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Tracked but not trapped: Negotiating body tracking technologies for embodiment and privacy protection in VR

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ABSTRACT

Emerging virtual reality (VR) devices have been built with a range of tracking technologies, including hand tracking, head tracking, facial expression recognition, and eye tracking. These technologies enable users to experience virtual selves through diverse sensorimotor feedback. Meanwhile, body tracking has raised users' privacy concerns over the collection of biometric data. To understand how individuals perceive their embodiment experience and privacy risks, this study employs a blended approach, combining in-depth interviews and focus groups after engaging participants in multiple tracking-based VR activities. The findings suggest that body tracking elevated individuals' sense of embodiment through five different bodily experiences. Moreover, due to networked privacy challenges along both spatial and temporal dimensions, participants preferred to deactivate facial recognition in virtual spaces. Our findings seek to provide an updated framework for the sense of embodiment and capture how individuals balance their bodily experiences and perceived privacy risks based on the promises and perils of tracking technologies.

1. Introduction

Virtual reality (VR) has enabled individuals to embody in their virtual selves and interact with other avatars and agents. Embodiment occurs, for example, when users dress up their avatars and act as stand-up comedy performers in Meta's virtual social space *Horizon Worlds*, when users wear zoomorphic outfits in VR chatrooms for role-playing, and when early adopters of Apple Vision Pro use their artificial intelligence (AI)-created personae during FaceTime use. Embodiment is a key concept in VR research, as humans experience the virtual world by being inside a body that feels like their own (Kilteni et al., 2012). Our body, whether real or virtual, mediates the interactions between our minds and the external environments (Serino et al., 2016).

The importance of understanding embodiment is threefold. First, embodiment serves as a vehicle for understanding one's self. In the past, Cooley (1964) coined the sociological concept of the looking-glass self and suggested that one's thoughts and feelings are developed through communication with others. Today, VR has created an additional layer of looking glass that enables users to observe and interact with their virtual bodies, as well as to engage with others through these self-representations, both of which could lead to individuals' further reflection on their actual selves.

Second, theorizing embodiment can help elucidate the explanatory mechanisms of two frameworks often applied in VR research: the Proteus effect and homuncular flexibility. The Proteus effect suggests that embodiment in one's own avatars can reversely affect one's own behaviors and attitudes (Ratan & Hasler, 2009). For example, research suggests that online users who are assigned taller avatars tend to act more aggressively in face-to-face negotiation tasks than those assigned shorter avatars (Yee et al., 2009). Homuncular flexibility refers to individuals' adaptability to novel bodies in VR (Won et al., 2014). For instance, VR users can embody in sea turtles and develop compassion for their casualties (Pimentel & Kalyanaraman, 2022). Both VR experiences are grounded in the sense of embodiment that necessitates users' mental and behavioral adaptations to virtual characters.

Third, embodiment has been considered as a key antecedent of self-presence (Haans & IJsselsteijn, 2012; Kilteni et al., 2012). Self-presence is "a psychological state in which virtual (para-authentic or artificial) self/selves are experienced as actual self in either sensory or non-sensory ways" (Lee, 2004, p. 46). It is an illusion in which individuals to some extent overlook the role of technology in their experience and perceive the virtual selves as real selves. Understanding the formation of

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embodiment can help VR developers enhance users' self-presence and create a natural and engaging experience.

Despite ample research on the effects of VR on embodiment (Ahn et al., 2016; Haans & IJsselsteijn, 2012; Kruzan & Won, 2019; Suh, 2023; Won et al., 2015), relatively less is known about how different tracking features of VR have fostered users' sense of embodiment. Understanding body tracking is especially important given that today's VR devices have been equipped with multiple features, such as hand tracking, head tracking, body motion tracking, facial expression recognition, eye tracking, and blink detection, which can provide users with real-time proprioceptive, vestibular, visuomotor, visuospatial, and visuotactile feedback. Those features can fundamentally enhance our immersive experience and determine how much we perceive virtual representations as our own (Steptoe et al., 2013). Thus, the first goal of the study is to understand how body tracking technologies can forge VR users' embodiment experience and how users evaluate the contribution of individual body tracking features to their VR experience.

