within a wider framework that aims to explain such processes as a global need for coherence between internal processes and our behavior. Therefore, we also include H4 in our framework.

Additionally, having a better understanding of how avatar embodiment (H5), and its sub-components, play a role in the Proteus effect would provide crucial details about the underlying mechanisms of the effect. Preliminary research on the matter does seem to indicate that the sense of embodiment of the user inside the virtual environment could influence the strength of the effect. Therefore, future research should aim to deepen our understanding of this interplay between embodiment and Proteus effect. Nevertheless, we include H5 within our framework.

The last hypothesis (H6) focused on the view that avatar embodiment could induce a perspective-taking experience in the user by seeing the world through the eyes of someone else. Even if perspective-taking studies have demonstrated that it is possible to increase empathy for the avatar through the use of virtual reality, these studies use different methods that are specifically aimed at inducing such feelings in the user. We choose to reject H6 as it cannot explain all the results found within the Proteus effect literature since they often contradict the predictions made by the perspective-taking framework.

All in all, we propose an alternative view of the underlying mechanisms of the Proteus effect. This view includes the idea that the use of immersive virtual reality, virtual environments, and avatars induces a sense of deindividuation within the user. This state makes the user more likely to conform to the behavioral and attitudinal expectations evoked by the appearance of the avatar. In addition, we also hypothesize that this behavioral and/or attitudinal change is also encouraged by a drive to minimize any possible dissonance felt when the avatar's appearance is incongruent with the behavior of the user. Finally, this framework also takes into account the sense of embodiment experienced by the user while embodying the avatar. Based on previous research we expect that a stronger sense of embodiment would result in a stronger Proteus effect.

It is important to note that the notions of deindividuation or cognitive dissonance have never been tested in the context of the Proteus effect and therefore remain rather hypothetical. Future research should aim to refine our understanding of these processes. For example, this can be done by systematically measuring the sense of embodiment of users, testing whether deindividuation or self-perception processes are at play in the effect, or even differentiating the processes at play in perspective-taking experiences from the Proteus effect.

6 Conclusions

Overall, this review highlights the need for a better theoretical understanding of this phenomenon and the approaches that could help us do so. Research focused on how immersive technologies and virtual environments affect their users is crucial as these elements become increasingly common. Moreover, studying phenomena like the Proteus effect provides us with new unique insights into human cognition, which would not have been possible without the technology. In addition, this effect has the potential to be applied to a large number of domains in order to improve specific beneficial skills. It has already been shown to work within a professional context to tailor the creativity processes of workers to specific demands (Buisine et al., 2016).

Finally, from a wider perspective, the Proteus effect highlights an interesting human characteristic: our adaptability. From the outside, it can seem rather absurd that simply putting a virtual reality headset on and visualizing a new virtual body can automatically prompt us to act differently. However, this effect could reflect a deeper intrinsic quality that allows us to adapt to new situations such as using novel technologies.

This notion of adaptability is reminiscent of a scientific debate based on Lewin (1936)'s equation staging the person and the situation as fundamental drivers of human behavior. Some researchers claimed that people were not as consistent across situations as some research on personality traits had previously claimed (Mischel, 1968). In this argument, Mischel (1968) believed behavior to be more dependent on the situation than on fixed personality traits. Even though today's arguments are more nuanced about the contribution of each factor on behavior, this debate still highlights people's tendency to be more adaptable in response to different situations than we may think.

From an evolutionary perspective, having this degree of flexibility in response to new situations seems coherent. A good balance between flexibility and consistency would represent an evolutionary advantage. A completely inconsistent person that would change entirely depending on each situation would be too unreliable within a society. Likewise, an inflexible person, always behaving according to the same norms, would struggle to survive whenever their environment inevitably changes. The Proteus effect could therefore be a very modern demonstration of this intrinsic adaptability to new realities.

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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.

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Alone but not isolated: social presence and cognitive load in learning with 360 virtual reality videos

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Introduction: This study aimed to identify any differences in social presence and cognitive load among three types of 360 virtual reality (VR)-based videos lectures. We hypothesized that social presence would be higher when interactions among peers are visible in a 360 VR video lectures while the cognitive load would be also increased.

Methods: A total of 48 college students were randomly assigned to one of the three study groups to view an assigned 360 VR video lecture. The three groups were: (1) an instructor-only video viewing group, (2) a classroom lecture video viewing group, and (3) a classroom lecture and activity video viewing group. The video lectures were differently designed depending on the levels of peer visibility and the interactions between the instructor and peers. The participants watched one of the three types of assigned video lecture and subsequently completed two sets of questionnaires regarding social presence and cognitive load. A multivariate analysis of variance (MANOVA) was conducted with a planned contrast analysis for the type of video lectures.

Results: We found that, contrary to the hypotheses, students in the group 1 (instructor-only video) showed higher social presence scores than students in the groups 2 and 3. However, no significant differences were found in the cognitive load scores.

Discussion: The results show that 360 VR video lectures with an instructor-only are more effective at enhancing users' social presence than 360 VR video lectures with both the instructor and class-peers. We suggest creating 360 VR video lectures with the presence of the course instructor to offer learners the sense of actually participating in a lecture.

KEYWORDS

360 virtual reality, head mounted display, social presence, cognitive load, video lecture

1 Introduction

Although online video learning is becoming one of the most popular instructional methods, it is more difficult to create rich social environments for learners compared to face-to-face learning. Students have reported that when they perceive a sense of disconnection during online learning, their online experiences are less enjoyable, less helpful, and they experience more frustration than when they experience in-person interactions through their studies (Boling et al., 2012). Moreover, interactions with other people in learning environments have shown to be effective in helping learners organize their thoughts, reflect on their understanding, and identify gaps in their comprehension (Okita et al., 2012). Hence, video lectures delivered online need to be designed to enhance social connections and to provide various learner–system-interaction features (Breslow et al., 2013; Alraimi et al., 2015). Increasing interactions during online video learning to enhance social context would be essential.

To overcome the reported sense of disconnection, recent studies claimed that online video lectures need to consider improving sensory immersiveness to successfully engage students in the learning environment (Dede et al., 2017; Cesari et al., 2021). Especially, 360 virtual reality (VR) videos have been studied as an effective approach to add such immersiveness into online contents in higher education (Snelson and Hsu, 2020). 360 VR video lectures and its subsequent viewing using a VR headset together can imitate an authentic academic classroom setting, in which the students perceive a realistic scene in a lecture (Hebbel-Seeger et al., 2021). For this reason, 360 VR video lectures show potential as an effective educational tool (Lampropoulos et al., 2021) in that it is widely available (Shadiev et al., 2021), cost-effective (Ulrich et al., 2021), affordable, and easily accessible (Roche et al., 2021). Overall, 360 VR technology's positive aspects significantly enhance learners' immersive perception by effectively providing contextualized scenes during the learning process. This heightened immersiveness facilitates learners' engagement and paves the way for a more interactive and dynamic learning experience. The result is a more engaged learning experience, which leads to higher learning achievement.

One of the strengths of 360 VR video lectures is to create a virtual learning environment that elicits a high degree of social presence (Cheng and Tsai, 2019; Araiza-Alba et al., 2021; Roche et al., 2021). Social presence refers to the degree to which a person is perceived as a "real person" in mediated communication (Gunawardena and Zittle, 1997, p.9). Social presence helps reduce learner's feeling of isolation in online video learning (Borup et al., 2012) by offering visual representations of classroom and learning interactivity through the video (Oh et al., 2018). A 360 VR videos use real-world footage (Evens et al., 2022) with high visual-realism, can enhance both the immersive quality of the experience and the students' perception of social presence. A 360 VR video also can capture complex learning interactions between the course instructor and students that can be replayed as many times as needed (Andel et al., 2020). Therefore, 360 VR-video users can perceive the virtual environment as an authentic learning experience (Southgate, 2018) that enhance to learning by replicating the real-world environment (Cheng and Tsai, 2019; Araiza-Alba et al., 2021). Furthermore, user engagement increases when the 360 VR video allows users to explore video details (Roche et al., 2021). The spatial display by 360 VR brings authentic context so that the user may have strong perceptions of social presence.

However, it should be noted that 360 VR videos do not always have a positive influence on perceiving social presence. Paradoxically, the high visual realism of 360 VR videos creates several limitations in terms of effective design of such VR videos. First, possibility for user-interactions within the 360 VR video are often minimal (Pirker and Dengel, 2021). Because 360 VR applications cannot provide direct user interaction with the content (Torres et al., 2020). From the previous study, although users can interact with the recording by freely choosing their viewing direction, the recorded event cannot be manipulated as programmed virtual reality scenarios allow (Roche et al., 2021). The experiences within 360 VR videos are often designed to provide a fixed camera angle. This experience only permits simple operations, such as turning around and changing viewpoints. The interaction from 360 VR is not strong enough to enhance the social presence.

Another possible limitation of 360 VR video is the unnecessary cognitive load caused by the amount of visual information when conveyed through the VR-headset. Although complex visual representations and details in 360 VR videos offer high representational fidelity and can lead to higher user-presence, they can also result in higher extraneous cognitive load which decreases learning (Makransky and Peterson, 2021). In 360 VR videos, the visual load increases as the learner adjusts screen details, which increases the extrinsic cognitive load, especially when the 360 VR video provides little visual guidance due to the wide field of view (Beege et al., 2012). Moreover, because 360 VR video users can navigate freely with little-to-no guidance, certain events can be easily overlooked (Ardisara and Fung, 2018), especially when users switch their focus between their main information-target and other details (Lin et al., 2017). Moreover, the transient information present in 360 VR videos can cause learners to miss learning objectives because of inherent limits of people's working memory (Beege et al., 2023). Therefore, 360 VR videos require an appropriate design to lower the extraneous cognitive load while maintaining a high social presence.

Seeing other people who share or interact with the same virtual environment as the user increases social presence (Oh et al., 2018). The more prominent the person or character are to the user, the more they feel like they are sharing a space with him or her, even if there is no mutual recognition (Pimentel et al., 2021). For example, users can feel socially present by recognizing the presence of other learners in the virtual classroom. In addition, users can use the other learners to acquire their learning skills by mimicking how their peers learn, such as by asking questions. Even in cases where there are disagreements between the instructor and certain learners, this can increase user interaction and motivation to learn (Chi et al., 2017). However, even though the presence of peers in VR-learning videos can increase a user's social presence (Garrison and Cleveland-Innes, 2004; Zhu et al., 2022), sharing the VR-environment with other learners can compete with certain cognitive learning process. One study found that the larger the number of learners in the same virtual space, the perception of the task's difficulty increased, and the higher the cognitive load required to comprehend the learning content (Skuballa et al., 2019). It is necessary to compare the learning effects based on the presence and level of interaction with other peer learners when using VR videos to facilitate practical educational applications.

This study attempted to understand how the presence and interaction of instructor and peers in 360 VR videos influence students' perception of social presence and cognitive load. Three types of 360 VR videos were created: (1) instructor-only, (2) classroom-lecture, and (3) classroom lecture and activity. Because these combinations created a virtual learning situation, their use can be assumed analogous to that of the role of an instructor. Online learning using the three video types was classified depending on peer-presence and peer-interaction. We conducted a preplanned comparison of the effects of the video types based on the presence or absence of peers in the videos; (1) versus (2) + (3). We also compared the effectiveness between video types with and without instructor–peer interaction and activity; (1) + (2) vs. (3). Therefore, the purpose of this study was to investigate the effects of three types of 360 VR videos on students' perception of social presence and cognitive load.

1.1 Research questions and hypothesis

Two research questions guided this study as follows:

RQ1. Are there differences in social presence and cognitive load depending on the person featured (instructor-only vs. instructor and peers) in the 360 VR videos?

> *H*1: Participants that view the 360 VR video that contains peers will have a higher social presence than those who viewed the instructor-only video.
>
> *H*2: Participants who viewed the 360 VR video that contains peers will have a higher cognitive load than those who viewed the instructor-only video.

Justifications for hypotheses 1&2: RQ1 explores the difference between persons featured in 360 VR videos. Because it is assumed that educational videos are based in a classroom setting, it is natural for instructors or peers to appear in the video. In this study, we developed two types of videos, one featuring only the instructor and the other featuring both the instructor and peers. H1 and H2 are our hypotheses regarding the first research question. The presence or absence of characters in 360 videos can make a significant difference in social presence. The more prominent the characters are to the user, the more they feel like they are with them, even if there is no mutual recognition (Pimentel et al., 2021). In contrast, the more other students are present, the greater the number of distractions, which competes for finite working-memory resources, and the task is perceived by the viewer as being more difficult (Skuballa et al., 2019). It is crucial to identify how the presence of persons will have an impact on cognitive load to make a good balance for learning.

RQ2. Are there differences in social presence and cognitive load between video types with and without instructor–peer interaction and activity (with instructor–peer interaction and activity vs. without instructor–peer interaction and activity) in the 360 VR videos?

> *H*3: The participants who viewed the 360 VR video with instructor–peer interaction and activity will have a higher social presence than those who viewed the video without instructor–peer interaction and activity.
>
> *H*4: The participants who viewed the 360 VR video with instructor–peer interaction and activity will have a higher cognitive load than those who viewed the video without instructor–peer interaction and activity.

Justifications for hypotheses 3 & 4: RQ2 is designed to identify any differences among interaction types in the three 360 VR videos. We developed two types of videos, one with instructor–peer interaction and activity and the other without instructor–peer interaction and activity. H3 and H4 are our expectations of the second research question. The 360 VR video showing peers' interaction and activity gives the users the feeling of being in a real classroom (Garrison and Cleveland-Innes, 2004). Additionally, in immersive environments, the presence or absence of vividness and interactivity has a significant impact on the sense of presence (Wallach et al., 2010). Whereas instructor interaction is often spontaneous and unintentional compared to peer interaction (Mehall, 2020). Peer interaction and activity in the instructional video might cause an unnecessarily higher cognitive load.

1.2 Theoretical frameworks

1.2.1 Instructional 360 VR video

Notably, 360 VR can be an effective educational tool when students are training for high-risk or high-cost job roles that are difficult to practice in real-world settings. In addition, 360 VR videos allow users to perceive the virtual environment as an authentic scenario and they can explore the virtual situation freely (Southgate, 2018). The user is therefore no longer a passive spectator, but they are actively engaged in the learning experience they can explore deeply learning details embedded within the VR video (Roche et al., 2021). This also means that users can experience increased motivation, engagement, and presence of learning when in a real-world-like environment (Cheng and Tsai, 2019; Araiza-Alba et al., 2021). Furthermore, because 360 VR videos can be used as a tool for teaching and learning, they have similar cognitive learning effects with other tools—such as traditional videos and posters—although learners who experienced 360 VR videos report higher levels of interest and enjoyment than those trained using traditional media (Araiza-Alba et al., 2021). The positive feature of 360 VR is pervasive for educational purposes to provide situated learning experiences.

Due to common design processes, 360 VR videos often only provide visual stimuli. They are designed as a video experience, where the user's only available interaction is the ability to move their heads and change their point-of-view (Pirker and Dengel, 2021). A freely selectable view of 360 VR videos mean that certain events can be easily overlooked when watching 360 VR videos (Ardisara and Fung, 2018). Therefore, users should continuously switch the focus of attention between the main target and other information in 360 VR videos (Lin et al., 2017). These additional requirements can detract from the overall user experience, leading users to miss some important events while they are still searching or exploring the scenario (Lin et al., 2017) and increasing perceived workload (Gold and Windscheid, 2020). Hence, additional design features are needed to enhance user-immersion and reduce unnecessary cognitive load. For this reason, some researchers have questioned the benefits of instructional 360 VR for content delivery, while conceding that the technique can increase learner engagement and interest (Lee et al., 2017; Hebbel-Seeger et al., 2021). Nevertheless, instructional 360 VR videos can favor learners' understanding of theories or concepts related to a subject-specific topic (Ranieri et al., 2022). The immersive nature of 360 VR videos can improve student concentration on course content (Taubert et al., 2019). Hyttinen and Hatakka (2020) found that although 360 VR technology is suitable for lecturing, it is less suited to small group work or and promoting participation in discussions. Additionally, successfully implementing lectures using 360 VR videos requires the resolution of the inherent pedagogical and didactical challenges. For those instructors intending to use 360 VR videos in their teaching, they should consider appropriate teaching methods and strategies to promote learner engagement. The design considerations when creating 360 VR videos, such as the height of the 360 VR camera and the proximity and actions of people appearing in the videos, also influence learners' viewing experiences and social presence (Saarinen et al., 2017; Keskinen et al., 2019). Through experiments, Keskinen et al. (2019) demonstrated that a camera height of approximately 150 cm and a distance of over 1 m between the camera and individuals provide the most comfortable viewing experience.

In sum, when developing 360 VR videos, it is essential to consider some factors that can affect the users' social presence and cognitive load. Especially in instructional 360 VR videos for lecturing, the presence and interaction of the instructor and peers are important factors, because they create a learning atmosphere emulating a real classroom setting, ultimately affecting students' learning experiences in the virtual environment.

1.2.2 Social presence in instructional videos

Social presence is defined as a psychological phenomenon where someone is perceived as "real" during the communication process; it is the subjective feeling of being with other salient social actors in a technologically mediated space (Weidlich et al., 2018, p. 2146). In online learning, social–emotional aspects are essential factors during the design process. Social–emotional experiences should be differently designed in online learning from those in face-to-face learning. Unlike face-to-face environments that naturally provide rich social interactions, online learning demands unique instructional design strategies. It is challenging to imbue the online environment with meaningful social elements (Weidlich and Bastiaens, 2019) and to incorporate emotional, cognitive, and behavioral strategies that boost learner engagement and experience (Pentaraki and Burkholder, 2017). Online learning requires unique design approaches to emulate the rich social context of traditional face-to-face environments.

An increased perception of social presence can lead to increased task performance in multimedia learning environments (Schneider et al., 2022). While early studies on the predictors of social presence focused almost entirely on immersive qualities (e.g., visual representation, interactivity, haptic feedback, depth cues, audio quality, and display), more recent studies considered the impact of contextual and individual factors (e.g., personality/character traits of a virtual human, agency, physical proximity, task-type, social cues, identity cues, and psychological traits), perhaps as an acknowledgment of social presence as a subjective experience (Oh et al., 2018). Learners will engage in learning and then outperform their achievement by projecting individuals in the learning context in a trusting digital environment.

Within the virtual setting, the instructor's role is important to enhance social presence. According to social agency theory, instructors who use social cues—such as tone of voice and speaking style—can promote social presence, stimulate cognitive processing, and improve learning outcomes (Mayer, 2014). In addition, when an instructor's face is shown in a video lesson, it provides nonverbal communication cues, such as eye contact, gestures, and facial expressions; cues replicate the social aspect of human face-to-face interaction to the learners (Wang and Antonenko, 2017). Increased user social presence due to the inclusion of an instructor can result in deeper cognitive processing of learning content due to the activation of social interaction schema (Clark and Mayer, 2016). However, in a social learning environment, the role of peers cannot be overlooked. Social presence is heavily shaped through peer interaction (Garrison and Cleveland-Innes, 2004). According to the theory of social interaction, individuals not only perceive the existence of peers but also interact with peers through verbal and nonverbal means, which in turn leads to deeply cognition process and understanding for themselves (Zhu et al., 2022). Additionally, perceiving others may make learners change perspectives on the learning content or own learning processes (Schneider et al., 2022). From the results of previous studies, it is crucial to examine whether instructor or peers has more impact on a learner's social presence in a 360 VR learning environment. The presence of peers may increase the sense of social presence rather than a single instructor's influence on the learners.

1.2.3 Cognitive load in 360 VR videos

When designing 360 VR videos for educational purposes, there should be consideration of the leaners' ability to maintain concentration and the cognitive effort required to view the videos. In fact, 360 VR requires additional cognitive load for users to continue to focus on intended targets and refocus on another target (Lin et al., 2017). In addition, learners need to identify important information in the 360 VR videos, focus on it, and filter out relatively less important information. As a result, an instructional designer provides additional cues to mark important elements so users can adjust to the increased visual complexity, and make learners pay attention to specific points (Evens et al., 2022). Instructional considerations must be designed to keep learners attentive during 360 VR learning.

The presence of an instructor in instructional videos increases cognitive effort. Although social cues are intended to prime deeper processing in learning, a potential confounding factor is the role of cognitive load (Mayer, 2014). According to cognitive load theory, adding an image of the instructor may hinder attention engagement with the lecture's content due to the split-attention effect (Ng and Przybyłek, 2021). In contrast, Henderson and Schroeder (2021) performed a systematic review of instructor presence in instructional videos, and did not find that an on-screen instructor increases extraneous processing and overall cognitive load. The researchers reported that further research is needed to better understand the effects of instructor's gestures, facial expressions, and other components of the instructor's appearance and their role within the learning environment. However, Hebbel-Seeger et al. (2021) found that an instructor-centered video is unsuitable for spherical projection due to its spatial setting, where only one viewing direction is used. For an instructor-centered lecture, the video needs to use the entire space, or focus on the content by combining the recorded lecture with additional visual elements. Conversely, studies have also shown that providing too much information, including interaction, in 360 VR videos can cause unnecessary cognitive loads on learners, so learners could not learn efficiently (Detyna and Dommett, 2021). The complexity of the video and excessive visual stimulation reduces the learner's attention and can even lead to side effects such as VR motion sickness.