Whereas body tracking technologies can enhance the behavioral realism of users' interactions in VR, they may simultaneously bring about privacy threats. Concerns have grown regarding the use of various body tracking technologies for biometric identification (Paik et al., 2022; Prabhakar et al., 2003). Because body tracking technologies can extensively scan, process, and collect users' facial expressions, fingerprints, irises, and hand geometry, they may lead users to inadvertently disclose personal information, including geo-locations and demographics (Lin et al., 2022). Meanwhile, behavioral data such as users' positions and head orientations may lead to similar privacy intrusion (Miller et al., 2020). Hence, the second goal of this study is to investigate how users perceive privacy risks and balance the promises and perils of relying on body tracking technologies for embodiment in VR.

We develop our research questions by first introducing how sense of embodiment serves as an important mechanism in presence experience. Then we demonstrate the relationships between tracking technologies and embodiment, followed by applying the concept of networked privacy to understand individuals' subjective interpretation and management of body privacy. Using in-depth interviews and focus groups, we extend the sense of embodiment framework and parse how individuals navigate their bodily experiences and perceived privacy perils in VR.

2. Literature review

2.1. Self-presence and sense of embodiment

Presence has been central to theorizing users' engagement with technology interfaces (Lee, 2004; Steuer et al., 1995). Lombard and Ditton (1997) referred to presence as the "perceptual illusion of non-mediation" (Presence Explicated). Lee (2004) conceptualized presence as a psychological state in which individuals experience virtual objects as actual objects. Presence can broadly be categorized into physical presence, social presence, and self-presence. While physical presence and social presence have often been referred to as the sense of being there (Biocca, 1997) and the sense of being with another (Biocca et al., 2003), self-presence is conceptualized as the psychological state in which individuals experience their virtual selves as actual selves (Lee, 2004).

Two major streams of research have been linked to how individuals experience self-presence and interact with their virtual selves. The first stream centers on the Proteus effect and theorizes how individuals infer their expected behaviors and attitudes based on their avatars' appearances and behaviors (Yee et al., 2009). In a recent study that has tested the Milgram's paradigm in VR, Peña et al. (2022) found that those embodied in a hero's avatar delivered less intense electric shocks to a virtual human compared to those in a villain's avatar. Fox and Bailenson (2009) found that seeing one's own virtual representation being rewarded for losing weight or punished for gaining weight in VR encouraged users' consequent exercising behavior.

The second stream examines the idea of homuncular flexibility, suggesting that users can embody in not only humanlike avatars but also non-humanlike ones in VR (Won et al., 2014). Specifically, Won and colleagues (2014) suggested that homuncular flexibility necessitates individuals' sense of embodiment, which consists of three components: morphology, body schema, and body image. Morphology refers to the number, location, and types of limbs, muscles, and sensory receptors of a body. It determines what actions users can take in VR (Haans & IJsselsteijn, 2012). Body schema refers to "a dynamic distributed network of procedures aimed at guiding behavior" (Haans & IJsselsteijn, 2012, p. 216). It can be understood as the automatic performance of the body. Body schema is highly adaptive, allowing users to quickly adapt to technological artifacts as the extensions of the body (Won et al., 2014). Body image, also known as body transfer, refers to the extent to which users interpret the virtual bodies as their own (Won et al., 2014). This body transfer phenomenon evolved from the rubber hand illusion, in which Botvinick and Cohen (1998) found that when individuals observe a rubber hand being stroked in synchrony with one of their own hands occluded, they feel that the rubber hand belongs to themselves. Overall, homuncular flexibility suggests that the plasticity of virtual body representations can evoke users' experience of the virtual bodies as their own (Steptoe et al., 2013).

While literature on the Proteus effect and homuncular flexibility has touched upon the role of embodiment, Kilteni et al. (2012) proposed a more comprehensive framework for theorizing sense of embodiment (SoE) as a key mechanism of self-presence. Defining it as "the ensemble of sensations that arise in conjunction with being inside, having, and controlling a body" (p. 375), Kilteni et al. (2012) explicated three factors that constitute SoE: self-location, body agency, and body ownership. Specifically, sense of self-location refers to one's spatial experience of being inside an avatar's body. It concerns how much individuals perceive themselves as if they were in a different body. Sense of body agency refers to the subjective experience of actions. It results from the synchrony between the predicted sensory consequences and the actual consequences of actions (Kilteni et al., 2012). For example, when individuals' physical body actions match the actions of virtual representations, SoE will likely increase. Sense of body ownership refers to "one's self-attribution of a body" (p. 377). The strength of body ownership is reliant on the morphological similarity between individuals' body parts and their virtually presented body parts. If one's virtual body is in a different spatial configuration to one's own body, the sense of ownership may diminish. Drawing on these conceptualizations, Kim et al. (2020) manipulated different forms of avatars and found that human avatars involved a higher level of body ownership than point-light avatars, while point-light avatars featured a higher level of self-location than out-of-body point-light avatars.

Despite the theorization of SoE (Kilteni et al., 2012), three areas remain underexplored. First, little research has been conducted to systematically understand how body tracking technologies in VR contribute to users' SoE. Although prior literature has identified a range of predictors of embodiment, including media forms (e.g., screen size, field of view, image resolution), media content (e.g., thrillers, sci-fi), and individual differences (e.g., age, use experiences, knowledge) (Lombard & Ditton, 1997), the specific effects of tracking technologies, such as eye tracking, facial expression recognition, hand tracking, boundary space sensing, and body motion tracking, have been fragmentary and understudied, especially against the backdrop of the growing incorporation of these technologies in emerging VR devices (e.g., Meta Quest Pro, Apple Vision Pro).

Second, the interrelationships among the constructs underlying Kilteni et al.'s (2012) framework of SoE have not been sufficiently theorized. For example, Kilteni et al. (2012) acknowledged that it remains unclear whether breaking the sense of self-location would concomitantly undermine the sense of body ownership. Additionally, it is not clear whether body agency and body ownership can be dissociated from each other, as body actions in VR may already imply users' ownership of their bodies. Thus, the relationships among these constructs could be further examined.

Third, within the framework of SoE, it has been unclear whether the sense of self-location, sense of agency, and sense of body ownership can adequately capture all the embodiment experiences individuals can develop during VR use. As VR continues to improve existing body tracking features and further incorporate new ones, such as facial expression recognition and eye tracking, it is possible that new components of SoE could arise. Therefore, this study first seeks to revisit this framework of SoE and draws on users' subjective experience of VR's tracking technologies to unpack the relationships between body tracking and SoE. Through in-depth interviews, we aim to gather rich, lived insights into how individuals perceive their bodily experiences.

RQ1. How do body tracking technologies evoke users' different senses of embodiment in VR?

2.2. Body tracking and bodily experiences

Scholars have investigated a range of bodily experiences fostered by VR's tracking technology. For example, Hartbrich et al. (2023, pp. 270–278) asked participants to present six emotions in front of a virtual mirror. They found that face tracking and eye tracking contributed to users' sense of virtual face ownership. Head tracking caused users to experience more postural sway and stronger presence experience in VR (Wu et al., 2019). In a meta-analysis of the relationship between immersive technologies and presence, higher tracking levels, e.g., more natural motion tracking, served as one of the technology features that imposed a medium-sized effect on users' presence experience (Cummings & Bailenson, 2016). Similarly, Sanchez-Vives and Slater (2005) identified the extent of tracking as one of the factors that affect immersion.

Different combinations of body tracking technologies can create different morphologies in VR, such as body reductions, body distortions, and body extensions (Steptoe et al., 2013). One study on body reductions assigned participants to three conditions: a full-bodied avatar without hand or feet tracking, a full-bodied avatar with head and hand tracking, and a first-person avatar with floating head and hand movements using both head and hand tracking (Herrera et al., 2020). Researchers found that the first-person avatar with both head and hand tracking led to greater self-presence and interpersonal attraction than the other two conditions. Participants in the tracking conditions also rotated their hands and heads more frequently than those in the non-tracking condition (Herrera et al., 2020).

Body tracking may also foster the sense of body distortion. For example, Serino et al. (2016) found that after experiencing a virtual body with a skinny belly, participants perceived their real bodies as skinnier. The sense of body distortion may further lead users to develop empathy for those who have different physical status or cultural identities. Hershfield (2011) found that embodiment in aged avatars motivated users to make more future-oriented final decisions.