1.2.4 Presence and interaction of instructor and peers

In general, greater interaction in an online learning environment increases the learner's social presence (Horzum, 2017). However, interaction alone does not presume that one is engaged in a process if inquiry and cognitive presence exist (Picciano, 2002). In addition, the quality of interaction, not the quantity, is important to foster deep learning: high levels of interaction do not necessarily facilitate meaningful learning (Garrison and Cleveland-Innes, 2005). Therefore, interactions in VR may not always be purposeful, valuable, or contribute to student learning. Conversely, some interactions that do not directly relate to course content or learning objectives are without purpose and/or student benefit (Mehall, 2020). For this reason, the influence of interaction is different depending upon whom with the interaction, either peers or instructors for learners. The instructors are more concerned with fulfilling interaction needs (Hay et al., 2004). The instructor's presence and interactions are planned to help learners meet the learning objectives, whereas peer interactions are often spontaneous and unintentional (Mehall, 2020). The primary reason for this differentiation by peers and instructors is that peers and instructors have influenced learners.

In online courses, interaction with instructors has a much larger effect than interaction with peers on satisfaction and perceived learning (Swan, 2001). The perceived presence of instructors may be a more influential factor in determining student satisfaction than the perceived presence of peers (Swan, 2001; Hay et al., 2004; Swan and Shih, 2005; Lowenthal and Dunlap, 2018). Similarly, Martin and Bolliger (2018) found that learner–instructor interaction is the most important among Moore's three types of interactions: learner–instructor, learner–content, and learner–learner (Moore, 1989). Instructors can improve student engagement and learning by providing a variety of communication channels, support, encouragement, and timely feedback (Martin and Bolliger, 2018). Nevertheless, peer presence is an important factor to predict learners' social presence. Swan and Shih (2005) found that the correlation between the perceived presence of instructors and perceived interaction lost significance when its relationship with the perceived presence of peers was controlled for, while the relationship between the perceived presence of peers and perceived interaction remained significant. This finding indicates that peer presence alone influences students' perceptions of interactivity during course discussions.

Perceiving peer presence through modeling or observation can induce effectiveness when using digital materials, even if there are no "real" social interactions (Bandura, 1986). For example, many learners report feelings of intimidation when peers appear to have a deep understanding of the concepts being discussed (Cleveland-Innes et al., 2007). Moreover, some learners feel safe when they can share concerns and realize reassuringly that others shared similar worries (Peacock and Hooper, 2007). Thus, the instructor's presence and interaction are normally intentional and have a significant impact on improving learners' social presence and their learning (Swan, 2001; Hay et al., 2004; Swan and Shih, 2005; Lowenthal and Dunlap, 2018; Martin and Bolliger, 2018). However, learners tend to perceive the effect of peer presence and interaction differently depending on their individual learning styles or the course content (Swan and Shih, 2005; Mehall, 2020; Zhu et al., 2022). Therefore, when designing instructional 360 VR videos, the presence and interaction of the instructor should be considered first, but the presence and interaction of peers also needs to be carefully designed according to the purpose of the video.

2 Methods

2.1 Participants

A total of 48 college students (men = 19, women = 29) at a university located in a southwestern South Korean city participated in the experiment. The average age was 22.45 years (SD = 1.52). Among the 48 students, 11 were freshmen (22.9%), 18 were sophomores (37.5%), 13 were juniors (27.1%), and 6 were seniors (12.5%). Participants were randomly assigned to one of the three groups described above and they watched the video matched to the type of presence and interaction to their group.

2.2 Research design

A preplanned contrast analysis was employed to compare the three groups. We produced the three types of videos and assigned the participants randomly to each group. The participants were assigned into one of the three experimental settings, and they completed the surveys of social presence and cognitive load.

We set two components of video design; person featured in videos (instructor-only, instructor and peers) and instructor–peer interaction and activity (with instructor–peer interaction and activity, without instructor–peer interaction and activity). We designed the videos with the combinations of two components. Because it is impossible for the instructor to have peer interaction alone, "instructor-only × with instructor–peer interaction and activity" combination was excluded. Hence, we used three combinations: (1) instructor-only × without instructor–peer interaction and activity, (2) instructor and peers × without instructor–peer interaction and activity, and (3) instructor and peers × with instructor–peer interaction and activity. Each combination was matched to one of the three lecture video groups: (G1) instructor-only video, (G2) classroom lecture video, and (G3) classroom lecture and activity video. To determine which design is the most effective and practical among 360 VR videos for educational purposes, we measured participants' social presence and cognitive load.

The research design of this study assumed the planned comparison to examine the specific effect of the independent variables. RQ1 addressed the effect of the person featured in 360 VR videos, so we compared G1 and G2 + G3 (planned comparison 1). Additionally, RQ2 evaluated the effect of instructor–peer interaction and activity in 360 VR videos, so we compared G1 + G2 and G3 (planned comparison 2). The contrast coefficient used for planned comparison 1 was as follows: $\psi(G1) = -2$, $\psi(G2) = 1$, $\psi(G3) = 1$, and in comparison plan 2 it was: $\psi(G1) = 1$, $\psi(G2) = 1$, $\psi(G3) = -2$.

2.3 Learning materials

The 360 VR videos were filmed in a classroom to ensure that only essential elements for the learning content—excluding people, tools, and materials—appeared. Unrelated individuals or objects could unnecessarily burden learners cognitively and disrupt their concentration. In all conditions, the instructor, a man in his mid-30s, remained consistent, as did the electric drills, woods, and tables used.

The content of the videos was the instructor's classroom-based lecture, captured by a 360 VR camera, Insta 360° Pro2 (Insta360, 2024). Three types of 360 VR videos were designed and created for the instructional goals of basic carpentry practice with an electric drill as follows: (1) to learn the name of each component of an electric drill, (2) to learn how to use an electric drill when driving nails into wood, and (3) to understand how to prevent injuries that may occur when using an electrical drill. The target audience of the videos was university students who have no experience of carpentry practice. The videos included one instructor's visual demonstration and verbal explanation about common practical steps when using an electric drill, and the video run-time was approximately 6 mins.

When filming the videos, the 360 VR camera was placed in the center of the classroom, and the instructor and/or peers were located around the camera. The position of the camera lens would be the ultimate viewpoint of the participant watching the 360 VR video. As shown in Figure 1, the height of the camera was 150 cm (4 ft. 11in), from which the viewers feel comfortable, regardless of their true height (Keskinen et al., 2019). In addition, the distance between the camera and the person featured was about 120 cm (3 ft. 11in), which is an appropriate distance so that participants do not feel burdened or disturbed when viewing the video (Saarinen et al., 2017). The size of video file was 7,680 mm × 4,320 mm, and the frame per second rate was 30.

2.4 Types of videos

The three types of 360 VR videos, as shown in Figure 2, were as follows: (G1) Instructor-only video, (G2) Classroom lecture video and (G3) Classroom lecture and activity video. In G1, as shown in Figure 3, the video only shows the instructor who gave the lecture. All participants depicted in the figures of this study have provided their informed consent as documented by signed consent forms. The instructor explained and demonstrated the learning contents while directly looking at the 360 VR camera, as if the camera was a student in the classroom. From a participant's viewpoint, the instructor continued to talk while looking only at them. Therefore, from their point-of-view, there were no others in the class and participants might feel as if only themselves and the instructor were in the virtual classroom.

In G2, as shown in Figure 4, the video showed both the instructor and other students in the classroom. However, there were no direct verbal or non-verbal interactions between the instructor and the students in the video. From the participant's viewpoint, the instructor talked directly to the participant. In this case, the participant may feel that there were other students that attended the lesson, and were listening to the instructor, even if the instructor did not focus on the other students. Using the VR headset, participants could change their point-of-view whenever they wanted, and could choose to look at the instructor or their peers, but the other students did not perform any learning activities, they only listened to the instructor's explanation and watching his demonstration.

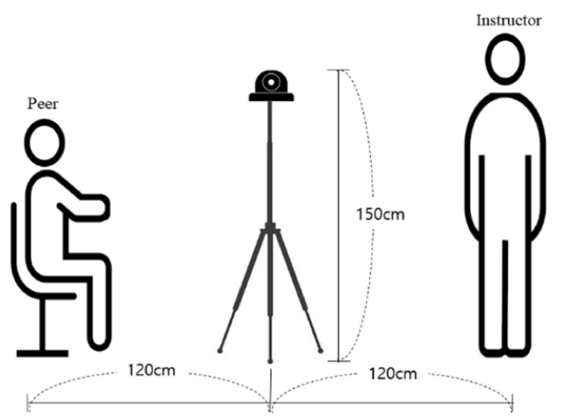

FIGURE 1
The camera height and distance from the viewer.

In G3, as shown in Figure 5, the video showed both the instructor and other students in the classroom. Additionally, the lecture included active interaction sections, such as questions and answers, guidance, and practice activities with the instructor and students. These verbal and non-verbal interactions did not appear in G2. The instructor only occasionally glanced at the camera, and their main focus was the other students in the classroom. It was possible for participants to see the instructor's explanations and demonstrations, as well as their peers' learning activities, by altering their viewpoint using the VR headset.

2.5 Measurement

2.5.1 Social presence

To evaluate the participants' social presence while watching the 360 VR safety lesson video, the participants completed a questionnaire developed by Weidlich and Bastiaens (2019), after watching the lesson. This questionnaire consisted of 10 questions and its internal consistency was strong ($\alpha = 0.90$). The examples of survey items were as follows: "In this learning environment, it feels as if we are a face-to-face group"; "In this learning environment, it feels as if all my fellow students are 'real' physical persons"; "In this learning environment, I imagine that I really can 'see' my fellow students in front of me."

2.5.2 Cognitive load

To evaluate the participants' cognitive load while watching the 360 VR video, participants completed a questionnaire developed by Ryu and Yim (2009) after the lesson. The questionnaire had five subscales of cognitive load including task demand, mental effort, perceived task difficulty, self-evaluation, and material design. The questionnaire consisted of 20 items, with four items for each subscale. Additionally, the internal consistency subscales were good ($0.57 \leq \alpha \leq .84$). We provided the participants with a questionnaire translated into Korean. The examples of survey items are as follows: "I felt spent after the task [task demand]"; "I focused on the task to be performed [mental effort]"; "The difficulty of the task was high [perceived task difficulty]"; "I think that successfully understood the learning material [self-evaluation]."

2.5.3 Procedures

The purpose of the study and the data collection procedure were explained before the experiment, and participants provided informed consent before the study began. Each participant wore an HMD and viewed the safety training lesson as assigned to their group. Participants were informed that they may stop the experiment at any time if they felt abnormal symptoms such as dizziness or cybersickness.

2.5.4 Data analysis

The test results of social presence and cognitive load collected from the participants were analyzed using SPSS. Analysis of variance (ANOVA) was employed to analyze participants' social presence. Also, a multivariate analysis of variance (MANOVA) was conducted to examine the different effects among and within groups. The process of verifying whether the assumptions, such as multivariate normality and homogeneity of variance–covariance matrices were met to ensure the

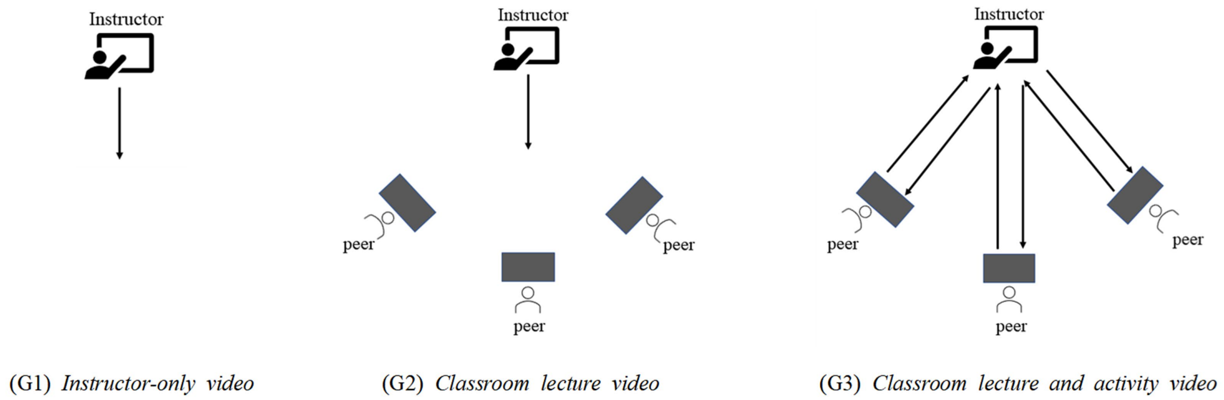

FIGURE 2
The three types of 360-degree VR videos. The arrows indicate the interaction and direction of both verbal and non-verbal interactions of the instructor and/or peers.

FIGURE 3
Screenshots of the instructor-only video. **(A)** full view; **(B)** participant view.

validity of the MANOVA test results was included. The group effect of the 360 VR video types was calculated by overall group means using the F-ratio and the significant value. Two planned comparisons were then conducted. The first planned comparison was conducted to test the effect of the person featured; instructor-only (G1) vs. instructor and peer (G2 + G3). Additionally, the second planned comparison was conducted to test the effect of instructor–peer interaction and activity; without instructor–peer interaction and activity (G1 + G2) vs. with instructor–peer interaction and activity (G3).

3 Results

3.1 Social presence

Table 1 shows the descriptive statistical results of social presence scores by group. As a result of Levene's test, error variances were the same ($p = 0.714$). ANOVA analysis found that there were no between-group effects [F (2, 45) = 2.41, $p = 0.102$]. Specifically, a planned comparison was conducted to determine differences in social presence among videos G1–G3. The first comparison was to confirm whether there are differences between the presence of peers. The results of the first planned comparison showed that 360 VR video without peers (G1) scored significantly higher as compared to G2 and G3 [t (45) = −2.09, $p = 0.042$] as shown in Figure 6. The second comparison examined the difference with and without instructor–peer interaction and learning activity. In this comparison, there was no difference in social presence [t (45) = 1.62, $p = 0.112$].

3.2 Cognitive load

Table 1 shows the descriptive statistical results of cognitive load scores by group. Cognitive load was classified into five subscales: task

FIGURE 4
Screenshots of the classroom lecture video. **(A)** full view; **(B)** participant view.

FIGURE 5
Screenshots of classroom lecture and activity video. **(A)** full view; **(B)** participant view.

demand, mental effort, perceived task difficulty, self-evaluation, and material design. Box's M test found that the assumption of equality of covariance was satisfied ($p = 0.305$) and Wilks' lambda value was also satisfied ($p = 0.183$). As a result of Levene's test, error variances were the same for all subscales ($p > 0.05$) and there were no between-group effects ($p > 0.05$). The second comparison to see the difference with and without peer interaction result in no difference in social presence [$t\,(45) = 1.62$, $p = 0.112$].

TABLE 1 Mean and standard deviation of social presence.

Group category		G1 (n = 16)	G2 (n = 16)	G3 (n = 16)	Total (N = 48)
		M (SD)	*M (SD)*	*M (SD)*	*M (SD)*
Social presence		5.99 (0.88)	5.46 (1.08)	5.22 (1.07)	5.55 (1.04)
Cognitive Load	Task Demand	2.91 (1.63)	2.75 (1.70)	2.02 (1.19)	2.56 (1.54)
	Mental Effort	5.50 (1.43)	5.67 (1.23)	6.08 (0.90)	5.75 (1.21)
	Perceived Task Difficulty	6.16 (0.81)	6.30 (0.75)	6.27 (0.75)	6.24 (0.81)
	Self-Evaluation	6.38 (0.59)	6.33 (0.86)	6.25 (0.65)	6.32 (0.69)

N = 48. G1: Instructor-only video, G2: Classroom lecture video, G3: Classroom lecture and activity video.

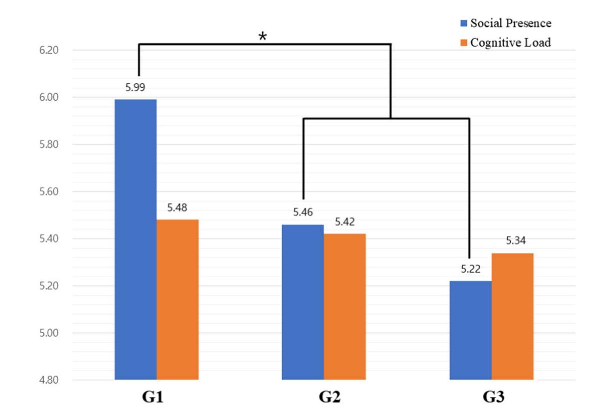

FIGURE 6
Mean Plot of Social Presence. N = 48. G1: Instructor-only video, G2: Classroom lecture video, G3: Classroom lecture and activity video.

A planned contrasts test was conducted to find out the difference in cognitive load by the characteristics of 360 VR videos. The first contrast was to confirm whether there are differences between the presence of peers. The results of the first planned contrast showed that there was no difference in all subscales of cognitive load; task demand [t (45) = −1.12, p = 0.267], mental effort [t (45) = 1.01, p = 0.317], perceived task difficulty [t (45) = 0.50, p = 0.623], self- evaluation [t (45) = −0.40, p = 0.695], and material design 0[t (45) = −1.89, p = 0.065]. The second contrast found no difference among all subscales; task demand [t (45) = 1.75, p = 0.088], mental effort [t (45) = −1.33, p = 0.191], perceived task difficulty [t (45) = −0.16, p = 0.878], self-evaluation [t (45) = 0.47, p = 0.643], and material design [t (45) = 0.79, p = 0.433].

4 Discussion and conclusion

The purpose of this study was to examine the effects of instructor and peers' presence and interaction in 360 VR instructional videos on students perceived social presence and cognitive load. We developed three types of 360 VR videos. After watching one type of video, participants completed questionnaires that assessed their social presence and cognitive load. The data was used to assess the effects of each type of 360 VR video.

In this study, the participants reported the highest level of social presence in the instructor-only video (G1). This is probably due to the nature of the video format. Only one-instructor showed on the video, and the instructor's explanation was only toward the participants. From the viewer's perspective, the participant of G1 would perceive direct interaction with the instructor. The instructor continued to look into camera lens, and therefore lectured to the participant. These social cues used by the instructor enhance users' social presence (Swan, 2001; Hay et al., 2004; Swan and Shih, 2005; Lowenthal and Dunlap, 2018; Martin and Bolliger, 2018). Notably however, peer presence impeded establishing participants' social presence. This result is inconsistent with previous studies that suggest that peer presence promotes learners' social presence (Cleveland-Innes et al., 2007; Peacock and Hooper, 2007). It is possible that the participants found the peer presence less useful than the lesson content or the instructor's explanations in the 360 VR video (Zhu et al., 2022). When watching the 360 VR videos, participants could change their point-of-view freely, so it was possible to only view the instructor, therefore some participants might not have looked around and watched their peers. Participants not moving their head to look at their peers during the lecture may be the reason that there was no difference in participants' cognitive load among all video types (G1–G3), including comparisons of peer presence and peer interaction. We can infer that all participants paid similar amounts of mental efforts for learning in all groups. Furthermore, participants' learning was unaffected by the presence of peers or peer interactions in the videos. Participants in G1, based only on the instructor's explanations, understood the content as well as their counterparts in G2 and G3. This supports findings reported in other studies based on instructional videos, where learners perceived interaction with instructors more influential and valuable than interaction with peers on perceived learning (Swan, 2001; Hay et al., 2004; Swan and Shih, 2005; Lowenthal and Dunlap, 2018).

The findings of this study reaffirm those in the literature that in non-face-to-face learning, the instructor's presence might be more critical than peer presence and peer interaction. Instructor interaction is decisive for predicting delivery effectiveness in online courses and achieving learning success (Hay et al., 2004; Belair, 2012), while peer interaction may not directly contribute to learners' success (Keaton and Gilbert, 2020). Although a previous study found that 360 VR is an effective learning tool when presenting the entire spherical space (Pirker and Dengel, 2021), this study showed that only including the instructor and their interactions can be equally effective. This result may be due to the immersive nature of the 360 VR videos, which facilitates learners' concentration on content (Taubert et al., 2019). There was no significant difference in cognitive load among the groups. No significant impact may be because participants in this study did not have to find the focus of the video, as the instructor was easy to locate in the virtual classroom. The lack of visual clues and additional guidance embedded in the 360 VR videos may have prevented learners from missing important content.

Some limitations of the study should be noted. It is difficult to generalize the results of this study because the teaching materials used were limited to safety training for woodworking and the use of an electric drill. Moreover, the peer–peer interactions in the videos were very simple. Further 360 VR research that includes meaningful peer–peer interactions in other settings is needed. Indeed, it is essential to acknowledge that the primary focus of this study was on measuring perceptual changes in engagement during learning rather than on direct measures of learning achievement. While engagement is a critical precursor to learning, it does not necessarily predict the acquisition of knowledge or skills directly. Consequently, this study's findings primarily indicate shifts in learner engagement and may not directly reflect changes in academic achievement or proficiency. These limitations suggest the need for further research that explicitly assesses the impact of non-face-to-face learning environments on measurable learning outcomes.

In conclusion, this study confirms the effects of the instructor and peer presence and interactions on learners' social presence and cognitive load. When only an instructor is present and instructor–learner interaction can be viewed, learners report high levels of social presence. Lower levels of social presence are reported when learners only view their class peers and no meaningful peer–peer or instructor–peer interactions are included in the video. Therefore, when developing 360 VR videos, educators should design the virtual location primarily considering the user's view, and focus on the presence and interactions of instructors rather than peers. Except in the case of discussion or cooperative learning where interaction between peers is essential and meaningful, there is no need to include the presence or interaction of peers into the video.

Learners who use educational 360 VR videos tend to follow the lesson based on social clues, such as the instructor's voice and their facial expressions. These features allow learners to take part in the virtual lecture without reporting excessive cognitive loads. However, long video run-times may increase boredom levels in instructor-centered lectures when there is no peer–peer interactions. In these cases, visual cues are recommended to maintain students' attention to the instructor and the content. The inclusion of peer-to-peer interaction should be chosen carefully, taking into account the content and context of the learning.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by Chonnam National University Institutional Review Board. 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. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

SK: Writing – original draft, Writing – review & editing. SP: Writing – review & editing. JR: Writing – review & editing. JK: Writing – original draft. IK: Validation, Writing – review & 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.

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Virtual reality and travel anxiety during the COVID-19 pandemic: the moderating role of blockade intensity

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The COVID-19 pandemic has deprived travelers of the right to continue their travel or leisure activities, while creating concerns about the safety of travel. In view of the great impact of the COVID-19 pandemic on travelers, we discussed the impact of virtual reality on travel anxiety during the COVID-19 pandemic, and considered the regulatory effect of blockade intensity. In order to explore the relationship between virtual reality and travel anxiety in depth, this study conducted a questionnaire survey on 299 Chinese tourists who had experienced virtual reality activities related to travel, and empirically analyzed the questionnaire data using SPSS 26 software. The results show that virtual reality has a significant negative effect on travel anxiety during the COVID-19 pandemic, i.e., virtual reality technology can provide a safer virtual travel experience for people and reduce their travel anxiety. At the same time, the relationship between virtual reality and travel anxiety varied to some extent depending on the intensity of the lockdown in each region, with the mitigating effect of virtual reality on travel anxiety being enhanced by high levels of lockdown. Therefore, we believe that although lockdown policies are necessary for some time to come, travel companies need to make further efforts to provide more convenient virtual reality services to alleviate travel anxiety caused by COVID-19 pandemic and lockdown to tourists. At the same time, virtual reality opens up new ideas for travel businesses under the impact of COVID-19 and contributes to the sustainable development of the travel industry.

KEYWORDS

virtual reality, travel anxiety, lockdown, virtual travel, COVID-19

1 Introduction

As of June 2020, more than 54 million people have been diagnosed with pneumonia caused by COVID-19 worldwide, resulting in more than 6.32 million deaths. Governments around the world have imposed restrictions such as border closures, community lockdowns, flight suspensions, and public place closures to avoid the spread of the epidemic (Yao et al., 2022). It is clear that all these restrictions fundamentally disrupt the global tourism market and its mobility (Gössling et al., 2020). According to the travel restrictions report published by the United Nations World Tourism Organization (UNWTO), travel restrictions related to the COVID-19 pandemic are implemented in 100% of global destinations (United Nations World Tourism Organization [UNWTO], 2020), while domestic tourism activities are prohibited by COVID-19 disease policies at the national level. Studies have shown that people experience unpleasant states when behavioral freedom is eliminated or threatened by uncontrolled events (Irimiás and Mitev, 2021b). This unexpected restriction of daily social and recreational activities deprives them of their rights as tourists, triggering a strong desire to expect a return to normalcy in tourism. In this situation, tourists and travelers are unable to continue traveling or engaging in leisure activities, they become fearful of risking their lives while traveling, become concerned about travel safety, and even become nervous or anxious about traveling when they see news about COVID-19.

One study found that because people are confined to their homes, a large group of people are shifting their activities to the virtual world, significantly increasing the frequency of virtual travel experiences using virtual reality (VR) technology (Leung et al., 2022). In the tourism industry, VR can be used to create virtual environments that enable virtual travel experiences by providing synthesized or realistically filmed 360-degree content, as well as powerful non-immersive, semi-immersive, or fully immersive VR systems that stimulate the visual and potentially other senses (Beck et al., 2019). VR-based travel allows travelers to comply with government-mandated social distance or lockdown requirements while still allowing for a valuable consumer experience (Itani and Hollebeek, 2021). Although VR was previously seen as a threat to travel, he today offers a safe travel opportunity for people to overcome the challenges of a pandemic, and virtual reality technology can provide a safer virtual travel experience that refreshes their mental state when they are anxious and concerned about the feasibility and safety of travel during a pandemic.

Furthermore, we believe that when travelers are completely restricted from traveling due to the potential risk of COVID-19 infection, it will be more difficult to inhibit their willingness to travel and will more likely motivate them to shift their interest from the unbalanced real world to the near-ideal virtual reality, thus alleviating realistic travel anxiety. In order to contain COVID-19 pandemic, most governments have imposed lockdowns, yet the extent of the lockdown depends on the severity of the COVID-19 pandemic, and people in areas with severe outbreaks are even strictly required to stay at home. Tourists in high lockdown situations have stronger cognitive desires and emotional experiences than those in areas with lower levels of lockdown (Irimiás and Mitev, 2021a). Psychological reactance theory (Miron and Brehm, 2006) suggests that individuals experience resistance when their behavioral freedom is threatened, restricted, or lost, and that psychological reactance motivates behavioral and emotional efforts to cope with the deprivation of their freedom. We therefore argue that tourists in highly lockdown areas are more willing to travel due to the severe restrictions on their freedom, and the more restricted they are, the more likely they are to choose to release their travel anxiety through virtual means, and the more profound the travel experience using virtual reality technology.

Based on the above discussion, previous studies have examined the role of VR in heritage preservation (Bec et al., 2019), retailing (Wedel et al., 2020), and consumer perception (Park and Yoo, 2020), and for tourism, scholars have focused on the impact of virtual travel on realistic travel intentions (Bogicevic et al., 2019), destination marketing (Lin et al., 2020), tourism recovery (El-Said and Aziz, 2022), tourist behavior intention (Leung et al., 2022), tourist sentiment (Zhang et al., 2022), etc., while ignoring the effect of virtual reality on travel anxiety during COVID-19. In fact, virtual reality technology is being used in daily life. Whether it can reduce passengers' travel anxiety, e.g., by providing virtual experience, training, reassurance and self-control, has not been answered by existing studies. By surveying 299 Chinese respondents on their perceptions of VR and travel during the COVID-19, our study applies the theory of psychological reactance to explore the impact of virtual reality anxiety during the COVID-19 and validates the moderating role of lockdown policies between the two. From a theoretical perspective, the study expands the contextual application of psychological resistance theory and explores the complex mechanisms of virtual reality's impact on travel anxiety. From a practical perspective, the study provides practical guidance for travel companies on how to reduce travel anxiety during the COVID-19.

2 Literature review

2.1 Virtual tour application

As virtual reality technology enters and becomes a high-tech that attracts much attention in the field of tourism (Lin et al., 2020). Researchers have conducted rich studies based on the supply side perspective, exploring the application of virtual reality technology in scenic area development, destination services and marketing.

Virtual reality has helped tourist attractions to realize digital and 3D design. VR digital scenic design based on ArcGIS (Xu et al., 2009), 3D-GIS (Huang et al., 2016), and virtual reality design of scenic spots with 3D model technology (Poux et al., 2020) have been widely used. Many tourist attractions have developed game experiences based on virtual reality technology, such as Orava Castle in Czechoslovakia, where a cell phone AR game was developed (Mesáro et al., 2016), and Geevor Tin Coal Mining Site in England, where an AR treasure finding game was developed (Jung and Tom Dieck, 2017) to enhance the interactive experience of tourists. Virtual reality technology also plays an important role in destination services and marketing. For example, the smartphone application APP Mtrips applies AR to city travel guides, where users take a view by using the smartphone camera, and detailed information such as attraction ratings of tourist destinations will be displayed on the phone, serving as a service recommendation and word-of-mouth marketing.

2.2 Virtual travel experience

Virtual reality creates a new travel platform and travel mode for tourists, bringing them a new travel experience. Based on the content analysis of existing virtual tourism literature, this paper understands virtual tourism experience from two aspects: virtual tourism hardware experience and psychological experience.

Existing literature mainly focuses on user acceptance and perceived evaluation of virtual tours. Perceived usefulness and perceived ease of use have been commonly used by existing researchers to evaluate people's acceptance of virtual tours. Chung and Koo (2015) proposed a model that includes a combination of technology readiness level, visual attractiveness, and convenience to reveal consumer acceptance of virtual tours. Javornik (2016) argued that the hardware responsiveness and control affects people's acceptance of virtual tours. Tourists' perceived evaluation of virtual tour technology involves factors such as functionality, content, technical ease of use, and interactivity. Olsson et al. (2013) revealed four major dimensions of virtual tour functionality, including information accessibility, navigability, interactivity, and novelty.

Virtual reality technology is characterized by visualization, immersion and interactivity, which can quickly reproduce real tourist attractions and bring a new revolution to the tourism experience. Existing research on virtual tourism experience mainly focuses on sensory enjoyment and emotional experience, and sense of presence and sense of immersion are often used to measure the sensory enjoyment of virtual tourism users. Sense of immersion refers to the degree of immersion of users in virtual reality, and sense of presence refers to the user's feeling of being present in the virtual environment. Jung and Tom Dieck (2017) revealed the positive effects of social presence on tourists' educational experience, aesthetic experience, entertainment experience, and escape experience in a museum's virtual reality scenario. Hyun and O'Keefe (2012) found that tourist information helps to construct a sense of presence in the virtual context, and that the sense of presence facilitates the formation of virtual cognitive-emotional imagery of the destination. Spielmann and Mantonakis (2018) identified the sense of interaction of human-computer interaction in the virtual tourism experience as an important antecedent factor affecting the sense of presence.

2.3 Travel intention

Some scholars have explored the antecedent mechanisms that influence tourism willingness and behavior from different perspectives. For example, Shoukat et al. (2023a) investigated the antecedents of nostalgia related cultural travel behavior. They found that tourists' intrinsic, integrated, and identified motivations help to awaken their willingness to revisit, which in turn has a positive impact on actual visiting behavior. The willingness to revisit plays a strong mediating role between actual visiting behavior and autonomous motivation. In addition, they also found that the image of the visited destination and the past experiences of tourists can affect the willingness to revisit, thereby having a positive impact on actual visiting behavior. Building on previous research, Shoukat et al. (2023b) investigated the travel willingness of medical tourists in the post pandemic era. They found that the Medical Travel Index helps alleviate travel anxiety and fear among tourists, thereby increasing their willingness to travel to countries with unique medical tourism potential. Travel anxiety mediates the correlation between medical travel index and travel intention. In addition, they also found that the perceived severity of the COVID-19 epidemic will increase the travel anxiety of medical tourists.

2.4 Virtual tourism and sustainable tourism development

More researchers believe that virtual tourism has a positive impact on the sustainable development of tourism, which is mainly reflected in the following two aspects. First, virtual reality technology as a new tool for tourism marketing, consumers can use the technology for pre-trip pre-experience before making travel decisions (Lin et al., 2020). Virtual reality technology provides a rich environmental resource for potential tourists to pre-explore destinations, allowing tourists to experience destinations in a holistic and immersive way before traveling (Huang et al., 2016). Pantano and Servidio (2011) found that virtual tour participants aspired to real tourist attractions and compared real attractions to virtual ones. As consumers' virtual tour participation increased, their positive feelings toward the destination increased (Kim et al., 2020), which positively influenced their attitudes toward travel, and travel behavior decisions (Lin et al., 2020). Marasco et al. (2018) found that the emotional experience of virtual tours based on wearable devices positively affects the willingness to visit cultural heritage sites. Secondly, virtual tours are considered as a complementary approach to field tourism experiences. The combination of virtual reality and real environment, through augmented reality (AR), mixed reality (MR), and other virtual reality technologies, can enrich the dimensions of the field tourism experience and enhance tourists' sense of reality experience (Guttentag, 2010).

3 Research hypotheses

3.1 Virtual reality and travel anxiety

Virtual Reality (VR) is a computer-generated scenario used to simulate immersive, life-like experiences based on reality. Virtual reality technology offers a new way of traveling that can help consumers overcome the geographical constraints of travel and enjoy a realistic travel experience at the attractions they want to travel to Subawa et al. (2021). Virtual reality can be realized by creating a virtual environment that provides synthetic or 360-degree realistically captured content and a powerful non-immersive, semi-immersive, or fully immersive VR system to achieve a virtual travel experience that stimulates the visual and potentially other senses.

Virtual travel technology can increase consumer engagement, provide them with a safer virtual travel experience, and alleviate travel anxiety due to COVID-19 blockade within. Attractions (e.g., museums, theme parks) had already begun to adopt virtual reality technology for enhanced user experiences prior to the outbreak of COVID-19 (Li et al., 2021). During the period of COVID-19, more and more travel companies introduced virtual reality services to provide travelers with a virtual travel experience, and virtual reality technology has become an important platform for travel companies to maintain revenue (Merkx and Nawijn, 2021). Due to the potential contagiousness of COVID-19, governments have implemented embargo policies to varying degrees, and tourists who have their freedom restricted are like birds in a cage; according to the theory of psychological resistance, the more tourists are restricted, the stronger their desire to travel (Li et al., 2021). At the same time, due to the health threat of COVID-19, tourists also have concerns about travel safety, and thus may experience varying degrees of travel anxiety (Walters et al., 2022). Virtual Reality (VR) can help travelers to travel virtually by using computer-generated images or videos that simulate real-life experiences and provide safe travel options during COVID-19. Travelers will feel a sense of presence in a highly immersive virtual environment, which will reduce stress and worry about the safety and feasibility of travel, and alleviate internal travel anxiety. In summary, the following hypotheses are proposed:

> **H1:** Virtual reality can alleviate travel anxiety and has a negative effect on travel anxiety.

3.2 Moderating effects of blockade intensity

When tourists are completely restricted from traveling due to the potential risk of COVID-19 infection, it will be more difficult to suppress their inner willingness to travel, and it is more likely to motivate them to shift their interest from the unbalanced real world to the near-ideal virtual reality, thus alleviating the reality of travel anxiety (Iacovino et al., 2020). In order to contain COVID-19, most governments imposed a blockade, yet the extent of the blockade depended on the severity of the COVID-19 pandemic, with people in areas with severe outbreaks even being severely restricted from traveling. Tourists under high levels of blockade develop stronger cognitive desires and emotional experiences compared to those in areas with lower levels of blockade (Li et al., 2021). Psychological resistance theory suggests that when an individual's freedom of behavior is threatened, restricted, or lost, they resist the restriction, prompting behavioral and emotional efforts to cope with the deprivation of their freedom (Akhtar et al., 2021). Therefore, tourists in highly blocked areas have a stronger willingness to travel due to severe restrictions on their freedom, and the higher the degree of restriction, the more likely tourists are to choose virtual reality as a way to release their inner travel anxiety, and the travel experience they get by using virtual reality technology will be more profound. In summary, the following hypotheses are proposed:

> **H2:** Blocking intensity has a positive moderating effect in the process of virtual reality affecting travel anxiety.

4 Materials and methods

4.1 Questionnaire design

According to the standardized questionnaire design process, the questionnaire process used in this study is as follows:

First, determine the research variables and construct a theoretical model. On the basis of literature combing on virtual reality, travel anxiety, and blockade intensity, this paper further analyzes the role relationship between virtual reality, travel anxiety, and blockade intensity, and constructs a theoretical research model.

Second, the design of the initial scale. Focusing on the related studies of virtual reality, travel anxiety, and blockade intensity, the domestic and international mature scales that are most compatible with the research background and content of this paper, with high citation rate, qualified reliability and validity, and published in international Top journals are collated and screened out, and selected as the initial scales of this paper.

Third, questionnaire content design. The questionnaire content of this paper mainly contains two parts. (1) Description of the questionnaire. This part describes the research purpose of the questionnaire, the main content involved and the rules for filling in the questionnaire, etc., and in the questionnaire instructions, it is stated that "the information of the respondents will be kept strictly confidential to ensure that the results of the survey will only be used for academic research." (2) The main part. This part contains the main variables involved in this paper (virtual reality, travel anxiety, blockade intensity) and the measurement of the control variables, all of which are closed-ended questions, and are mainly scored on a seven-point Likert scale.

Fourth, formal research. We randomly sampled 500 Chinese tourists who had experienced travel related virtual reality activities. A total of 326 questionnaire data were collected. After excluding three or more missing questions and those with obvious filling methods, a total of 299 valid questionnaires were obtained, with an effective response rate of 59.8%.

4.2 Sample and data collection

The purpose of this study was to examine the relationship between virtual reality and travel anxiety during COVID-19 pandemic and its relationship with lockdown intensity. This study was conducted in April 2022, when China was experiencing a new COVID-19 pandemic centered in Shanghai. Full lockdowns began in some areas and most domestic and international travel remained required to be closed. An online questionnaire was sent to 500 Chinese travelers who experienced travel-related virtual reality activities through a purposive sampling method. A total of 500 questionnaires were sent out by our team from April 2022 to June 2022, and 326 questionnaire data were collected. A total of 299 valid questionnaires were finally obtained by excluding those with 3 or more missing questions and those with obvious patterns of filling out the questionnaire, with a valid return rate of 59.8%.

4.3 Variable measurement

The dependent variable in this paper was travel anxiety during the COVID-19 pandemic, which was measured mainly by the measure developed and validated by Zenker et al. (2021) on a scale of 1 (strongly disagree) to 7 (strongly agree), and consisted of five measurement items, "I intend to try a virtual reality tour offered by an attraction's Web site," "I predict that I will use virtual reality services offered by an attraction's Web site," "I plan to visit an attraction using a virtual reality service," "I am very likely to use a virtual reality service to visit an attraction," and "I have already used virtual reality services offered by an attraction."

TABLE 1 Measurement index and results of reliability and validity testing.

Variable	Measurement index	References	Factor loadings	Cronbach's alpha	CR	AVE
Virtual reality	I'm going to try the virtual reality tours offered by the attractions website.	Itani and Hollebeek, 2021	0.742	0.906	0.926	0.642
	I predict that I will use the virtual reality services offered by the attractions website.		0.736			
	I plan to use virtual reality services to visit attractions.		0.869			
	I will most likely use virtual reality services to visit attractions.		0.708			
	I have used the virtual reality services offered by the attraction.		0.778			
Travel anxiety	COVID-19 makes me very worried about my normal way of traveling.	Zenker et al., 2021	0.873	0.929	0.933	0.636
	Because of COVID-19, I am afraid to risk my life while traveling.		0.749			
	While planning my vacation, I felt sick thinking about the COVID-19.		0.746			
	I get nervous or anxious about traveling when I read the news about the COVID-19.		0.718			
	Due to the COVID-19, I feel unsafe to travel.		0.806			
Lockdown	Close public transportation	Hale et al., 2021	0.822	0.937	0.918	0.648
	Cancellation of public events		0.783			
	Restrictions on international travel		0.835			
	Schools switch to online teaching		0.716			
	Public places closed (scenic spots, theaters, gyms, etc.)		0.827			
	Restricted gatherings (family and friend reunions, annual company meetings, etc.)		0.736			
	Home Isolation		0.801			

TABLE 2 Confirmatory factor analysis results.

Model	χ 2/ Df	RMSEA	GFI	CFI	TLI	IFI
Three-factor model	1.720	0.049	0.930	0.990	0.988	0.990
Two-factor model	16.846	0.231	0.556	0.775	0.741	0.776
Single-factor model	31.297	0.319	0.373	0.566	0.505	0.567

N = 299. Three factor model: virtual reality, travel anxiety, blockade intensity; Two factor model: merging virtual reality and travel anxiety, blockade intensity; Single factor model: All variables are merged.

The independent variable in this paper is virtual reality. The measure of virtual reality was mainly based on the measure developed and validated by Itani and Hollebeek (2021), with a scale ranging from 1 (strongly disagree) to 7 (strongly agree) and included 5 measures such as "COVID-19 makes me very worried about my normal way of traveling," "Because of COVID-19, I am afraid of risking my life while traveling," "When planning a vacation, the thought of C. neoformans pneumonia makes me uncomfortable," "When I read news about C. neoformans pneumonia, I get nervous or anxious about traveling," "I feel nervous or anxious about traveling," and "I don't feel safe to travel because of pneumococcal pneumonia."

The moderating variable in this paper is lockdown. The measure of lockdown intensity was based on the measure developed and validated by Hale et al. (2021), with a scale ranging from 1 (strongly disagree) to 7 (strongly agree), including "closure of public transportation," "cancellation of public events,"' "restricting international travel," "schools switching to online instruction," and "closure of public places (scenic spots, theaters, gyms, etc.)," "Limit gatherings (family and friend reunions, annual company meetings, etc.)," and "Home segregation" 7 measurement question items.

In addition, to investigate the relationship between the key explanatory variables and the explanatory variables, and to reduce the errors caused by individual differences in the regression results, we included age, education level, monthly income, whether one is a pandemic prevention and control worker, and whether one is confirmed as control variables in the model.

4.4 Equations

First, the first equation is used to test the effect of virtual reality on travel anxiety by creating the following OLS model for baseline regression:

$$Travel\ Anxiety_i = a_0 + a_1 Virtual\ Reality_i + \sum Control_i + \gamma_i$$

Where $Travel\ Anxiety_i$ stands for travel anxiety, $Virtual\ Reality_i$ stands for Virtual Reality, i is individual, $Control_i$ represents the control variable, γ_i is the standard error term.