Body tracking technologies can further create the sense of body extensions. Steptoe et al. (2013) assigned tails to users' virtual human bodies and compared the effects between controlled tail movements and random tail movements. They found that participants who could control their tails via hip movements demonstrated greater body ownership and body agency than those whose tails moved randomly. This study underscored the importance of visuomotor synchrony by testing users' reactions to humanoid avatars with tails, which highlighted humans' adaptability to extended forms of virtual human bodies.

Overall, research has indicated that different combinations of tracking technologies may have their distinctive contributions to users' embodiment experience. Yet, how individuals evaluate and perceive the importance of each individual tracking feature remains to be explored. Thus, drawing on individuals' subjective experience, we propose the second research question.

RQ2. How do VR users evaluate the importance of individual body tracking technologies in their sense of embodiment?

2.3. Body tracking and networked privacy

In addition to SoE, this study further examines how body tracking technologies may evoke users' privacy concerns and consequently influence users' body privacy management. Past literature has witnessed important theory advancement regarding privacy management. Based on the definition of privacy as a dialectic and dynamic boundary regulation process (Altman, 1975), communication privacy management (CPM) theory assumes that individuals equate privacy to their personal possessions and have full control over their information flow (Child & Petronio, 2011). When users lose the control over their private information, they may experience privacy turbulence and thus feel the invasion of their privacy (Petronio & Child, 2020).

While CPM has been widely applied in interpersonal communication and online media contexts, such as blogging and social network services (e.g., Child et al., 2009; Waters & Ackerman, 2011; Zhang & Fu, 2020), Palen and Dourish (2003) advanced that privacy is not rule-based but context- and culture-driven. This perspective was further elaborated in Nissenbaum's (2004) framework of contextual integrity (CI), which holds that privacy intrusion is contingent upon social settings. Contexts that afford the social norms and information flow determine individuals' privacy regulation behavior (Nissenbaum, 2004). For example, Paik et al. (2022) found that people were uncomfortable with biometric technologies in grocery stores if they were used for targeted marketing purposes, but comfortable if they were used to thwart shoplifters.

Following the discussion about CI, Marwick and Boyd (2014) further proposed networked privacy to illustrate the challenges of privacy management in today's media landscape. They argued that individuals may no longer fully understand the social contexts when they disclose their personal information. The rapid flow of information from one context to another will likely violate individuals' privacy regulation in a networked society. As emerging technologies such as machine learning algorithms have parsed users' data along with others' data to make personalized recommendations, individuals may no longer understand or control how their data are collected and analyzed, just as Boyd (2012), "our interpreted selves aren't simply the product of our own actions and tastes; they're constructed by recognizing similar patterns across millions of people" (p. 349).

Considering that information will flow through the network and privacy can easily be violated when individuals are connected to other users' data, Marwick and Boyd (2014) indicated that privacy management and interpretation are dependent upon a constellation of factors, including social relationships, social norms, and technology affordances. As contexts collapse or destabilize, social norms and social relationships may fluctuate. They are co-constructed by all participants in the network and they shift frequently (Marwick & Boyd, 2014).

These networked privacy challenges exist in VR settings as well. Users may disclose their biometric data by allowing tracking technologies to capture their facial expressions or body movements. The biometric data become part of the network over which users no longer have control. As part of machine learning and computer vision training, users' data might be parsed along with others' data for more accurate recognition and better presence experience. Meanwhile, behavioral traces in VR spaces, including users' chats, gestures, and facial expressions could flow through the network and become vulnerable to institutional misuse. As was mentioned by Maloney et al. (2020, pp. 1–9), managing private information in social VR became inevitably a balancing act. Thus, to understand how users perceive and manage networked privacy in virtual worlds, we propose the following research question.

RQ3. How do users perceive the benefits of embodiment and the privacy risks in VR?

3. Method

3.1. Participants

A total of 32 participants were recruited from a large public university on the east coast of the U.S. to voluntarily participate in the study. Sixteen participants from different ethnicity groups were first recruited via flyers posted on campus announcement boards. Then each of them was asked to invite one friend to participate in the study together. The final sample included 16 dyads of participants from four different ethnicities: Black/African Americans, Caucasians/White, Asians, and Hispanic/Latinx. All participants received a $35 Amazon gift card as compensation. Among them, 10 were males and 21 were females. The other identified self as transgender. They were aged 18 to 24 ($M = 19.47$, $SD = 1.41$). Their VR use experiences were described in Table 1.