Second, we added an interaction term between virtual reality and blockade intensity to the model to test the moderating effect of blockade intensity in the process of virtual reality influencing travel anxiety.

$$Travel\ Anxiety_i = c_0 + c_1 Virtual\ Reality_i + c_2 Virtual\ Reality_i =$$

$$Blocking\ Intensity_i + \sum Control_i + \delta_i$$

TABLE 3 Descriptive statistics and correlation analysis.

Variables	Mean	S.D.	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
(1) Age	2.330	1.034	1.000							
(2) Education	4.330	1.165	−0.099	1.000						
(3) Income	2.500	0.748	0.079	0.0780	1.000					
(4) Worker	1.830	0.374	−0.263**	0.214**	−0.157**	1.000				
(5) Confirmed	3.760	0.626	−0.228**	0.203**	−0.058	0.372**	1.000			
(6) VR	5.020	1.572	0.062	−0.030	0.089	−0.057	0.086	1.000		
(7) Lockdown	4.930	1.669	0.065	−0.062	0.083	−0.051	0.053	0.644**	1.000	
(8) Travel anxiety	3.480	1.546	0.033	0.113	−0.085	0.101	−0.008	−0.590**	−0.593**	1.000

Standard errors are in parentheses; $N = 299$; $^{**}p < 0.01$.

Where *Travel Anxiety*$_i$ stands for travel anxiety, *Virtual Reality*$_i$ stands for Virtual Reality, i is individual, *Control*$_i$ represents the control variable, γ_i is the standard error term.

5 Results

5.1 Common method variance tests

The data generated by the single respondent survey may have the problem of common method variance (CMV). In order to solve this problem, this study stated in the questionnaire guidelines that "respondents' information will be kept strictly confidential and the results of the survey will be guaranteed to be used only for academic research" to prevent the accuracy of the survey results from being affected by the respondents' intentional exaggeration of facts. In addition, this paper also evaluated the common method variance problem (CMV) through factor analysis with the Harman one-way ANOVA test. The results showed that the variance explained by the first principal component was 37.5% and the total variance explained was 74.6%, which did not exceed 50% of the total explained variance, indicating that the impact of the common method variance problem in this study was small.

TABLE 4 Analysis of hypothesis test results.

Variables	Travel anxiety				
	M_1	M_2	M_3	M_4	M_5
Control variables					
Age	0.064	0.102*	0.064	0.110*	0.103*
Education	0.117	0.091	0.117	0.074	0.073
Income	−0.087	−0.037	−0.087	−0.027	−0.027
Worker	0.101	0.060	0.101	0.060	0.059
Confirmed	−0.060	0.023	−0.060	0.028	0.027
Independent variable					
VR		−0.589**		−0.359**	−0.314**
Moderating variable					
Lockdown				−0.361**	−0.321**
interaction term					
VR*Lockdown					0.116*
R^2	0.033	0.370	0.033	0.446	0.454
ΔR^2	0.033	0.337	0.033	0.413	0.008
F	2.023	28.617**	2.023	33.487**	30.104**

Standard errors are in parentheses; $N = 299$; $^{**}p < 0.01$, $^{*}p < 0.05$.

5.2 Exploratory factor analysis

In this study, KMO and Bartlett's test were conducted to test the appropriateness of the collected sample data. If the KMO is greater than 0.6, the validity of the scale is good; if the significance of the Bartlett's test is less than 0.01, the scale of this study is qualified for factor analysis. The KMO and Bartlett's test showed that the KMO value was 0.718. At the same time, the significance of Bartlett's test is lower than 0.01, indicating that the study scale is suitable for factor analysis.

5.3 Reliability analysis

For the reliability test, we evaluated by calculating the Cranbach's alpha coefficient and the combined reliability (CR). As shown in Table 1, the Cranbach's alpha coefficient for virtual reality was 0.906, the Cranbach's alpha coefficient for travel anxiety was 0.929, and the Cranbach's alpha coefficient for blockade intensity was 0.937. Next, the factor loadings were calculated for each of the combined reliability (CR) corresponding to the variables. As shown in Table 1, the CR value of virtual reality was 0.926, the CR value of travel anxiety was 0.929, and the CR value of blockade intensity was 0.918. In summary, the Cranbach's α coefficient values and CR values of all variables were above 0.7, indicating that the scale as a whole had good reliability. The results are shown in Table 1.

5.4 Validity analysis

To test the validity of our constructed model, validated factor analysis (CFA) was first conducted to test the discriminant validity. The results of the analysis are shown in Table 2, and the three-factor model (χ^2/ Df = 1.720, $p < 0.05$; RMSEA = 0.049, GFI = 0.930,

TABLE 5 Robustness test results.

	Model 1					Model 2				
	β	SE	T	LLCI	ULCI	β	SE	T	LLCI	ULCI
Control variables										
Age	0.1525	0.0730	2.0899*	0.0089	0.2961	0.1545	0.0684	2.25908	0.0199	0.2892
Education	0.1205	0.0642	1.8772	−0.0058	0.2468	0.0962	0.0601	1.6011	−0.0221	0.2145
Income	−0.0766	0.0983	−0.7793	−0.2700	0.1168	−0.0555	0.0919	−0.6035	−0.2364	0.1254
Worker	0.2484	0.2162	1.1489	−0.1771	0.6740	0.2457	0.2021	1.2159	−0.1520	0.6435
Confirmed	0.0573	0.1271	0.4507	−0.1929	0.3075	0.0671	0.1188	0.5647	−0.1668	0.3010
Independent variable										
VR	−0.5792	0.0463	−12.4991**	−0.6703	−0.4880	−0.5665	0.1205	−4.7018**	−0.8037	−0.3294
Moderating variable										
Lockdown						−0.5598	0.1244	−4.5012**	−0.8046	−0.3150
interaction term										
VR*Lockdown						0.0525	0.0263	2.0015*	0.0009	0.1042
R^2	0.3703					0.4537				
F	28.6166					30.1044				

Standard errors are in parentheses; $N = 299$; $^{**}p < 0.01$, $^{*}p < 0.05$.

CFI = 0.990, TLI = 0.988, IFI = 0.990) had the best fit indices compared to the two-factor and one-factor models. In addition, the square root of the AVE values of each variable is greater than the correlation coefficients with other variables, indicating that the study model has good discriminant validity among the constructs. In terms of convergent validity, the three-factor model fit was better (χ^2/ Df = 1.720, $p < 0.05$; RMSEA = 0.049, GFI = 0.930, CFI = 0.990, TLI = 0.988, IFI = 0.990). Also, the factor loadings corresponding to the question items were all greater than 0.7 and the AVE values were all greater than 0.5, indicating that our measures had good convergent validity. The results are shown in Table 2.

5.5 Correlation analysis

To ensure that multicollinearity did not influence the results, descriptive statistical analyses were performed on the variables. The results showed that the correlation coefficients between all variables were below 0.70, indicating that the problem of multicollinearity is small. Also, as can be seen in Table 3, there was a significant negative correlation between virtual reality and travel anxiety ($r = -0.590$; $p < 0.01$), which is consistent with our research hypothesis. The specific results are shown in Table 3.

4.6 Regression analysis

In Table 4, we used OLS regression to examine the relationship between virtual reality and travel anxiety.

First, Model 1 and Model 2 examined the effect of virtual reality on travel anxiety. Model 1 contains the results of the baseline model with control variables only. In Model 2, we included the independent variable (Virtual Reality), and the results showed a significant negative effect of virtual reality on travel anxiety ($\beta = -0.589$, $p < 0.01$). As expected, virtual reality technology can provide a safer virtual travel experience for people and reduce their travel anxiety. Hypothesis 1 was tested.

Second, models 3, 4, and 5 tested the moderating effect of lockdown intensity in the process of virtual reality affecting travel anxiety. In model 5, we added the interaction term of virtual reality and lockdown intensity. As Table 4 shows, the coefficient of the interaction term between virtual reality and lockdown intensity was positive and statistically significant ($\beta = 0.116$, $p < 0.05$), indicating that lockdown intensity has a positive moderating effect in the process of virtual reality affecting travel anxiety. Hypothesis 2 was tested.

5.7 Robustness test

Due to the small number of questionnaires collected, there may be bias in the empirical results of this article. Therefore, this article further validates the main effect and the moderating effect of blocking intensity using the Process macro program. From Equation 1 in Table 5, it can be seen that the value of virtual reality is β is −0.5792, the t-value is −12.4991, and the confidence interval at the 95% level is (−0.6703, −0.4880), which does not include 0, indicating that virtual reality has alleviated the travel anxiety of tourists during the COVID-19 epidemic, and H1 has been verified again. In addition, from Equation 2, it can be seen that the β-value of the interaction terms normalized for virtual reality and blockade intensity is 0.0525, and the t-value is 2.0015; At the same time, the confidence interval at the 95% level is (0.0009, 0.1042), without including 0, indicating that blockade intensity has a moderating effect in the impact of virtual reality on travel anxiety. H2 has been once again verified.

6 Discussion and conclusion

This study developed a theoretical framework to explore the impact of virtual reality on travel. Our study found that VR not only provides a viable alternative to traditional travel during pandemics but also opens up new avenues for the sustainable development of the tourism industry under the impact of COVID-19. To be more specific, the study found that VR can significantly alleviate travel anxiety, especially under high lockdown conditions, as it allows tourists to experience travel virtually, reducing concerns about travel safety and feasibility. This effect is enhanced by the intensity of lockdowns, with stronger travel desires arising under more restrictive conditions.

6.1 Theoretical contributions

Previous research has explored VR's role in areas like marketing, attitude, and visitor in tourism (Tussyadiah et al., 2018; Lo and Cheng, 2020; Yung et al., 2021). However, the specific focus on VR's impact on travel anxiety during COVID-19 is a novel aspect of the field. Furthermore, prior studies have looked at VR's influence on realistic travel intentions, destination marketing, and tourist behavior (Li and Chen, 2019; Ying et al., 2022; Saleh, 2023; Wang et al., 2023), but this research uniquely integrates the concept of lockdown intensity as a moderating factor. Our study fills a gap in existing literature by linking VR technology with psychological aspects of travel during a pandemic, offering practical insights for the tourism industry during challenging times.

6.2 Practical implications

From a practical and managerial perspective, our study can provide some suggestions. Based on the significant positive impact of virtual reality on traveler travel anxiety during the COVID-19 pandemic, travel companies can take advantage of this virtual travel trend by preparing to change their business models and strategies. Traditional travel businesses can partner with technology companies to offer self-service virtual reality technology services to meet the growing demand for VR tourism from tourists during the COVID-19 pandemic. In addition, since VR tourism allows tourists to escape reality and reduce negative emotions, virtual reality business operators should be able to enhance the immersive experience in a virtual reality environment by creating role-playing stories or developing mini games to create a higher sense of immersion and presence for tourists. At the same time, virtual reality opens up new ideas for travel businesses under the impact of COVID-19 and contributes to the sustainable development of the tourism industry.

6.3 Implications and limitations

As with any study, there are limitations to our work. One notable limitation is the study's geographical focus on China, which may limit the generalizability of the findings to other cultural contexts. In terms of future research directions, the article suggests exploring the impact of VR in different cultural contexts to understand how cultural differences might affect its effectiveness in reducing travel anxiety. Future research could expand to different cultural contexts to validate the findings and employ more objective measures of anxiety. Furthermore, the research primarily used self-reported measures, which could be subject to biases like social desirability or recall bias. Additionally, longitudinal studies could offer insights into the long-term effects of VR on travel anxiety. The study also opens avenues for exploring the impact of different types of VR experiences (e.g., interactive vs. non-interactive) on travel anxiety.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the patients/participants or patients/participants legal guardian/next of kin was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

QW: Conceptualization, Writing – review and editing. RS: Investigation, Writing – review and editing. KZ: Writing – original draft. XL: Data curation, Methodology, Writing – original draft.

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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.

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The neurosociological paradigm of the metaverse

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Metaverse integrates people into the virtual world, and challenges depend on advances in human, technological, and procedural dimensions. Until now, solutions to these challenges have not involved extensive neurosociological research. The study explores the pioneering neurosociological paradigm in metaverse, emphasizing its potential to revolutionize our understanding of social interactions through advanced methodologies such as hyperscanning and interbrain synchrony. This convergence presents unprecedented opportunities for neurotypical and neurodivergent individuals due to technology personalization. Traditional face-to-face, interbrain coupling, and metaverse interactions are empirically substantiated. Biomarkers of social interaction as feedback between social brain networks and metaverse is presented. The innovative contribution of findings to the broader literature on metaverse and neurosociology is substantiated. This article also discusses the ethical aspects of integrating the neurosociological paradigm into the metaverse.

KEYWORDS

metaverse, neurosociological paradigm, social brain networks, hyperscanning, interbrain synchrony, social virtual reality, ethics, neurodiversity

1 Introduction

1.1 From sociology to neurosociology

Social interaction, as a key social behavioral motive in human society, is the subject of sociology (Suckert, 2022; Beckert and Suckert, 2021; Abbott, 2016). Sociology uses qualitative and quantitative social research methods to study the social experiences of small and large groups of people (Foster et al., 2021). Until recently, sociology has lacked a direction related to the study of social behavioral acts in the paradigm of neural mechanisms of social homeostasis with the participation of social brain centers (Matthews and Tye, 2019). Studies of socially motivated behavior that is regulated by the main social neural networks of the human brain are beginning to appear in the literature. These social neural networks are the central executive network (CEN), the salience network (SN)—which specializes in the control of social behavior—the default mode network (DMN), and the subcortical network (SCN) (Feng et al., 2021).

Previously, numerous functional magnetic resonance imaging (fMRI) studies have substantiated the role of the social neural networks of the brain in the context of various forms of socially determined responses in the static "brain-tasks" conditions (Montague et al., 2002). However, as part of the evolution of new knowledge about the social neural networks and pioneering work in the field of fMRI-based hyperscanning (Montague et al., 2002), the concept of neurosociology was formed (TenHouten et al., 2022). It has become evident that the development of the subjective nature of social experience, as a key element of its integration into social behavior, is a function of the neural networks of the social brain. At the same time, significant social experience is formed by the social neural networks during the process of dynamic face-to-face communication (Hirsch et al., 2021; Schwartz et al., 2024), which can be studied and analyzed in real time from the standpoint of neurosociology. It should be emphasized that the "gold standard" of human communication (face-to-face), which represents the majority of the people's daily experience, especially between close people (Subrahmanyam et al., 2020), has never been a subject of interest for sociologists. The studies by many authors prove that this is the only and most important form of interaction at all stages of human age-related social development (Davies, 2012; Aslan et al., 2024; de Leeuw et al., 2024), as it offers a vibrant form of social interaction, with its synchronous exchange of multimodal social signals.

As digital spaces such as the metaverse emerge, the need to understand social interactions through the lens of neurosociology becomes increasingly critical. The metaverse offers a unique environment where neurosociological principles can be applied to study social behavior in ways the traditional settings cannot. Indeed, neurosociology is focused as much as possible on uncovering the neurophysiological mechanisms of a key form of "face-to-face" social interaction between people (de Leeuw et al., 2024), which has been impossible to do within sociological research. In modern conditions, when the Internet is being replaced by the metaverse with its cardinal feature of "the feeling of being fully present," neurosociology under conditions of dynamic hyperscanning becomes a powerful scientific and practical direction in studying and reconstructing the new digital subjective and objective world. The metaverse has great potential to revolutionize our understanding of social interactions by leveraging advanced methodologies, such as hyperscanning and interbrain synchrony. In addition, the merging of neurosociology and the metaverse presents unprecedented opportunities for both neurotypical and neurodivergent individuals.

1.2 The neurosociological paradigm and neurodivergence

Indeed, the neurosociological paradigm, in alliance with the metaverse opens unlimited perspectives of social interactions for all people. Despite that, majority of the people are "neurotypical" (Alkhaldi et al., 2021). This means that the social brain of "neurotypical" people, and the associated main social neural networks (CEN, DMN, and SN), operate and process information in the way that society expects, meaning "neurotypical" people fit into the norm of thinking (Szechy and O'Donnell, 2024). At the same time, one one-fifth of people on the planet are considered neurodivergent (Goldberg, 2023). Neurodiversity is characterized by diversity of thought and social dynamics, which are natural, healthy, and valuable forms of human diversity because there is no naturally "normal" or "right" style of the human mind. Neurodivergent states are not a deviation from the norm, but natural differences in the functioning of the human brain that do not need to be "fixed" or "corrected" (Milton, 2012; Milton et al., 2022). Meanwhile, neurodivergent individuals show unique manifestations in the cognitive domains, such as verbal learning, planning, attention, emotional processing, and memory functions (Mohamed et al., 2021; Velikonja et al., 2019). However, neurodivergent children, adolescents, adults, and their families with neurodiversity sometimes face significant barriers to accessing services and society. For example, the well-known dual empathy problem (Milton, 2012; Milton et al., 2022; Crompton et al., 2021) is associated with the great difficulty of neurodivergent individuals to empathize with each other.

In contrast to the medical and social models of neurodivergence (Casanova and Widman, 2021; Dwyera, 2022; Moore et al., 2024), the benefits of integrating the metaverse with neurosociology technologies have enormous potential for personalized solutions to the specific problems people with a whole range of different neurodivergent conditions face currently.

So, the metaverse, equipped with neurosociological tools such as hyperscanning, offers a new frontier for addressing the dual empathy problem in neurodivergent populations. It is important to emphasize that the metaverse can equally provide a rich digital social form of behavior for neurotypical and neurodivergent individuals (Hutson, 2022), given the uniqueness of the methodology of the neurosociological paradigm in the metaverse.

1.3 Methodological basis of the neurosociological paradigm in the metaverse

The methodological basis for realizing the unique capabilities of the neurosociological paradigm in the metaverse is the hyperscanning technology and the phenomenon of synchrony of neurophysiological brain biomarkers during real social interaction. As it is known, initially and until now the brain hyperscanning started to be applied in the study of social interaction in the dyads paradigm, when neurosynchrony of electrical (electroencephalography [EEG] method) and/or metabolic activity (fNIRS method) of the social neural networks is recorded and analyzed, as a rule, in two subjects under the dynamic conditions of "face-to-face" communication (Dikker et al., 2017; Liu et al., 2017; Wang et al., 2018; Barde et al., 2020; Feng et al., 2021; Hirsch et al., 2021; Schwartz et al., 2024).

Registration and real-time analysis of interbrain neural synchrony in the cortex cerebral hemispheres objectively indicate the success of targeted social understanding and real opportunities for empathy formation depending on the context of social activity in the virtual environment. Obviously, the methodology of the neurosociological paradigm in the metaverse can be supplemented by the phenomenon of synchronization taking place during the social interaction at the level of physiological parameters of the executive functions. For example, the synchronized physiological responses have been shown to be recorded in dyads such as the electrodermal activity and the peripheral skin temperature (Hanshans et al., 2024), the heart rate variability (HRV), and pulse variability (Rockstroh et al., 2019; Immanuela et al., 2023). The stronger HRV synchrony during conflict in pairs can predict greater mood reactivity (Wilson et al., 2018). Physiological synchrony is explained by the specific emotional state of participants in virtual reality (VR). The VR technologies have potential as stress reduction techniques (Ladakis et al., 2024), and personalized VR experience increases emotional empathy (Martingano et al., 2021). The phenomenology of brain-to-brain coupling synchrony and synchrony of physiological system' parameters support the view that the social virtual environments create a "sense of total presence" (Hameed and Perkis, 2024; Moharana et al., 2023) and identity (Yang et al., 2024a,b) with the real environment. Methodological perspectives in the neurosociological paradigm of the metaverse are open for revolutionary development, as the peculiarity of VR is that it needs to be richer and personalized to develop social communication (Kandalaft et al., 2013; Didehbani et al., 2016; Yin et al., 2022; Liu et al., 2024).

So, our general point of view is that in the metaverse, hyperscanning can be used to monitor interbrain synchrony during virtual meetings, providing insights into group dynamics and decision-making processes that are not possible in traditional settings. The application of hyperscanning methodology in the communication process of subjects immersed in the metaverse provides technological novelty, which has human adoption as one of its first and the most important challenges (dos Santos et al., 2024).

1.4 Theoretical basis of the neurosociological paradigm in the metaverse

The theoretical basis for realizing the methodological perspective of the neurosociological paradigm in the metaverse is the symbolic interactionism theory (Lee and Joo, 2022) and Piaget's theory of genetic epistemology (Ke and Qiwei, 2020).

According to the symbolic interactionist theory, the meaning, interaction, and human activity are placed at the center of understanding social life (Sandstrom and Kleinman, 2005)—the neurophysiological content of which is the subject of neurosociology. The symbolic interactionism theory analyzes the way society is created and maintained through the personal, repeated, and meaningful interactions between people (collective behavior and social movement), as well as social context and environment (Carter and Fuller, 2016). Moreover, the notions of symbolic signals and improvised self-representations in symbolic interactionism have a wide application to the study of computer-mediated communication and self-construction in social environments (Udoudom et al., 2024). The importance of the evolution of the neurosociological paradigm within the symbolic interactionist theory is supported by the key role of the universal seamless cross-xR experience in the metaverse (Tümler et al., 2022), which is created by the combination of VR with a personal computer and Hololens 2, in which the human dimension most fully realizes people's abilities to understand and use the data shared, as well as their willingness to collaborate (Yang et al., 2024a,b). Another descriptive aspect of the neurosociological paradigm within the symbolic interactionist theory stems from the key role of dynamically changing symbols of VR in real time (Shen et al., 2022), which are measured by the neurosociological hyperscanning technology. This is confirmed by a recent study in the metaverse paradigm based on the symbolic interactionism theory (Lee and Joo, 2022). The authors found that personal, repetitive, meaningful interactions between individuals in the real world shape the users' own identities and differences in the metaverse, which subsequent analysis of the data showed they related to the presence or absence of ongoing communication with others in the real world (Lee and Joo, 2022).

Another crucial theoretical basis for the neurosociological paradigm in the metaverse is Piaget's theory of genetic epistemology, as it implies the adaptation of the organism to the environment and solution of "hard problems," such as the "problem of the other mind" (Ke and Qiwei, 2020). In our subject area, the first aspect is related to the adaptation of the social brain to the social interaction processes in VR, and the second is to the adaptation of the social cognitive state under neurodivergent conditions. Yin et al. (2022) proposed a social virtual model of restructuring the patients' schema modes in personality disorders, which can be achieved due to the VR exceptional ability to create a "sense of total presence" (Slater and Sanchez-Vives, 2016; Riches et al., 2019; Hameed and Perkis, 2024) and identity (Yang et al., 2024a,b).

Piaget's theory of genetic epistemology, when applied within the metaverse, could provide a framework for understanding how users adapt to and learn from immersive digital environments, thereby reshaping social norms and behaviors. The social virtual model created by the authors for patients with personality disorders is ideally suited to lead in its clinical application to adaptive and more inclusive patient interactions with the real world to support adaptive behavior and restore a capability of emotional regulation. In contrast to the clinically oriented model (Yin et al., 2022) the neurodivergent model (Dwyera, 2022), within the neurosociological paradigm in the metaverse according to Piaget's theory of genetic epistemology will aim to improve social communication based on neurophysiological mechanisms of neuroplastic remodeling of the social neural networks.

1.5 Development of the neurosociological paradigm in the metaverse

The development of the neurosociological paradigm in the metaverse can be viewed as a three-phase process: initial integration of neurosociological tools, real-time monitoring and feedback, and eventual adaptation of social norms within the virtual environments. In its most conceptual form, it can be stated that the theory, methodology, and software of the neurosociological paradigm are already represented in objective reality (Figure 1).

Currently, the participants wearing fNIRS or EEG head helmets can enter the virtual reality of different content via VR, augmented reality (AR), or mixed reality (MR). Our study demonstrates how neurosociological tools are being integrated with VR technologies. Thus, in the comparative study on interbrain synchrony in virtual environments using hyperscanning, an increase in interbrain synchrony during collaborative tasks in VR is shown (Gumilar et al., 2021). Moreover, intra- and interbrain connections have patterns of neural synchronization across all EEG bands in both leaders and followers (Chuang et al., 2024). However, the studies were conducted outside the metaverse paradigm in these studies.

The virtual world (metaverse) is represented by digital twins, virtual elements that may or may not correspond to the compartments of the physical world and, more importantly, interact with the physical world. Moreover, the metaverse will be fully realized if the interaction between the two worlds has the highest level of independence (Shi et al., 2023; AbuKhousa et al., 2023). The main events taking place in the metaverse are generated by people who interact with each other, for example, through the avatars (Rogers et al., 2022; Crespo-Pereira et al., 2023), transact, create, play, work, and teleport through spaces (AbuKhousa et al., 2023). The evolution of the metaverse is associated with the development of digital technologies (fifth-generation [5G] networks, blockchain, artificial intelligence (AI), Internet of Things, computing, VR, AR, MR, and extended reality). The social interactions

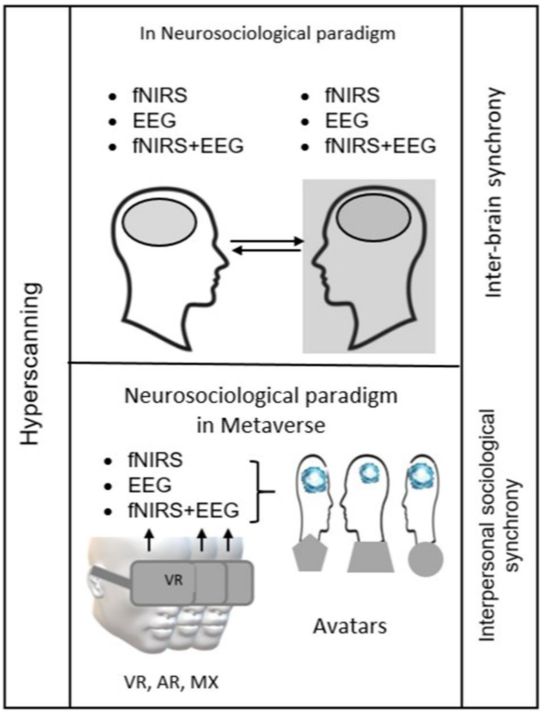

FIGURE 1
Brain-to-brain hyperscanning using fNIRS and EEG as the key methods for studying social interaction synchrony within the neurosociological paradigm. The figure demonstrates how different conditions (free, inpatient, and laboratory) enable the detailed mapping and synchronization of the brain signals, which is essential for understanding social behavior in both real and virtual environments (above). Neurosociological methodology of multipersonal hyperscanning and interbrain synchrony via controlled avatars and digital virtual objects of the social virtual platforms are necessary for revolutionizing our understanding of social interactions by leveraging advanced methodologies (below).

of users in the metaverse digital space by the avatars facilitate the joint creation of virtual values that, translationally with the participation of AI, can determine the technological progress of the physical universe (Buhalis et al., 2023). Moreover, social interaction during a three-dimensional (3D) immersive experience leads to a multicognitive lifestyle (Buhalis et al., 2023). The majority of the studies of the metaverse phenomenon are viewed from a technological perspective. However, it should be emphasized in future studies that the metaverse has an essential social and neurosocial component (Park and Kim, 2022). This is because people's social interactions in the physical world are determined by the function of the social brain's neural networks (Adolphs, 2009), fostering the users' immersion in the metaverse platforms.

The stage of the real-time monitoring and feedback between the neurosociological tools and the metaverse (Figure 1) can be revolutionized by targeting the neurosociological paradigm in the metaverse to study the main social neural networks—the default mode networks (DMN), the salience network (SN), the central executive network (CEN), and the subcortex network (SCN) of rewards (Feng et al., 2021) represented by striatum in the context of social behavior. The focus of the neurosociological paradigm in the metaverse on the CEN will make it possible to reveal new aspects of its global role in controlling all main neural networks of the brain and especially social neural networks. Based on this, it can be assumed that socially motivated activity in the metaverse will be aimed at stimulating the processes of the neural network's plasticity in the social brain, which can be monitored and analyzed by the hyperscanning technology in real time. This point of view is confirmed by the significant increase in intra- and internetwork integration of SN and CEN during a video game, according to fMRI data preprocessing in professionals relative to amateurs (Gong et al., 2016). In the same aspect, the brain-to-brain hyperscanning based on fNIRS and EEG methods is an alternative and promising method for social brain research in neurosociology (Hirsch et al., 2021; Hirsch et al., 2022; Maslova et al., 2022). The combination of EEG and fNIRS techniques provides spatial and temporal resolution of the activity of the same brain point, which promotes investigating the neurovascular interaction due to recruited neuronal activity (Lin et al., 2023; Blanco et al., 2024). Brain-to-brain hyperscanning (EEG and/or fNIRS)—synchronization of neural activity in the transcortical context—is a correlate of positive social interaction between subjects (Melloni et al., 2007; Maslova et al., 2022) and can reach the revolutionizing level in the metaverse. The transforming theoretical basis of the real-time monitoring and feedback stage is the theory of quantization of social interaction in the metaverse based on the neurosociological paradigm we propose, which will be discussed in the "Discussion" section.

The highest form of development of the neurosociological paradigm in the metaverse is the adaptation of social norms within the virtual environments, set by the social value of the metaverse, which is the natural digital space where the human social brain will operate. Therefore, the neurosociological perspective enables the creation of meaningful and impactful experiences and a better understanding of social, cognitive, and emotional processes that drive human behavior in the metaverse (Crespo-Pereira et al., 2023). The future of the metaverse is related technological innovation and its acceptance by society in the form of adaptation of social norms in the virtual environment of the metaverse. The enormous neurosociological dataset in the metaverse by the real-time monitoring and feedback will be exploited through the implementation of blockchain (Elsadig et al., 2024) and AI (Soliman et al., 2024), the application of which is already widely analyzed in neuroscience (Harris, 2024), but a detailed analysis of their role in the future development of the neurosociological paradigm in the metaverse is beyond the scope of this study.

As a general conclusion, we can say that this study aims is to uncover the transformative potential of integrating the neurosociological paradigm with the metaverse for the present and the future of humanity's digital world.

2 Social brain as a neurosociological transformation of sociology

The initial impetus for the transformative potential of modern integration of neurosociology with the metaverse was due to the advances in neuroscience, especially brain neuroimaging in different social contexts, which showed that the relationship between mind and society is a function of neural networks of the social brain (Adolphs, 2009; Franks, 2010; Franks and Turner, 2013; Kalkhoff et al., 2016; Firat, 2019). Over the past two decades, the lines of research on neural networks mediating human social interactions have emerged in neuropsychology (Lin et al., 2012; Barrett and Satpute, 2013), social neuroscience (Adolphs, 2009; Cacioppo and Decety, 2011), neuroeconomics (Walter et al., 2005), and evolutionary neuroscience (Chin et al., 2023). Studies in evolutionary neurobiology have shown a unique organization of neural networks in the human brain, namely, the transmission of information through the parallel pathways that act as the main links between unimodal and transmodal neurosystems (Griffa et al., 2023). This evolution of communication development in the human brain differs significantly from that in the primate brain. It determines the peculiarities of its higher social functions and, consequently, approaches to their research "neurosupport." This has been achieved by applying comparative neuroimaging to investigate the structural and functional specialization of neural networks from an evolutionary perspective (van den Heuvel et al., 2016; Friedrich et al., 2021).

The personal, repeated, meaningful interactions between people and dynamic human activity are the core of understanding social life (Sandstrom and Kleinman, 2005; Carter and Fuller, 2016). Based on the symbolic interactionism theory (Lee and Joo, 2022), in the metaverse this understanding is achieved through the neurosociological paradigm analyzing social dynamically changing the VR symbol signals in real time (Shen et al., 2022), the universal seamless cross-xR experience in the metaverse (Tümler et al., 2022) and improvised self-representations which have a wide application to the study of computer-mediated communication and self-construction in social environments (Udoudom et al., 2024). All these symbolic signals are measured by the neurosociological hyperscanning technology and synchrony in the social neural networks as the compartments of the social brain. When applied within the metaverse, Piaget's theory of genetic epistemology could provide a framework for understanding how users adapt to and learn from immersive digital environments, which is also due to the flexible processes of the neural networks of the social brain.

The social brain conditions all forms of human social interaction, when there is a reciprocal relationship between two or more actors (Feng et al., 2022). Sociology, as a science that studies social interaction outside the concept of the social brain, looks to the present and the past, and still, to a large extent and up to the present, "looks back at the causes funneling into a final result" (Beckert and Suckert, 2021; Abbott, 2016). At the same time, some sociologists draw attention to the fact that the new paradigm in sociology, according to which the most significant theories of sociology are primarily concerned with the future, is promising (Suckert, 2022). The prospect of successfully addressing the sociology's most significant theories can be related to the metaverse, equipped with neurosociological tools such as hyperscanning, and offering a new frontier for addressing the social brain. Especially since the modeling of social exchange shows that productive forms generate the strongest micro-order (Lawler et al., 2008). This position is significant for neurosociology because it reveals the brain mechanisms of such social behavior in the metaverse modeling. One of the key directions of transformation "back to the future" (Suckert, 2022) is precisely the relationship between neurosociology and the metaverse. Neurosociological paradigm in the metaverse in the present/past and the imagined future, opens a new approach to solving the issues of sociological research. Moreover, according to the literature, many sociological publications are rediscovering the future as a theoretical perspective, analytical category and object of study (Rona-Tas, 2020; Beckert and Suckert, 2021).

Current basic understanding of the key role of the social brain in human social cognition have been formed by studying such socially related functions of the neural networks as the mirror system, and the four specific brain regions considered to have a role in social cognition: the posterior superior temporal sulcus and the adjacent temporoparietal junction; the amygdala; the temporal poles; the medial prefrontal cortex; and the adjacent anterior cingulate cortex (ACC) (Frith, 2007; Frith and Frith, 2010; Adolphs, 2009). These neural network compartments in the social brain paradigm are a part of the structure of the main social neural networks of the human brain, DMN, SN, and CEN, which determine different forms of social behavior, and, also, according to Feng et al. (2021), subcortical network, as a striatum, a social rewarding network.

In the framework of the symbolic interactionism theory (Lee and Joo, 2022), the socially relevant symbolic factors and thus influence social connectedness and social well-being of individuals modulate activity in the medial prefrontal cortex and ACC regions as a CEN compartment (Kim and Sul, 2023). On the contrary, with the long environmental monotony and prolonged physical and social isolation, there is a structural and functional reorganization of the main neural network in the form of lower gray-matter volume in the right dorsolateral prefrontal cortex, the left orbitofrontal cortex, and the left parahippocampal gyrus than in the controls (Stahn et al., 2019), and disturbed sleep, impaired cognitive abilities, negative emotions, interpersonal tension, and conflicts (Palinkas and Suedfeld, 2008). According to the symbolic interactionism theory, any change in the goal of social behavior can transform the social specificity of intraneural network interactions (Lockwood et al., 2020) and be a causal factor affecting social outcomes (Suckert, 2022), which diversely can be modeled in the social environment of the metaverse. The reward responses that shape human behavior (Bhanji and Delgado, 2014) and show that the neural circuitry of reward, particularly the striatum, is also involved in processing social information and making decisions in social situations, which allows understanding the development of social experience, social interaction, motivation, and decision-making. Consequently, the compartments of the social brain along the ventromedial prefrontal cortex, lateral prefrontal cortex, the amygdala, and striatum play roles in social behavior (Cardinal et al., 2002).

Integrating social brain research within the framework of Piaget's theory of genetic epistemology provides a better understanding of the correlates of neuroplasticity's restructuring of the complex hierarchy in the networks of the social brain—DMN, SN, and CEN—in different types of social interactions.

In the human brain, variability in functional connectivity is highest in the frontal, temporal, and parietal regions of the association cortex, which with their functions of sensory awareness, visual imagination, speech, and spatial learning, perform the highest cognitive functions. As we move on to further discussion, these cortical areas are also related to the main neural networks, SN, DMN, and CEN, which condition social behavior. Moreover, these brain regions are phylogenetically late-developing regions of the cerebral cortex (Smaers et al., 2011). The trajectories of the neurosociological paradigm in the metaverse may be directed toward particularly pronounced functional variability in the main social neural networks, that is positively traced in long-range cortical–cortical interactions and negatively with local intranetwork variability. Functional connectivity variation has been shown to influence the anatomical variability of neural structures. Similar structural and functional variability biomarkers are found in the lateral frontal and temporoparietal regions according to the thickness of motor area layers. To a lesser extent, this is detected in the frontoparietal network (CEN) and in the DMN, in the expression of furrows (Mueller et al., 2013). For example, a well-known example of neurodiversity is left-handedness, which occurs in 10–15% of the world's population. Interestingly, left-handedness was once debated within the social norm (Brandler and Paracchini, 2014). Such a theoretical basis for the realization of the neurosociological paradigm in the metaverse will contribute to the development of a diversity of thought and social dynamics, as well as solving such a pressing problem as the dual empathy of the neurotypical and neurodivergent people. At the same time, social neural networks interact with others main neural networks (sensorimotor network, limbic system, dorsal attention network, visual system) (Fox et al., 2006; Yeo et al., 2011; Glasser et al., 2016; Androulakis et al., 2018), and three brain subnetworks—auditory system, ventral attention network, and language network (Schirmer et al., 2012; Bernard et al., 2020; Vossel et al., 2014; Figure 2). In the concept of the social brain, the development of the neurosociological paradigm in the dynamically changing metaverse leads to the control of specific functions, and four social neural networks mediate the complex forms of social interaction between humans. The DMN, SN, CEN, and SCN mediating social cognition, motivation, and cognitive control during various interactive contexts play a key role in human social interactions.

Therefore, integrating social brain research with sociological theories contributes to a more nuanced understanding of social interactions, especially within the complex and dynamic metaverse environments.

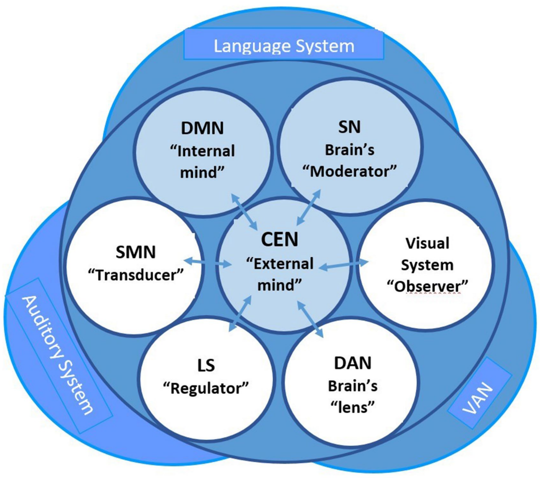

FIGURE 2
Interaction of the main neural networks in social behavior, highlighting the role of CEN, DMN, and SN in modulating cognitive and emotional processes. This balance is critical for optimizing social interactions within the dynamic environments of the metaverse. In doing so, multistage quanta of the neurosociological paradigm in the metaverse increase the information processing at the global internetwork and local intranetwork levels of DMN and CEN in their current control by SN.

3 The neurosociological paradigm

As we emphasized earlier, research on the main neural networks (DMN, SN, and CEN) of the social brain has been conducted outside the field of real social interaction since it should involve the dyads paradigm and their relationships influence behavior and/or consciousness (Feng et al., 2022). Therefore, research on intra- and intergroup social behavior is still within the paradigm of sociology as a science that studies social interaction in its reference to the present and the past (Beckert and Suckert, 2021; Abbott, 2016). The functional portrait of large-scale social neural networks (DMN, SN, and CEN) in the human brain and the understanding of social learning is widely represented in numerous studies. Still, the neural dynamics of different parts of social neural networks have not been studied in the category of social interaction (Hari et al., 2015). The main characteristics of the brain networks across human social interactions are shown in Table 1.

In the "Introduction" section of this article, we showed that the functions of the main neural networks of the social brain determined social behavior are typically investigated in the "brain-tasks" paradigm (Raichle et al., 2001; Rilling et al., 2008; Wirth et al., 2011; Tomlin et al., 2013; Elton and Gao, 2014; Gabay et al., 2014; Lisofsky et al., 2014; Fareri, 2019; Rotge et al., 2015; Wu et al., 2016; Luo et al., 2018; Yin and Weber, 2018; Delgado-Herrera et al., 2021; Feng et al., 2021; Feng et al., 2022; Zoh et al., 2022; Zheltyakova et al., 2024), which is a precursor to the development of the hyperscanning technology. This is primarily due to the neuroimaging via the fMRI, and activity of the neural network of the social brain and other main neural networks evoked in its conditions is associated with the neural system responses based on past social learning. However, dual fMRI scanning or hyperscanning technology once showed that social interaction can best be studied by simultaneously brain scanning of at least two interacting subjects inside the tomograph (Montague et al., 2002). In general, fMRI provides excellent spatial location of brain activation but limited temporal resolution (Kim et al., 1997; Schmidt et al., 2023). Therefore, the advent of hyperscanning (Montague et al., 2002) and its refinement into "brain-to-brain" technology (Hasson et al, 2012; Scholkmann et al., 2013) has made it possible to investigate the cortical interpersonal brain mechanisms underlying social interaction (Hamilton, 2021). As a result, the neurosociological paradigm of "brain-to-brain" social interaction explores brain activity in connectedness during social communication in laboratory conditions (Dikker et al., 2017; Hirsch et al., 2021; Hirsch et al., 2022; Maslova et al., 2022; TenHouten et al., 2022; Shamay-Tsoory et al., 2024). However, this opens dynamic possibilities in decoding specific socially conditioned brain algorithms and their dynamics in real-world social cognition (Nam et al., 2020; Zamm et al., 2024) and presents a modern methodology of the neurosociological paradigm in the form of hyperscanning and interbrain synchrony.

The advent of affordable mobile fNIRS-based devices creates increased opportunities to uncover the mechanisms underlying social interactions within and across generations (Moffat et al., 2024). To date, the hyperscanning method with fNIRS neuroimaging technology (Dikker et al., 2017; Liu et al., 2017; Hirsch et al., 2021; Acuña et al., 2024) and EEG (Maslova et al., 2022; Ogawa and Shimada, 2023) in free behavior has already shown its promise in the study of interbrain connectivity dynamics of the neural networks of the social brain.

Previously, we presented data on the application of fMRI to study the social brain's maps in different testing contexts ("brain-tasks") of

TABLE 1 The characters of the main neural networks across human social interactions.