3.2. Settings and procedures

Two Meta Quest Pro headsets were provided for participants. The headsets are equipped with five infrared eye and face tracking sensors. The headset performs six degree-of-freedom tracking, including three spatial directions and three angles of orientation. The controllers are equipped with three camera sensors that allowed for 360-degree range of hand motion in virtual space. Meta Quest Pro uses its headset cameras to track hand movements and body movements. The headsets are also equipped with inward facing sensors that enable eye tracking, which analyzes images of users' eyes and captures the direction users look in within virtual environments. Regarding facial expression recognition, Meta Quest Pro also analyzes images of users' faces and captures users' facial movements.

The study was conducted in a lab space where two 25-inch computer monitors were placed on two adjoining desks (see Fig. 1). To allow researchers to observe participants' experience and give instructions, the monitors cast participants' real-time behavior in VR.

Each dyad entered the lab together and signed the consent forms. They first filled out online questionnaires that asked about their demographic information and prior VR use experiences. Then, they were instructed to wear the VR headsets and experience the virtual wall that differentiated the virtual space and the real space. This step was designed to make participants aware that their body locations were tracked. If participants were close to the boundaries, the virtual wall would appear.

Next, participants were asked to try two pre-downloaded applications: *First Steps* and *Horizon Worlds*. *First Steps* offered participants experiences of grabbing objects, flying paper planes, playing ping-pong, and dancing with a virtual agent. It was selected because the app involves hand tracking, head tracking, boundary space sensing, and body motion tracking. It is also an introductory app that familiarizes users with all the navigation features in VR spaces.

After *First Steps*, participants were instructed to use *Horizon Worlds*. Participants were first asked to walk to a virtual mirror and customize their avatars based on their preferences. After setting up their avatars, participants were asked to observe themselves in the virtual mirror and try different actions such as lifting arms, using facial expressions, and trying eye movements (e.g., blinking, winking). Then, the dyads were led to *Venues*, a virtual public space in *Horizon Worlds*. They were asked to look at each other and explore the activities they could do together, such as giving thumbs-up, sending confetti, and taking selfies. These activities were designed because 1) they allowed participants to be involved with a constellation of tracking technologies, such as facial expression recognition, body motion tracking, and eye tracking, and 2)

Table 1
Interviewees' demographics.

Participant #	Age	Gender	Ethnicity Groups	Academic Background	Prior VR Experience	VR Headsets Used
01	20	M	H/L	Computer Science & Math	Yes	MO, PS
02	19	M	H/L	English & Computer Science	Yes	MO, Public
03	21	F	H/L	Digital Arts	Yes	MO
04	21	F	H/L	Digital Arts	Yes	MQP, MO, Public
05	21	M	W	Media Production	Yes	MO, PS, GC
06	21	M	W	Mechanical Engineering	Yes	MO
07	21	F	H/L	Advertising & Music	No	/
08	21	F	H/L	Business Administration	Yes	MO
09	20	F	A	Advertising	Yes	MO
10	21	F	A	Psychology	Yes	Public
11	19	F	B/A	Biology	No	/
12	19	F	B/A	Psychology	Yes	Public
13	20	F	A	Economics & Geography	Yes	Public
14	19	F	A	Pre-Med	Yes	PS
15	20	F	W	Astrophysics & Geology	Yes	Public
16	20	M	W	Nuclear Engineering & Astronomy	Yes	MO, Public
17	21	F	W	Animal Science & Microbiology	Yes	Public
18	21	Other	W	International Relations	Yes	HTC
19	18	F	B/A	Family, Youth & Community	Yes	MQP
20	18	F	B/A	Accounting	Yes	Public
21	18	F	B/A	Health Sciences	Yes	MO
22	18	F	B/A	Computer Science	No	/
23	18	F	H/L	Psychology	No	/
24	18	F	H/L	Finance	No	/
25	18	M	W	English	Yes	Public
26	18	M	W	Engineering	No	/
27	20	F	A	Nursing	Yes	Public
28	20	M	A	Nutritional Sciences	Yes	MO
29	19	F	A	Psychology & French	Yes	Public
30	19	F	A	Data Science & Psychology	Yes	MO
31	18	M	B/A	Biochemistry	Yes	MO
32	18	M	B/A	Aerospace Engineering	Yes	Public