The integration with the neural networks	The neurosociological side of the social neural network's functions
Central executive network (CEN) integrates with DMN, SN, sensorimotor network, limbic system, visual system, and DAN	The dominant control neural network of the brain performing high-level cognitive tasks, integrating information from the other neural networks. CEN acts as an "external mind" in implementing the neurosociological paradigm in the metaverse, and this is particularly important in the controlled processing of information (attention), involving working memory, decision-making, organizing social behavior based on personal motives, subjective preferences and choice.
Default mode network (DMN) integrates with CEN, SN, limbic system, visual system, language subnetwork, sensorimotor network, DAN, DMN, VAN, and auditory system	DMN immediately activates after a task is completed or stopped, and there is a certain anticorrelation with CEN, which makes DMN very important in the monitoring of the internal and external environment, emotional control, and emotional memory extraction in the pauses between the neurosociological sessions in the metaverse. Increased DMN or DMN and CEN activity is associated with numerous psychiatric disorders. DMN is also referred to as the "Internal mind," when people idly daydream or think about a new idea. The high sensitivity of DMN to cross-domain task transitions facilitates the study of the mechanisms of state transitions between the social virtual platforms.
Salience network (SN) integrates with CEN, DMN, and limbic system	SN regulates the switching between internal and external information processing involving the DMN and CEN, causing reciprocal levels of activity of these two networks in the healthy brain, which is crucial for social interaction in the dynamically changing virtual environment of the metaverse.

the social neural networks. Despite its high spatial resolution, this method is, nevertheless, not applicable to studying social neural networks in free social interaction. fNIRS, as an artifact-free method, is used for hyperscanning in the paradigm of neurosocial interaction (Dikker et al., 2017; Balconi and Fronda, 2020; Hirsch et al., 2021; Acuña et al., 2024; Zhang et al., 2024).

The fNIRS and EEG methods have their advantages and limitations, as fNIRS and EEG have different threshold capabilities in temporal and spatial resolution scales (TenHouten et al., 2022). In combination, fNIRS and EEG allow both electrophysiological and hemodynamic brain activity data to be examined with high temporal and spatial resolution simultaneously and at the cortical location (Kaewkamnerdpong et al., 2024). The real opportunity to combine fNIRS with emerging technologies such as VR, AR, and AI not only opens a new possibility for immersive studies of brain function in clinical practice (Rahman et al., 2020) but also expands methodological possibilities in social brain research.

Neurosociological studies of the social brain in the brain-to-brain paradigm (dyads hyperscanning) are now becoming routine at the current stage of neurosociology development (Maslova et al., 2022; TenHouten et al., 2022). However, there is a dearth of brain-to-brain research based on the social brain theory and functional dynamics of the social brain. The current hyperscanning methodology in social interaction is not directly associated with the social brain theory, whose structures include the social neural networks DMN, SN, and CEN. The CEN is one of the dominant control networks in the brain, performing high-level cognitive tasks and functions alongside or in anticorrelation with the other six main neural networks (Niendam et al., 2012; Goulden et al., 2014). The CEN functions are driven by frontal (goal setting, working memory, episodic memory, awareness of complex visual information, attention, cognitive abstraction, integrative motor acts, semantics, linguistics), parietal (decision making, non-spatial attention, working memory, motor planning, speech) and temporal areas (visual awareness, visual working memory) that deactivated during speech and especially during the theory of mind (Niendam et al., 2012). Understanding the role of the CEN in reflective thought is crucial for designing the metaverse environments that promote deep social connections as a dominant control neural network performing high-level cognitive functions in integrating information from the other brain networks (Vincent et al., 2008). As a result, the CEN acts as an "external mind" in implementing the neurosociological paradigm in the metaverse, implying controlled processing of information (attention), involving working memory, decision making, and organizing social behavior based on personal motives, subjective preferences, and choice.

At the same time, the complex questions about the CEN processes (Zink et al., 2021), such as flexibility, working memory, initiation, and inhibition, previously thought to be separate processes of social behavior, may be answered in the dynamically changing metaverse based on the neurosociological paradigm.

DMN is a network of active regions during passive mental states linked to internally directed cognition including recollection of the past and thinking about the future (Buckner et al., 2008; Raichle et al., 2001). This network of the social brain has the activity pattern in undirected task states and its metabolic properties, which led to the designation of the activity observed in rest states (Raichle et al., 2001). This type of spontaneous activity relates to mind wandering and spontaneous use of recollection and future-oriented thought (Buckner et al., 2008; Mason et al., 2007). DMN immediately activates after a task is completed or stopped, and their activities have a certain anticorrelation with the CEN (Greicius et al., 2003; Lee et al., 2012). The DMN is defined as the "internal mind," when people idly daydream or think about a new idea. The DMN high sensitivity to cross-domain task transitions facilitates the study of the neurosocial mechanisms of state transitions between the social VR platforms (Zhou et al., 2024).

Increased activity of the DMN or DMN and CEN is associated with numerous psychiatric disorders, which also opens new possibilities for the neurosociological paradigm in the modeled metaverse. Hence, understanding the DMN role in reflective thought is crucial for designing the metaverse environments that promote deep social connections and empathy among users (Luo et al., 2024).

The SN monitors the external world and carefully decides how other neural networks react to new information and stimuli. The SN moderates switching between the internal and external processing of the brain's two main control networks: the default mode network and the central executive network (Figure 3). The SN accounts for the reciprocal activity levels of these two neural networks in the healthy brain, which is critical to understanding the SN role in designing the metaverse environments that promote deep social connections (Elton and Gao, 2014; Goulden et al., 2014).

4 The social neural networks' basis of the neurosociological paradigm

By now, the main compartments of the human social brain have been well studied in the context of different types of social interaction, in which the neuronal nucleus of the DMN, SN, CEN modulus, and the subcortical network (SCN) of the reward are activated or inhibited (Feng et al., 2021). In the context of social interaction that induces social pain—due to social threat, exclusion, rejection, loss, or negative evaluation—it activates the neural networks of the ACC (Rotge et al., 2015). At the same time, different types of social tasks activate different subregions of ACC neural networks. In general, it has been found that the set of cognitive functions mediated by ACC includes cognitive concentration and working memory when performing tasks or tests, behavioral decision-making, analysis of internal and external states, emotional and motivational displays, and evaluation of the meaning of social information. ACC is a subnetwork of the DMN, which mediates human social cognition (Feng et al., 2021).

At the same time, the DMN plays a coordinating role with the other main neural networks of the brain during the passive sensory processing (Greicius et al., 2003; Andrews-Hanna et al., 2014). For example, the coordination of the DMN with the brain's visual network is enhanced when the mind subconsciously evaluates an aesthetic beauty (Vessel et al., 2019), especially when perceiving outstanding works of art or architecture. The DMN, along with the language subnetwork, is involved in semantic processing when encoding or translating meaning into spoken or written words. Semantic brain regions (dorsal medial prefrontal cortex, anterior cingulate cortex, retrosplenial cortex, angular gyrus, middle temporal gyrus, anterior temporal region, and right cerebellum) demonstrate spatial and functional involvement in the DMN (Wirth et al., 2011). The DMN interacts with the limbic system to process or evaluate the personal emotions and emotions of others (Raichle et al., 2001). The DMN is involved in modulating other people's feelings, intentions, and traits to model, explain, and predict the behavior of others (Krueger et al., 2009; Menon, 2023). Social comparison is ubiquitous in social interaction and significantly impacts on people's well-being and decision-making. According to neuroimaging data, this type of social interaction according to neuroimaging data (Luo et al., 2018) is driven by activation within several neural networks in the brain, which are nevertheless related to the main socially conditioned neural network, namely, the SN (Elton and Gao, 2014). The functional complexity of the DMN social role, responsible for the above cognitive processes, necessitates a multidimensional application of the neurosociological paradigm in the metaverse to enhance and/or develop social interaction.

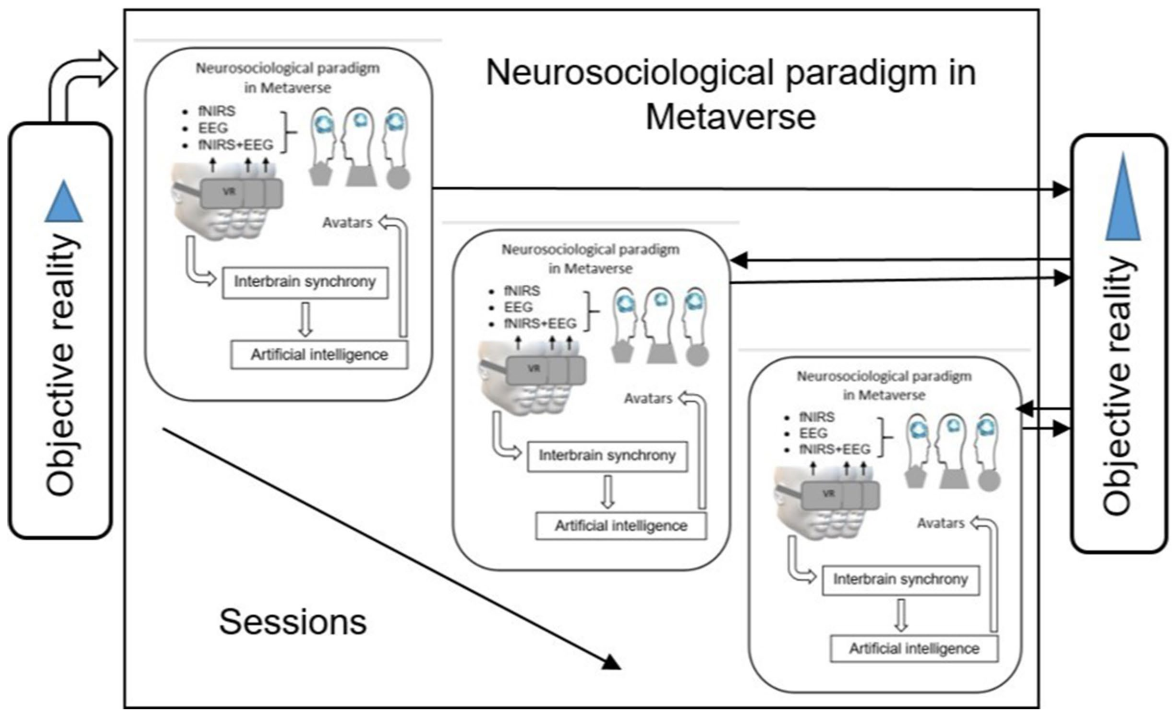

FIGURE 3
Multistage integration of the neurosociological paradigm within the metaverse, showing how EEG and fNIRS are used to monitor brain activity and achieve interbrain synchrony during social interactions. AI provides real-time feedback, guiding users through the dynamically changing virtual environments to optimize social communication. Based on our quantization hypothesis of the neurosociological paradigm, the multistage integration can represent a stream of quanta: 1. Series of quanta at the level of global interbrain synchronization of the social neural networks in the personalized metaverse for neurotypical or neurodivergent individuals. 2. Series of quanta at the level of intranetwork interbrain synchronization of the social neural networks (DMN, CEN, and SN). 3. Series of quanta of the neurosociological paradigm in the metaverse using different neurotechnologies: fNIRS, EEG, or fNIRS in combination with EEG, or using simple/complex VR scenarios.

The main functional fields of the SN are located within the anterior cingulate, the anterior insula (Seeley, 2019; Uddin, 2014), and in the presupplementary motor areas (Bonnelle et al., 2012). The SN also includes neural structures in the amygdala, hypothalamus, ventral striatum, thalamus and brainstem nuclei, ACC, medial temporal network, parahippocampal gyrus, olfactory lobe, and ventral tegmental areas (Luo et al., 2018). Moreover, the ventral striatum and ventromedial prefrontal cortex are activated depending on the direction of social comparison from the SN subnetworks in the process of downward social comparison, and in upward social comparison, consistent involvement of the anterior insula and dorsal anterior cingulate cortex.

The most important decisions are made in the context of social interactions because people live and interact in very complex social environments (Rilling et al., 2008). A model example of social interaction is the Ultimatum Game (UG) (Gabay et al., 2014). The UG is a task often used to study social decision-making and originates from behavioral economics (Gabay et al., 2014). In this task, different compartments of the socially conditioned SN are activated when seeking a fair solution. In response to unfair offers compared to fair offers, consistent activations were seen in the anterior insula, anterior mid-cingulate cortex, ACC, and medial prefrontal cortex. In contrast, in response to injustice during the UG participation, there is sequential activation of the bilateral mid-anterior insula, anterior mid-cingulate cortex/ACC, medial supplementary motor area, and cerebellum (Gabay et al., 2014). In social interaction, trust and reciprocity are relevant to all human interactions and facilitate cooperation (Vilares et al., 2011; Bellucci et al., 2016). Trust is associated to some degree with a healthier, more egalitarian, and productive society (Krueger et al., 2007).

This context of social interaction activates many of the neural networks underlying trust, reciprocity, and feedback learning (Gabay et al., 2014). The response activation occurs in the anterior insula during trust decisions in the one-shot of the investment game (IG) and decisions to reciprocate in the multiround IG, likely related to representations of aversive feelings. However, at the feedback level, other neural networks, such as the intraparietal sulcus, are engaged in the context of trust learning, and in the multiround the IG permanently activated the ventral striatum, associated with erroneous expectation of reward. Model-based analyses show that the choice to trust is based on a differential evaluation of reciprocity depending on social proximity to the partner. This critical social evaluation is encoded in the neural networks of the ventral striatum and medial prefrontal cortex (Fareri, 2019), which are subnetworks of one of the key social neural networks, namely, the SN (Seeley, 2019).

In the context of social conformity, human social behavior often aims to agree with the group opinion (Wu et al., 2016). This form of social interaction is related to the functions of the ventral striatum, dorsal posterior medial frontal cortex, and the anterior insula, which are part of the SN—social neural network. It is assumed that among the main brain and the subnetworks, there is a “common” neural system consisting of the dorsal posterior medial frontal cortex and the anterior insula to detect deviations from the group norms to facilitate the adjustment of behavior by the normative opinions (Montague and Lohrenz, 2007; Tomlin et al., 2013; Xiang et al., 2013). The functional interaction between SN and CEN is that an increase in SN information activity initiates the generation of a control signal in CEN, which switches this neural network to monitor attention and perform executive control (Menon and Uddin, 2010).

Therefore, the salience network, responsible for detecting and filtering stimuli, can be a key in adapting the virtual environments to enhance user engagement and focus, particularly in scenarios requiring rapid decision-making.

Social interaction in the context of social cooperation based on kinship and reciprocity is characteristic of primates and humans. Cooperation is an essential component of human social behavior. As such, humans are unique in their ability to represent shared goals and self-regulate to comply with and enforce cooperative norms on a large scale (Zoh et al., 2022). Brain neuroimaging under enforced cooperation has shown that the social neural networks primarily conditioning reward responses, namely brain regions such as the striatum and the orbitofrontal cortex, are involved in processing (Bhanji and Delgado, 2014). In contrast, disruption of different types of cooperation (with self and others), caused by the manifestation of negative emotions, activates neural networks of the insular cortex (Yang et al., 2019), representing a subnetwork of the DMN. In human social interaction, deception is a ubiquitous behavior that plays a vital role in everyday life and is found in a wide range of situations (Lisofsky et al., 2014). The neurobiology of deceptive behavior is well understood and is represented by the involvement of the primary neural networks (Zheltyakova et al., 2024). This has been shown in numerous neuroimaging studies about error detection, attention shifting, image recognition, inhibition, components of decision-making, language, which is accompanied by activation of the social brain’s regions (Vendemia and Nye, 2018). Thus, the angular, inferior frontal, and postcentral gyrus are activated in differentiation lying from truth-telling (Feng et al., 2022). This network includes the bilateral prefrontal cortex, left middle frontal gyrus, insular cortex, right ACC, inferior parietal lobe, and intraparietal sulcus (Christ et al., 2009).

Moreover, prefrontal cortex activation is positively correlated with lying frequency across individuals (Yin and Weber, 2018), and lying is associated with activity in the left caudate, ventromedial prefrontal cortex, right inferior frontal gyrus, left dorsolateral prefrontal cortex (Yin and Weber, 2018). In summary, the extensive network of brain regions involved in the deception process includes the prefrontal cortex, insular cortex, ACC, and inferior parietal lobule. It is related to the two main social neural networks—SN and CEN—which mediate multiple social forms (Feng et al., 2022). Moreover, during lie preparation compared to lie execution, the specific areas in the superior parietal lobe become more active (Zheltyakova et al., 2024). Consequently, deception as a form of social interaction is due to the involvement of many cognitive systems (attention, memory, motivation, emotion) in the activity, but these neural systems are not exclusive to deception and are not universally involved in all forms of deceptive behavior (Vendemia and Nye, 2018; Feng et al., 2022). The social act of deception has been associated with activation in various neural networks mediating more than just social behavior (Lockwood et al., 2020). Moreover, the ACC, as an SN subnetwork, is important and involved in performing deception in tasks with high ecological validity (Delgado-Herrera et al., 2021; Zheltyakova et al., 2024).

Neuroimaging studies have revealed a vast network of brain regions involved in the deception process, including the prefrontal cortex and inferior parietal lobule as the CEN compartments, and the insular cortex and ACC as the SN compartments. In this context, we should mention the unique CEN function in social interaction as a key top-level neural network for controlling social behavior. Based on incoming data from other networks, the CEN processes various information such as social flexibility, working memory, initiation, and inhibition, which were previously considered separate processes but now are the neural network controlling social behavior (Niendam et al., 2012).

Thus, different types of social interactions are carried out under the control of the shared neural networks, DMN, SN, and CEN, which mediate social cognition, motivation, and cognitive control in the different interactive contexts. Large-scale neural networks are also involved in the hierarchical information processing related to social interactions (Alcalá-López et al., 2018; Schurz et al., 2021). For example, the DMN is involved in modeling other people's feelings, intentions, and traits to explain and predict other people's behavior (Krueger et al., 2009). The SN and SCN modules contained bilateral striatum are relevant to the general motivational system that encodes the reward/punishment properties of social options and outcomes, considering not only self-interest but also normative social principles (Luo et al., 2018; Montague and Lohrenz, 2007). The CEN is involved in integrating information encoded in the DMN (mental states) and SN (motivational salience) to optimize social behavior (Buckholtz and Marois, 2012; Krueger and Hoffman, 2016; Krueger et al., 2020). The CEN, the brain's external mind and the dominant network controlling task selection and behavior, uses data from other neural networks.

Since knowledge about the interactions between the brain systems that transiently change according to the patterns of social interaction is crucial for studying the plasticity of standard cognitive control (Cocchi et al., 2013), then the extraordinary possibilities of the neurosociological paradigm in the metaverse offer innovative scientific and applied perspectives in this direction. The critical brain networks across human social interactions are shown in Figure 2.

The interneural network interaction results in an assessment of internal drives and personal preferences, which ultimately guides the individual's choices. Furthermore, in neuroimaging studies, the underlying social neural networks represent the neural correlates of consciousness as emphasized by Crick and Koch (1990), making neurosociology a basis in studying conscious social learning and developing the neurobiological theory of consciousness.

To date, the majority of the studies of the primary neural networks (DMN, SN, and CEN) of the social brain have been conducted outside the field of real social interaction. The neurosociological paradigm in the metaverse is extremely promising in decoding specific social algorithms of the brain and their dynamics in socially connected behavior. It can reconsider the most relevant issues of sociology as a discipline from the innovative perspectives in the present and the future. Thus, the neurosociological paradigm in the metaverse based on the concept of the social brain and main social neural networks presents unprecedented opportunities for both neurotypical and neurodivergent individuals in their future social interactions.

5 Forward to the metaverse

It is widely recognized that the metaverse represents an opportunity to extend the physical world by applying technologies to seamlessly interact with real and simulated digital environments (Dwivedi et al., 2022). Following this logic, it can be argued that the metaverse represents an opportunity to infinitely extend neurosociology's ability to study unimpeded social interaction in the transition from reality to the immersive environments and in the virtual movement between the metaverse digital spaces. The absence of borders in the metaverse carries crucial social, economic, and geopolitical implications (To et al., 2024). In doing so, neurosociological research within the new concept of hyperscanning represents an environment that will enable the metaverse to be developed as a sustainable virtual society, even though the metaverse can motivate users and create a new digital society with feedback on the effects on social interaction in the real world (Limano, 2023).

AI can provide a limitless option for social accessibility of the metaverse by creating the realistic avatars, new digital products and services, and facilitating remote work and collaboration in different areas, including data science (Soliman et al., 2024). The characters in the virtual world should be in constant development with the users and react dynamically to unexpected social interaction situations, which can be a function of AI (Thakur et al., 2023).

In the metaverse, the neurosociological idea unites social interaction of people, avatars, and holographic images in the virtual world. The responses of social interaction in the metaverse will be reflected in the functional dynamics of the social neural networks and the specifics of regulation of the executive functions. Based on the above, we believe that all forms of social interaction in the metaverse will be a product of the social brain. This is the fundamental basis and a new goal for neurosociological studies of social interactions in the metaverse multicompartment digital space. However, it should be realized that while the metaverse provides ample opportunities for social interaction, ethical concerns such as data privacy, the digital divide, and the potential for social isolation must be carefully considered and addressed.