Note. F: Female. M: Male. A: Asian; B/A: Black/African American; H/L: Hispanic/Latinx; W: White/Caucasian. MQP: Meta Quest Pro. MO: Meta Oculus (e.g., Quest, Quest 2, Rift S). HTC: HTC VIVE. PS: Sony PlayStation VR/VR2. GC: Google Cardboard. Public: Used in public spaces but cannot recall the type.

Fig. 1. Lab settings.

they enabled participants to have social interactions with each other. Participants spent about 45–60 min on the two applications.

3.3. Interviews and focus groups

After the VR experience, participants were asked to take off their headsets and take a break. Then, two researchers began an in-depth semi-structured interview with the two participants. This study used experience-based interviews rather than lab-based experiments because it did not seek to understand the main effects of single body tracking technologies on users' psychological responses. Rather, it aims to understand individuals' subjective experiences in VR and probe how they reflect on their embodiment experiences and the roles of tracking technologies in fostering various dimensions of such experiences.

The interview questions asked about participants' 1) presence experience (e.g., describe your experience about feeling immersed/involved in the virtual environments), 2) sense of embodiment (e.g., how did you feel when you tried different facial expressions in front of the virtual mirror?), 3) their perceived importance of the tracking features (e.g., which tracking technology contributed the most to your overall experience and why?), and 4) perceptions of the relationship between tracking technologies and their privacy (e.g., if given the opportunity, which tracking technologies would you consider shutting off to protect your privacy and why?).

When interviewed about the attitudes toward the tracking technologies, participants were first asked to guess what tracking technologies were involved in their experience. Then, they were provided with a list of the body tracking technologies along with their definitions (i.e., head tracking, hand tracking, eye tracking, facial expression recognition, body motion tracking, boundary space sensing). Participants were asked to discuss with each other and reach consensus on the rankings for the importance of each tracking technology. Participants were also asked which tracking technologies they prefer to retain as part of their VR experience, which they would prefer to shut off, and what other tracking technologies they would like to see added in the future. The interview protocol and the definitions for different tracking technologies were provided in supplemental materials: https://osf.io/yjxdh/?view_only=767c47ccc40d4a83a895e3e9795dfcd2.

We purposefully asked each participant to invite a friend as their participation partner so that the two friends could maintain natural, spontaneous conversations. The two researchers asked interview questions to both participants during most sessions, except for the session in which participants were asked to rank the importance of the tracking technologies. During that session, participants were asked to discuss with each other and think aloud, allowing researchers to understand the factors the dyads took into consideration. In this situation, the two participants formed a mini focus group in which some issues and concerns the interviewers had not mentioned could be raised and discussed (Hesse-Biber & Leavy, 2010).

3.4. Data analyses

Textual analyses were used to understand participants' responses. We drew on Hesse-Biber and Leavy's (2010) four steps of data analyses: data preparation, data exploration, data reduction, and data interpretation. During data preparation, audio data were transcribed using Otter.ai. Two researchers manually checked the accuracy of the transcription and corrected errors. During this process, the researchers preserved participants' verbal styles by retaining filler words and interjections. The data were also uploaded to the software MAXQDA for coding purposes. For data exploration and reduction, the researchers first independently read all comments, assigned initial descriptive codes, and wrote memos. Next, the researchers compared codes and memos, clustering initial codes under different categories of analytical codes. Then, a tentative coding scheme consisting of these analytical codes and themes (e.g., "body detachment", "body alignment", "body ownership", "body extension", "desensitized to information collection") was produced. Following the coding scheme, the researchers revisited the data and coded them in a reflexive, inductive, and iterative way. The data and the themes were reviewed repeatedly until the themes of the data reached saturation (Charmaz, 2014; Yin, 2015). This approach was also supported by Reyes, Bogumil, and Welch (2024) living codebook approach which focuses on the dynamic process between coding and memo-writing. The inductive approach allowed the researchers to link data to existing theories, (e.g., SoE, networked privacy) and to understand how the data fit and challenge existing knowledge. Finally, based on these themes, data were interpreted and reported.