The metaverse can be characterized by four compartments, each representing a level of realization of the neurosociological paradigm. The first compartment is the environments which include realistic, unrealistic, and fused virtual environments. The second is the interface point of view, such as 3D, immersive, and physical methods. The third compartment is interaction as social networking and collaboration. The last one is persona dialogue in the metaverse social platform. These metaverse compartments have many degrees of freedom and, therefore, go beyond the realistic environments. It is important to highlight that social value is a key consideration when evaluating the worth of the metaverse related to the new benefits to society as a whole. The point is that the metaverse focuses on the interactions that, firstly, go beyond the conversations between users and non-playable characters. Second, the metaverse involves redefining the social meaning of the metaverse as a 3D society rather than a copy of the real world (Dwivedi et al., 2022). As a result, the virtual world is more than an attractive alternative sphere for human socio-cultural interaction (Dionisio et al., 2013). No matter how complex the authors present the development of the metaverse (Dwivedi et al., 2022; AbuKhousa et al., 2023), including in terms of information interplanetary platforms (Vanderdonckt et al., 2024), we believe that this will be the main social development of humanity. Although in its infancy, the development and even survival of the metaverse are human centric (Mourtzis et al., 2022).

The theoretical, methodological and experimental justifications of the neurosociological paradigm can accelerate the development of the metaverse. Whereas previously the virtual worlds were dominated by the platforms, such as Second Life, Cryworld, Utherverse, IMVU, and World of Warcraft, the metaverse as a new Internet technology is processing its development through a collaboration of giant companies, such as Epic Games, Meta, Niantic, Nvidia, Microsoft, Decentraland, and Apple (Buana, 2023).

Many authors believe that the key factors in the metaverse development are the new capabilities of devices, such as headphones/headsets and AR and VR glasses (Xie et al., 2021). The metaverse utilizes not only these devices but also blockchain technology and avatars as a part of a new integration of the physical and virtual worlds (Lee et al., 2021; Liu and Steed, 2021). The AR, VR, amd XR headsets and glasses create an effect of presence or immersion, represented in the metaverse to a greater extent than the operation of VR devices in the 3D environment (Dwivedi et al., 2022).

The VR headsets are opaque and block the surrounding space when used. In contrast, the AR-based devices are transparent and allow users to see the surrounding space in front of a person with an additional image projected onto it. After combining the possibilities of digital spaces generated by AR/VR into a new spectrum of reality-altering technologies, MR has emerged. In the MR experiences, the user can interact with both digital and physical elements in different conditions of the experience (Martens et al., 2019; Bouzbib et al., 2023; Salatino and Burin, 2024). The term "extended reality" (XR) defines VR, AR, MR, and any technology that blends the physical and digital worlds (Chhabhaiya et al., 2024). This virtual continuum is currently the basis of the extended metaverse (Alpala et al., 2022; Shin et al., 2024). In terms of technical and programmatic capabilities, VR, AR, and MR have already enabled the transition from two-dimensional (2D) to 3D. Still, they do not replace the existing digital platforms but enhance them by merging with the current Internet infrastructure to encourage a more diverse form of interaction, predominantly through today's smart devices (Cho et al., 2023).

Literature reviews show that transitioning from 2D to 3D (VR technology) is a useful tool in different applications and fields (Hamad and Jia, 2022). Notably a large panorama of the effective VR application has been demonstrated in the numerous studies of social cognitive training in the autistic neurodivergent group (Kandalaft et al., 2013; Didehbani et al., 2016; Liu L. et al., 2024). The literature analysis of the VR application shows that the traditional practice of improving VR-based social communication and social cognition skills in neurodivergent subjects presents a multicomponent model (Didehbani et al., 2016). Essential blocks of the model are the pre- and postmeasures, VR environments, demographic variables of the participants, intervention design, and the avatars represent a user in the virtual world, which were modeled to resemble each participant. This model has been successfully replicated to achieve the practical goals (Kandalaft et al., 2013; Didehbani et al., 2016). Combining new advances in VR, AR and MR with AI is a more innovative level of the immersive Internet-based digital landscape and massively multiplayer online games. Such integration of technologies ensures the development of the social and physical activity of subjects in VR, considering the multifactor nature of social motives and the large array of data obtained. These technologies use VR platforms and AI to extract categories or clusters of responses automatically. The effectiveness of the VR and AI integration (Sarupuri et al., 2024) indicates the key role of VR platform enhancement, big data analytics, and AI in the metaverse development. This is equally true for the role of blockchain technology (Elsadig et al., 2024; Huawei et al., 2023; Lee et al., 2023; Soni et al., 2023; Bashir et al., 2023), a discussion of which is beyond the scope of this study.

Thus, we can generalize that the neurosociological paradigm in the metaverse, whose different components now have been successfully proven in experimental and applied neuroscience, according to the references cited, represents the integrated technological system. As shown in our study, the theoretical foundations of the neurosociological paradigm in the metaverse are the symbolic interactionism theory and Piaget's theory of genetic epistemology. The methodological basis of the neurosociological paradigm in the metaverse is represented by technologies of interbrain hyperscanning (dyads and more individuals) and phenomena of synchrony of electrical and/or metabolic activity of the main social neural networks, as well as technologies of registration of the executive functions' synchrony. The digital technologies of the system are represented by the socially personalized VR platforms and automated big data analytics technologies using real-time AI and feedback based on the AI control of the metaverse.

5.1 The neurosociological paradigm in the metaverse for development of social communication

The metaverse digital space within the symbolic interactionism theory framework is considered a virtual environment of social interaction and human activity. Based on Piaget's theory of genetic epistemology we can predict that interaction with the metaverse virtual world will form a new cognitive structure of social neural networks, the biomarker of the formation of which will be interbrain synchrony of electrical (EEG-based) and/or metabolic (fNIRS-based) activity of the main social neural networks (CEN, DMN, and SN). On the neurophysiological basis of interbrain synchrony because of socially motivated activity in the metaverse, a new homeostasis of social interaction will be formed, and both empathy and dual empathy will be objectively solved, which cumulatively will improve the personal experience of social interaction in the post-metaverse behavior (Figure 4).

Section 1.5 in this article discusses about developing the neurosociological paradigm in the metaverse can be viewed as a three-phase process. Realization of one of these processes, namely, the real-time monitoring and feedback, is demonstrated in Figure 4 in the form of two frames when interbrain synchrony as the quant of the successful social interactions serves as a critical feedback mechanism between the social neural networks and the metaverse environments by AI. Therefore, we propose the hypothesis of quantization of the neurosociological paradigm in the metaverse as a theoretical framework to explain the realization of a social goal within a single virtual frame/session in the metaverse. The quantization of the neurosociological paradigm in the metaverse can be a result of social interaction both within one virtual social platform and as a result of changing virtual domains, which allows personalizing the structuring of the metaverse for use in the neurodivergent groups of people.

Figure 3 shows the quantization flow of the neurosociological paradigm in the metaverse. As a result, the integrated metaverse digital space through AI-enabled real-time feedback on the parameters of the users' cognitive, neurophysiological and emotional states will

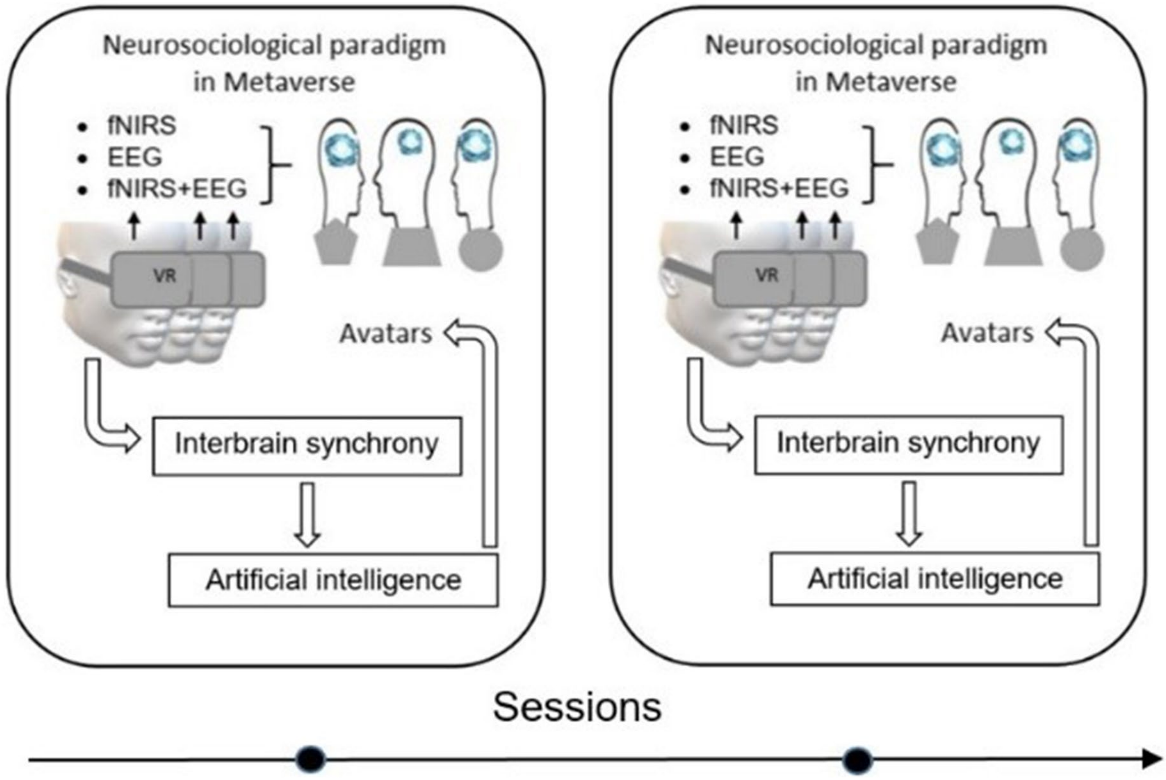

FIGURE 4
Implementation of the neurosociological paradigm in the metaverse, demonstrating how users engage with the VR platforms through EEG/fNIRS neurotechnologies. AI dynamically adjusts interactions based on real-time interbrain synchrony, creating a continuous feedback loop between virtual experiences and real-world cognitive processes.

be the basis of their personalized social experience (Guan and Morris, 2022). Meanwhile, the inclusive environment created in the metaverse should be informationally richer and more personalized than the objective reality of the environment (Yin et al., 2022).

The neurosociological paradigm in the metaverse based on AI control of the social VR platforms and neurophysiological processes of interbrain synchrony presented above will allow the neurodivergent groups, which are characterized by different ways of brain function, information interpretation, and environmental perception (Dwyera, 2022), to use the personalized profiles of the VR platforms during hyperscanning to achieve the controlled interbrain synchrony and get personal socially beneficial adaptive behavioral outcomes.

The potential for neurodivergent applications is promising. For neurodivergent people, the progressiveness of immersive environments is due to their high interactivity, which is positively reflected in the development of imagination and role learning, which is typical in real social situations (Lorenzo et al., 2016).

The general view of VR about the education of children with disabilities correlates with its inclusiveness, informativeness, and accessibility to information environments that are virtually inaccessible to some of them (Chițu et al., 2023). The greater accessibility of the learning environment in VR is about the development of social and emotional abilities (Didehbani et al., 2016; Fromm et al., 2021).

This is achieved by the fact that the metaverse opens up for neurodivergent groups of children and adults with huge possibilities of fast social communication and imitating the inner world through advanced 3D images and avatars. It is important to recognize that the neurodivergent states appear to be natural differences in the functioning of the human brain, not an aberration that, therefore, does not need to be "fixed" or "corrected" (Milton, 2012). The metaverse's passional advantage over the real world is its multiplatform capabilities (Alhasan et al., 2023).

The metaverse, as a set of social platforms with a large community and many virtual opportunities to build a personalized education strategy and express their creativity and scenarios, is available to other virtual community participants. At the same time, the metaverse is always connected with real life. The modern metaverse strategies for the neurodivergent groups provide social interaction through gamification and collaborative learning (Han et al., 2023; Lampropoulos and Kinshuk, 2024), and text and voice communication, which is a special feature for the development of cognitive and motor skills, further facilitating social interaction (Du et al., 2021). Finally, the metaverse, due to its unique properties of interpersonality into opening up opportunities for building social interaction, can successfully address the well-known dual empathy issue (Crompton et al., 2021; Milton, 2012; Milton et al., 2022).

The integration of the pioneering neurosociological paradigm in the context of the metaverse emphasizes its potential to revolutionize our understanding of social interactions by leveraging advanced methodologies such as hyperscanning, interbrain synchrony, and interpersonal empathy. The neurosociological paradigm with hyperscanning and interbrain synchrony technology in the metaverse provides the objective biomarkers for achieving successful social interactions to the interacting users (two or more subjects) at each stage of quantizing their behavior. In this sense, the integrative function of the neurosociological paradigm can be defined as a moderator of the provided capabilities of the metaverse platforms at the points of transition of the cognitive states during the moments of interbrain synchrony. The moderating role of the neurosociological paradigm can only be realized in integration with AI, which is the metaverse booster for users in achieving their social and behavioral outcomes.

AI increasingly intertwines with VR, creating a more personalized and intuitive user experience. The advantage of AI-based VR is the ability to analyze user behavior and preferences, subsequently adapting the virtual environment to individual needs. The integration of AI will lead to significant progress in the future of VR. We believe hyperscanning technology combined with AI in the metaverse will represent the key feedback between users and digital spaces. It all comes down to the fact that analytical predictions link the relevance of AI for the metaverse to the importance of big data processing to improve immersive experiences in virtual digital environments and provide human-like intelligence to the virtual agents (Huynh-The et al., 2023; Alotaibi, 2024; Zawish et al., 2024). As a result, the metaverse appears as a hypothetical upcoming Internet iteration that will support decentralized, long-term, three-dimensional virtualized online environments between the financial, virtual, and physical worlds that are becoming increasingly connected (Hovan George et al., 2021).

In the context of this paper, we focus on an essential aspect of XR, such as the ability of people to interact and communicate with each other in real time using VR technology. Combining XR with social interaction creates a VR perspective for people worldwide to communicate. The emergence of social VR platforms has become one of the fastest growing trends in VR. People can interact with each other in real time in a virtual environment, host parties, attend concerts, and play multiplayer games. Social VR platforms are becoming increasingly user-friendly, diverse, and community-oriented, evolving toward a more inclusive social future of VR (Dzardanova et al., 2024). In this aspect, the neurosociological transformation of the social VR platforms based on the neurosociological paradigm in the metaverse offers a great opportunity for studying the world's social flows and improving the metaverse. At the same time, a special goal of the social VR development in shared virtual spaces will be human-to-human communication and interaction, avatar creation, and personalization, which require an AI component of the metaverse (Huynh-The et al., 2023; Alotaibi, 2024; Zawish et al., 2024).

5.2 Empirical vision of the neurosociological paradigm in the metaverse

It should be noted that, at present, the merging of the physical and virtual worlds is not yet achieved without a gap between the digital and physical realities (Shen et al., 2022). Still, this merger will eventually turn the metaverse into an ideal social experience, regardless of the neurodivergence of social groups and the different motivations of users.

At this advanced stage, the social metaverse will be the mixed digital space of integrated realities. The integration goes beyond the traditional human visual experience as it will include the heteromodal sensations (Pham et al., 2022; Jot et al., 2021), the Internet of Things (Guan and Morris, 2022), digital twins (Tu et al., 2023), wireless non-invasive and invasive neurotechnological devices (Bozgeyikli, 2021; Alsamhi et al., 2023; Bashir et al., 2023), and biometric sensor technologies (Wang et al., 2023). This exploration promises to redefine human lifestyles and work paradigms. From a functional perspective, interoperability in the metaverse will be a universal digital ecosystem with social interaction in the form of seamless and secure information sharing and interactions between different systems or platforms, supported by consensus and common standards (Dionisio et al., 2013; Hyun, 2023; Behr et al., 2023).

5.2.1 Hyperscanning perspective

The hyperscanning interbrain synchronization has identified the regions of the association cortex (frontal, parietal, and temporal lobes) that form the crucial CEN whose function accounts for the interbrain coupling, according to available data from the fNIRS and/or EEG (Dikker et al., 2017; Liu et al., 2017; Wang et al., 2018; Barde et al., 2020; Feng et al., 2021; Hirsch et al., 2021; Schwartz et al., 2024). Furthermore, it can be argued that hyperscanning and interbrain synchrony is a new aspect in the development of modern sociology, namely neurosociology, which investigates the neurophysiological mechanisms of the social brain functioning in the dyads and more individuals.

5.2.2 Face-to-face and interbrain coupling perspective

The fact is the literature emphasizes the crucial role of face-to-face interactions to enhance the superior mode of communication for interpersonal connection (Hirsch et al., 2021; Schwartz et al., 2024). Mechanisms of interbrain coupling in the face-to-face interaction paradigm have received empirical evidence in many studies as one of the highly effective technologies for multifaceted solutions to the challenges similar to human challenges, main technological obstacles, and process challenges arising when using the metaverse (dos Santos et al., 2024). The literature on the empirical research in the subject area of our study actualizes the methodological revolutionarity of the neurosociological paradigm in the metaverse based on hyperscanning as a neurophysiological process of interbrain communication, which will be crucial for future metaverse initiatives. In support, we describe the empirical evidence below.

The empirical evidence for the link between traditional face-to-face interactions and interactions in the metaverse comes from musician hyperscanning data showing a high level of synchrony of dual intersound paired pianists' brain activity, which is hypothesized to result from the integration of external and internal sources of auditory information. At the same time, the neurophysiological mechanisms of interbrain synchrony in pianists were in alpha oscillations by the EEG data (Novembre et al., 2016).

The key role of the increased alpha-band in the interbrain synchrony as a predictor of the interpersonal behavioral synchrony across the participants is also shown in the study of the stimulatory effect of oxytocin on enhancing interbrain synchrony during social coordination in male adults (Mu et al., 2016). Alongside this, it is known that synchronization in the alpha and beta bands does not appear to be mediated by physical properties of speech but arises directly from the dyads (face-to-face) interactions (Pérez et al., 2017). These results emphasize that the neural basis of linguistic communication and the social essence of verbal communication should represent one of the bases for implementing the neurosociological paradigm in the metaverse.

A multipersonal learning situation with high levels of social dynamics can also be transferred to the metaverse on the basic condition that EEG portable headsets in a school classroom support interbrain synchrony data when many stimulus properties of all parties (teacher/students) are combined. For example, experience (Dikker et al., 2017) shows that face-to-face interaction before the class starts is a kind of "activator" of brain-to-brain synchrony between students during the study session. Consequently, in scenarios of the neurosociological paradigm realization in VR space, social dynamics in the metaverse within the face-to-face paradigms represents host real-time multisensory social interactions between two or more people that occur synchronously and involve the multiple senses sensor technologies and feedback of the neurosociological paradigm.

Hypothesizing an empirical link between traditional face-to-face interactions and interactions in the Education metaverse, it should be emphasized that brain-to-brain synchrony and learning outcomes vary by student-teacher dynamics (Bevilacqua et al., 2024). Thus, interbrain synchrony in students is significantly higher during a video than a lecture, and student engagement and teacher likeability during a lecture. Consequently, the social factors reflected on brain-to-brain synchrony in the real-world settings of the study group can be used in the neurosociological paradigm of the metaverse to predict, for example, cognitive outcomes of academic performance.

Interbrain synchronization without face-to-face communication also occurs during co-operative social engagement, which increases with improved team performance (Reinero et al., 2021). The study shows the potential role of interbrain synchrony in collective performance and intergroup interaction, which will be widely presented in the metaverse at the level of problem-solving tasks, VR games, and the team members' brain dynamics. We believe that the neurosociological paradigm can be successfully implemented in the metaverse based on interbrain synchrony, which according to Reinero et al. (2021), can serve as an implicit measure of predicting the team success or assessing the connectivity between neurodivergent subjects and/or groups.

The Musical metaverse as a multiuser musical environment holds significant potential for music-making in music composition and performance through virtual environments based on technologically mediated social interaction. Hyperscanning in conditions of musical improvisation, shows a higher number of main brain networks active at the delta (2–3 Hz) and theta (5–7 Hz) frequencies in the interbrain connectivity, and the difference of the activated networks, primarily CEN and SN between the two guitarists. This points to the brain regions that implement mechanisms and allow individuals to engage in the temporal coordination of cooperative actions (Sänger et al., 2012; Muller et al., 2013). Consequently, neurosociological hyperscanning technologies in the "Musical Metaverse" have great potential in investigating the neurophysiological basis of complex interpersonal coordination of actions in musical art. Interbrain synchrony in the delta and theta bands is mediated by speech signals in traditional hyperscanning (Pérez et al., 2017) and can be a biomarker of successful interbrain coupling in the metaverse.

An important aspect of the empirical experience from hyperscanning data in the metaverse is the high neural synchrony in romantic couples compared to unfamiliar pairs of people (Kinreich et al., 2017). Under these conditions, interbrain synchrony occurs in the temporoparietal regions of the social brain. It is manifested by a gamma rhythm that is conjugated with nonverbal social behavior and amplified during the moments of eye-to-eye interaction.

The empirical studies of a higher behavioral form, such as speech, show more interbrain synchrony in the "human–human" than "human–machine" tasks. Moreover, the same main neural networks of temporal and lateral-parietal regions are synchronized in the range of theta/alpha (6–12 Hz) EEG rhythms (Kawasaki et al., 2013). Interbrain synchrony in the delta and theta bands is also mediated by a speech signal in hyperscanning (Pérez et al., 2017). It can be a biomarker of the success of interbrain coupling in the metaverse. These results suggest that interbrain synchronization is closely related to speech synchronization between subjects and can be a major strategy of the neurosociological paradigm in the metaverse.

Finally, interbrain synchrony of brain electrical activity across multiple frequency bands can occur without physical presence or direct visual or auditory information about the participant in the interaction (Wikström et al., 2022). At the same time, the current capabilities of hyperscanning go far beyond the dyads paradigm (Maslova et al., 2022). Overall, this indicates the potential for interbrain synchrony to positively influence social relationships in a distributed network of the different metaverse platforms.

Spatial localization of neural networks using fNIRS hyperscanning technology showed the patterns of synchrony in the metabolic activity of the social brain networks in frontal, temporal, and parietal cortical regions in the face-to-face "parent–child" relationships as well as in romantic couples (Zhao et al., 2024). It is important to emphasize that the increased neural interactions in the brain regions mentioned above highlight their involvement in cognitive functions during the prolonged interaction with close partners and affection, benefiting from cooperation and collaboration.

Thus, the hyperscanning of traditional face-to-face or interbrain coupling and the real technological possibilities of transferring such coupling to the metaverse by fNIRS and EEG actualizes the overall methodological revolutionary nature of the neurosociological paradigm for the metaverse and makes it crucial for future metaverse initiatives.

In the metaverse, the neurosociological idea unites the social interaction of people, avatars, and holographic images in the virtual world. The responses of social interaction in the metaverse will be reflected in the functional dynamics of the neural networks of the social brain and the specifics of regulation of the executive functions. Based on the above, we believe that all forms of social interaction in the metaverse will be a product of the social brain, a fundamental basis and a new goal for neurosociological studies of social interactions in the metaverse digital space. From this point of view, hyperscanning by the fNIRS-based neuroimaging method or wired EEG-based is now able to reveal the phenomenon of interpersonal neural synchrony in the situations of social interaction (Zhao et al., 2024). According to the hyperscanning data, synchrony of neural networks plays a central role in establishing social connection or performing collective social action in social behavior (TenHouten et al., 2022). Typically, synchrony occurs within the prefrontal cortex in different contexts of social interaction, and/or synchrony captures subregions of the frontal cortex. Thus, synchrony during social behavior is primarily recorded in the brain's large-scale neural network CEN which controls the main social neural networks. The fNIRS-based hyperscanning in neurosociology also relies on synchrony (Czeszumski et al., 2020). Thus, the involvement of the social neural networks (DMN, SN, CEN) in social interaction remains a poorly explored area. Still, they are available for hyperscanning in the neurosociology paradigm and even more so in the metaverse. The EEG method of recording the electrical activity of cortical fields and its combination with fNIRS (Wang et al., 2024) is currently the most informative approach in studying the main social neural networks, as well as the main controlling neural network of the brain—CEN, but also from the perspective of interpersonal social synchrony. Recently, interbrain synchronization has been shown in the mixed-reality environment (Ogawa and Shimada, 2023), which is known to be the environment through which the metaverse can be entered. The transformation of the neurosociological paradigm from the real world to the virtual metaverse is showed in Table 2.

Thus, the neurosociological paradigm in the metaverse is extremely new for understanding the function of the social brain in its diversity, including in extraordinary conditions of social interaction in the virtual digital space. It can be assumed that the design of the future metaverse platforms, especially the AI-generated digital platforms, can be conditioned primarily by knowledge about the dynamic features of the functioning of the social neural networks.

6 Neurosociology, metaverse and ethics

The evolution of the neurosociological paradigm in the metaverse will be related to the ethics studies. It is well known that social research's ethical relevance is determined by the progressive codification, institutionalization of ethics research, and the growth of literature in this field (Surmiak and Męcfal, 2024). It is important to emphasize that one of the key factors of ethical issues in social research is the development of new technologies that may entail invasion of participants' privacy and confidentiality (Mathenjwa et al., 2023). Therefore, it is natural that neuroscience research and new advances in neuroscience raise ethical, social, and legal issues related to humans and their brains, contributing to debates about ethics (Fuchs, 2006; Pickersgill, 2013).

Neuroscience refers to the collection of disciplines concerned with the structure and function of the nervous system and brain (Cacioppo and Decety, 2011). For example, ethical discourse on fMRI is re-emerging, largely influenced by the new interdisciplinary field of neuroethics (Seixas and Ayres Basto, 2008; Shen et al., 2024). The platform providers in the metaverse can collect very large amounts of detailed personal data (records of websites visited, interactions with other users, and the environment). The metaverse can benefit people in the real universe by reducing discrimination, eliminating individual differences, and socialization. However, the metaverse is not exceptional regarding security and privacy concerns (Zhao et al., 2023), the impact of super-realism, and the effects of long-term exposure on the users' brains (Slater et al., 2020).

The leverage of technologies of the neurosociological paradigm in the metaverse creates new ethical issues that must be explored. The number of metaverse users is still small compared to the number of social media users. Therefore, existing social media regulation could be applied to the metaverse. Still, additional measures will be needed to protect the identity and autonomy of people in the metaverse regarding privacy, identity, property, fraud, abuse, and physical security (Haynes, 2023). An important aspect of maintaining privacy in the metaverse is the evaluation of new/open metaverse applications prior to the stage of anchoring them within the ethical design (Prillard et al., 2024). Finally, AI development in the metaverse will also raise new ethical challenges related to responsible content moderation, ensuring user privacy, and promoting inclusivity (Zhuk, 2024).

In this study, by addressing the ethical issues, we emphasize that while neurosociology has enormous positive potential in digital engagement with the metaverse, significant ethical concerns remain that need to be addressed and discussed.

7 Discussion

This study highlights the transformative potential of integrating neurosociology with the metaverse, a fundamentally new scientific

TABLE 2 Transformation of the neurosociological paradigm from the real world to the virtual metaverse.

The fields of social sciences	Methods and technologies	Science objects	Social communication
Sociology	Participant observation; non-participant observation; longitudinal study; surveys; interview; questionnaires; focus-group; sociological VR	Society, culture, and people; large populations with a manageable investment of time, effort, and money; a conversation between a researcher and respondent	Postsocial communicative experiences
Neurosociology	Hyperscanning, fMRI	Hyperscanning; social brain imaging; dyads or mini group	Model of social communication" brain-tasks"
	Hyperscanning, fNIRS, EEG	Hyperscanning; dyads or groups	Interbrain social imaging; interbrain social imaging synchrony and EEG synchrony; real social interpersonal communication
Neurosociology in VR	VR, Hyperscanning, fNIRS, EEG, BMI, body multimodal technologies, AI	Hyperscanning; dyads or groups	Interbrain virtual communication; interbrain synchrony; interfunctional synchrony; dyads or groups in VR social communication
Neurosociology in the metaverse	VR, AR, XR, hyperscanning, fNIRS, EEG, BMI, body multimodal technologies, AI	Hyperscanning; social groups, intercontinental groups, interplanetary groups, AI feedback metaverse control, BMI enhancing fNIRS, EEG, body multimodal technologies	Interbrain social imaging synchrony; interbrain EEG synchrony; inter-function synchrony; mega interbrain communication; mega interbody communication

and applied area. Future research should explore how these digital environments can be optimized to support diverse social needs including those of neurodivergent populations. In turn, the metaverse social platforms, when integrated with neurosociology, become the virtual environments of new self-managed social interaction for socially solving multidivergent human problems. The neurosociological paradigm in the metaverse developed based on the symbolic interactionism theory (Lee and Joo, 2022), Piaget's theory of genetic epistemology (Ke and Qiwei, 2020), and our quantization hypothesis will meet the social interests of the wide user audience.

The social aspects of the metaverse from the perspective of the symbolic interactionism theory (Lee and Joo, 2022), show a high degree of identity to the real world, as social interaction in the metaverse is based on the principles of repetitive actions of individuals, through communication in the form of exchange of meaning via language and symbols (Carter and Fuller, 2016).

In the metaverse, the actions of subjects, primarily interpersonal, take place according to the subjective meaning that objects in the real world have for them. In this case, the meanings arise from interactions with others through avatars and virtual objects and are realized in virtual social and cultural contexts. Social interactions with others in the metaverse create meanings and change them in the process of interpretation (Carter and Fuller, 2016). At the same time, however, our study shows that the metaverse as it becomes more widely participatory, demonstrates the phenomenon of limitless expansion and overcoming the limitations of the real world. The objective neurophysiological basis for the realization of the principles of symbolic interactionism in the metaverse as it expands extensively, in our opinion, is the neurosociological paradigm of hyperscanning and interbrain synchrony of the main neural networks of the social brain, which are described in Section 4 in this article.

According to Piaget's theory of genetic epistemology, subjective interaction with the subject world through actions develops the cognitive structure of social behavior, and recursive processes eventually lead to the achievement of adaptive homeostasis between the subject and the external world (Ke and Qiwei, 2020). According to this theory, the metaverse is the virtual subject world in which the 3D objects or avatars mediate the interaction between subjects in the learning process and forms an adaptive cognitive intersubjects homeostasis. Neurosociological technologies of hyperscanning and interbrain synchrony in social interpersonal interaction/learning in the metaverse objectify the achievement of cognitive adaptive homeostasis at the level of the neural networks of the social brain. The revolutionary nature of the neurosociological paradigm lies in the demand for new technological and social aspects of the metaverse in learning processes, including from the perspective of neurodivergence. In this regard, hyperscanning and interbrain synchrony technologies, in combination with AI, will present a key compartment of the tools for feedback-controlling the content of digital spaces and enhancing them (Figures 3, 4).

Moreover, the evolution of the neurosociological paradigm in the metaverse will lead to the self-evolving metaverse with a highly advanced AI. The neurosociological paradigm in the Metaverse can have applications in the study of healthy function of the social brain (Harris, 2024) as well as dysfunction of the social neural network (DMN, SN, and CEN) based on a pivotal role of AI in detecting disorders by leveraging advanced technologies to analyze vast amounts of data and aid in diagnosis (Jha and Kumar, 2024; Harris, 2024). For example, the demand for the creating the metaverse to promote healthy longevity is very high (Pillay et al., 2024), and the neurosociological paradigm in the metaverse, in our opinion, can represent a unique scientific and applied direction in the health of the social brain.

Cross-domain transitions in the digital spaces are also among the key factors in regulating the main social neural networks and social behavior in the metaverse. Their mechanisms are poorly understood (Zhou et al., 2024), but an unprecedented development of their research can be achieved by integrating the neurosociological paradigm with the metaverse.

The targets of the social brain for the neurosociological paradigm in the metaverse are the neural correlates of the social neural networks DMN, SN, CEN, and reward system at the level of the subcortical network, whose functional significance in the social behavior is well documented (Wirth et al., 2011; Rotge et al., 2015; Krueger et al., 2009; Luo et al., 2018; Elton and Gao, 2014; Seeley, 2019; Uddin, 2014; Bonnelle et al., 2012; Luo et al., 2018; Gabay et al., 2014; Vilares et al., 2011; Bellucci et al., 2016; Krueger et al., 2007; Fareri, 2019; Wu et al., 2016; Montague and Lohrenz, 2007; Tomlin et al., 2013; Xiang et al., 2013; Delgado-Herrera et al., 2021; Zheltyakova et al., 2024; Feng et al., 2021). In this case, the hierarchical interaction between the main social neural networks plays the key role of SN, which determines which network (CEN or DMN), and which nodes of these neural networks are in control at any given time of social behavior (Chand and Dhamala, 2016).

The relationship between the DMN and CEN is a critical balance, and the two networks should not be active simultaneously (Figure 5). Therefore, understanding the dynamic interaction between the large-scale neural networks, primarily DMN, SN, and CEN, when performing complex goal-oriented cognitive tasks in the metaverse defines the strategy for applying the neurosociological paradigm in studying the neurophysiological mechanisms of interaction both within and between DMN, SN, and CEN nodes when making decisions in the process of social interaction in the virtual environment. Moreover, the multistage information processing in the virtual environment increases the information processing ability in the local regions of CEN and SN (Rubinov and Sporns, 2009), which, is the basis of the multistage process of the pioneering neurosociological paradigm in the context of the metaverse. These two digital systems are integrated on the base of the quantization hypothesis of the neurosociological paradigm in the metaverse, the symbolic interactionism theory (Lee and Joo, 2022), and Piaget's theory of genetic epistemology (Ke and Qiwei, 2020). Based on our quantization hypothesis of the neurosociological paradigm in the

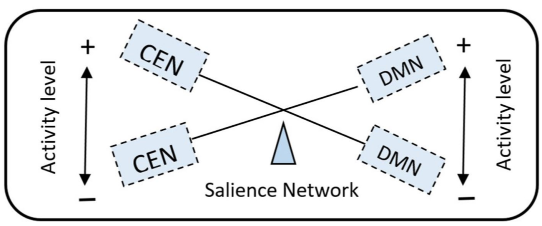

FIGURE 5
Illustration of the balance between the central executive network (CEN) and default mode network (DMN), regulated by the salience network (SN). This neurophysiological balance is critical for optimizing social behavior and cognitive processes within the metaverse, ensuring users can effectively navigate and interact in virtual environments.

metaverse, the directions of the integration can be addressed to improve people's cognitive activity during social interaction. For example, improving the cognitive processes of attention and/or working memory increases the functional integration of SN and CEN (Luo et al., 2014).

The key targets of integrating the neurosociological paradigm with the metaverse are the neuroplasticity processes in the social brain, which increase with the prolonged use of virtual technology. Thus, the experienced users of virtual systems demonstrate higher levels of processing network information at the level of the social neural networks (Gong et al., 2016). It can be assumed that similar positive results will be achieved by studying the neurodivergence of the social brain from the standpoint of the unique capabilities of the neurosociological paradigm in the metaverse. It should be recognized that the control of the neuroplasticity processes during hyperscanning and interbrain synchrony by biomarkers of social interaction serve as critical feedback mechanisms between the social neural networks and the metaverse environments. We believe that the success of achieving the goals of integration and implementation of the neurosociological paradigm in the metaverse will also be determined by the levels of improvement of the integration of the neurosociological tools with the social virtual platforms and the resources of the real-time monitoring and feedback.

Another key compartment in the hierarchy of social neural networks is the subcortical network (SCN), represented predominantly by the striatum (Feng et al., 2021), which is involved in the hierarchical information processing associated with the social interactions (Alcalá-López et al., 2018; Schurz et al., 2021). The striatum, as a likely input region for heteromodal (affective, cognitive, motor) information, is a heterogeneous structure in terms of intercentral connectivity and functionality that is directly related to the core neural networks of the social brain (Elton and Gao, 2014; Goulden et al., 2014; Greicius et al., 2003; Lee et al., 2012; Vessel et al., 2019), and performs the functions as a central cognitive mechanism of reward response. As a result of understanding the role of the subcortical network of the reward response, it will be possible to implement the affective, cognitive, and motor components of the design of the social virtual environments, which will facilitate the effective adaptation of people from different divergent groups when using the neurosociological paradigm in the metaverse.

Another crucial aspect of realizing the neurosociological paradigm in the metaverse is the inclusion of AI in the digital space. In our opinion, in terms of the new capabilities of AR, VR, and XR glasses for the neurosociological paradigm in the metaverse, these devices should be multisensory for hyperscanning other than electrical (EEG) and/or metabolic (fNIRS) activity of cortical neurons, biomarkers, for example, the levels of emotional states of the VR platforms' users. Recent findings in this area have been reflected in the recent publications highlighting such features as VR technologies, which have the potential as stress reduction techniques (Ladakis et al., 2024), and personalized VR experiences increasing emotional empathy (Martingano et al., 2021; van Loon et al., 2018). Moreover, the phenomenon of synchrony at the level of executive functions is manifested by physiological responses of the electrodermal activity, peripheral skin temperature (Hanshans et al., 2024), heart rate variability, and pulse variability (Rockstroh et al., 2019; Immanuela et al., 2023). Interestingly, situational factors induce synchrony of HRV in pairs. The stronger HRV synchrony during conflict in pairs predicts greater mood reactivity (Wilson et al., 2018), and it is a biomarker of interpersonal engagement that promotes adaptive learning and effective information sharing during collective decision-making (Sharika et al., 2024).

These facts add new aspects to the multiparameter regulation of subjects' social behavior in the metaverse and, in general, raise the importance of AI in implementing the VR platforms and improving multisensory VR headsets. They will represent a big data source of the metaverse management by AI, which, in turn, will make it possible to create new integrative indicators of human immersion in social interaction. It can be hypothesized that AI multisensory integration can be a source of the new AI-based feedback integrations in the neurosociological paradigm. A creative example of the realization of this idea can be the work, in which a new integrative index from multiparametric data of large human populations using a deep learning model is the automatic processing and analysis of big data of facial heat maps, metabolic parameters, sleep duration, expression of DNA repair, lipolysis, ATP genes in the blood transcriptome and physical exercises to predict biological age and disease (Yu et al., 2024).

Digital environments can be optimized to support diverse social needs. The brain–machine interface (BMI) facilitates personalized integration of the neurosociological paradigm in the metaverse and appears to be a promising prospect, through which a new channel of direct interaction between the brain, digital platforms, computers, or virtual twins without language and cultural barriers can be created and which will facilitate the development of digital user experience and the adoption of new interpersonal communication channels (Herbert, 2024; Liu Y. et al., 2024; Jia et al., 2024; Kritikos et al., 2023). Optimization to support diverse social needs is the evolution of AR, VR, and XR (Xie et al., 2021; Lee et al., 2021; Dwivedi et al., 2022) and the Internet as an iteration of the metaverse, and not only the social VR platforms within our planet (RecRoom, AltSpaceVR, VRChat, BigScreen, Mozilla Hubs, and Spatial) (Liu and Steed, 2021), but also in the interplanetary space (Vanderdonckt et al., 2024). At the same time, social VR platforms are convenient experimental sites for interdisciplinary neurosociological analysis. Table 2 shows the incredible technological evolution of the neurosociological paradigm in the metaverse, considering the different levels of improvement (Yang et al., 2024a,b) that has occurred in a relatively short period, when the "neurosociological idea" was formulated (TenHouten and Kaplan, 1973; TenHouten, 1997; von Scheve, 2003). This was facilitated by the announcement of the "decade of the brain" initiative which was prompted by neuroscience advances in significant progress in developmental neurobiology, molecular genetics, brain imaging, and computational neuroscience (Tendon, 2000). Since the known social platforms can be classified as precursors of the social metaverse, they allow users to create and manage social interactions in the virtual world. In general view, such a fundamental basis for the realization of the neurosociological paradigm in the metaverse will contribute to the development of a diversity of thought, and social dynamics, as well as solving such a pressing problem as the dual empathy of the neurotypical and neurodivergent people (Norton et al., 2022; Ogawa and Shimada, 2023). Our prospective study highlights the transformative potential of integrating neurosociology with the metaverse. So, on this fundamental basis, future research should explore how these digital environments can be optimized to support diverse social needs, including those of neurodivergent populations.

8 Conclusion

In this study we highlight the theoretical and methodological foundations of the neurosociological paradigm in the metaverse and the stages of integrating neurosociology with the metaverse. Currently, the core of the methodology of the neurosociological paradigm in the metaverse is represented by the fNIRS and EEG-based hyperscanning technology and the phenomenon of synchrony of neurophysiological brain biomarkers. The neurobiomarkers of social interaction serve as critical feedback mechanisms between the social neural networks and the metaverse environments during real social interaction. The social neural networks (DMN, SN, CEN and SCN), as well as the social brain as a whole, are the main targets of the research perspective of the transformative potential of neurosociology in the metaverse. Synchronizing biomarkers of the social brain's activity is a "hallmark" of social interbrain coupling during intergroup communication in the social metaverse. The study cites the digital technologies (AI, BMI and VR headsets) optimized to support diverse social needs. Neurosociology as the science of neural correlates of subjective social interactions, is, in its modern form, a paradigm for redefining the social meaning of the metaverse. The authors suggest that the development of the metaverse will significantly contribute to the technological and conceptual advances in neurosociology. The cutting-edge perspectives of neurosociology will evolve based on the demands of the metaverse rather than those of the real world. The study also discusses essential neurodiversity and ethical aspects of integrating the neurosociological paradigm into the metaverse.

9 Limitations

This study is limited to literature studies that examine hyperscanning and interbrain synchrony in VR in the context of the brain-to-brain interaction. The limiting factor in integrating the neurosociological paradigm with the metaverse is the absence of the fundamental technological developments at the real-time monitoring and feedback level. Equally limiting factors are the issues of governance, ethics, security, acceptable behavior, privacy, limited access of the population to the metaverse digital infrastructure, and unregulated social norms within the virtual environments. The crucial factor in the limitations of the neurosociological paradigm in the metaverse is subjective. When an individual is immersed in the virtual environment, risks are associated with the impact of rich and varied visual and auditory sensory experiences on the emotional well-being and physical sensations. It initiates anxiety, nausea and eye fatigue in users. Elderly adults exposed to VR experience an even greater range of limitations in the form of lack of skills in using interface/design applications, lack/low digital literacy, low awareness of cyber safety, and limited access to digital devices and the Internet. It should be recognized that fNIRS, EEG, and BMI headsets, as well as probable technological improvements in the field of application of the neurosociological paradigm in the form of multisensory technologies, will require developers of new solutions, since the above subjective and technical limitations are the experience of the previous development of the VR platforms and neurophysiological equipment. Limiting factors related to a general vision of the metaverse are discussed in the scientific debates (Cerasa et al., 2022; Dwivedi et al., 2022; Girginova, 2024).

Data availability statement

The original contributions presented in the study are included in the article/supplementary material; further inquiries can be directed to the corresponding author(s).

Author contributions

OM: Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing. NS: Project administration, Resources, Writing – original draft, Writing – review & editing, Formal analysis. VP: Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Resources, Supervision, Visualization, Writing – original draft, Writing – review & 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

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