4. Findings

4.1. Sense of embodiment

To understand how body tracking technologies evoke different SoE (RQ1), we focused on participants' subjective bodily experiences. Our findings suggested that interviewees experienced five types of embodiment: body agency, body ownership, body location, body encounters, and body extension.

4.1.1. Sense of body agency

Sense of body agency refers to users' experience of actions (Kilteni et al., 2012). Most participants described how they experienced their virtual selves through various action possibilities facilitated by hand tracking and head tracking. For example, one participant mentioned her experience of hitting a ball in *First Steps*: "I felt like I was actually making a fist. […] I was actually punching the ball. And then when I tried to stop it and hold it, that felt so real to me" (P21). She also described how being able to grab and pick up virtual objects seemed natural and real:

> Like the ping-pong, I felt I was actually holding it because you see it visually at your hand. And then also your other hand just putting it, backing it up, and you just let it go. It's just like immediately it was real. (P21)

Another participant suggested that being able to look around using head tracking is what makes VR different from keyboard-based or mouse-based games:

> I think a big part of being immersed in the experience is being able to have a 360 view of it and be able to feel like you're in that place. Because if you only could keep your head one way, it really takes away from being in virtual reality without it, just like you're looking at a computer screen. (P29)

One participant also referenced the 360-degree view, suggesting that being able to look around in VR spaces felt more natural than playing a video game with only a flat view. The actions they were able to make in VR allowed them to feel their virtual bodies.

4.1.2. Sense of body ownership

Body ownership emerges as another type of embodiment when participants were exposed to VR's tracking technologies. Specifically, participants' experience implied that feeling aligned with or detached from their virtual bodies had an impact on their sense of body ownership.

A few participants reported that seeing avatars mimic their behaviors amplified their sense of body ownership. When asked to face the virtual mirror and try different gestures and facial expressions, one participant noticed that the avatar copied her cheek puffing. Another participant remarked, "When I was looking up, she [avatar] looked up" (P22). Both participants inferred that their avatars' behavioral alignment with their actions made them aware that the avatars belonged to them. The perceived alignment underlined the significance of feedback provided by body motion tracking, eye tracking, and facial expression recognition.

By contrast, some other participants suggested that detachment from the avatars in the virtual mirror undermined their sense of body ownership. One commented, "When you look into a mirror like when you're brushing teeth, you see yourself looking back. But in this game, it's not my face looking back" (P5). A few participants corroborated that their avatars' appearances were different from their own, which undermined their sense of body ownership:

> I think it was just because it looked very cartoony. […] The eyes, they all looked very animated. […] I know like the Bitmoji thing. It has a selfie feature, where if you just take a picture of yourself, we'll try to make it as accurate as possible. And I feel that's what it tried to do when we originally looked into the mirror. And I think it was not as accurate as I would expect. (P14)

Additionally, lack of full body tracking also compromised participants' body ownership experience. Some participants felt like a "ghost wandering" (P7) when they realized that their avatars did not have legs in *Venues*, "It made me feel like floating. I didn't feel I was walking around. It felt like half a body like a ghost almost" (P5).

4.1.3. Sense of body location, body encounters, and body extension

Sense of body locations appeared as the third type of embodiment experience. We found that the more participants noticed the space they were located, the more they became aware of their virtual bodies. One participant commented:

> I did find that the longer I was in the [virtual] world the more my body wanted to walk physically instead of using the joystick which I think is counterintuitive. […] The longer I was there, the more like, oh, let's just walk. (P23)

Another participant echoed these feelings and added that the more time she spent in VR, the more her brain became adapted to the VR.

We further found that encounters with other users or objects can also enhance participants' embodiment experience. Such encounters in VR spaces further led to their sense of body location or body agency. For instance, one participant mentioned that when she entered *Venues*, she felt like she was in a carnival with different pop-ups, images, and places, which made her realize that her virtual body was in the VR world. She further recalled her experience with facial expression recognition, "I think the person [in *Venues*] I was talking to, he made a joke and I was smiling. He's like, you're laughing, huh? Oh, it was so funny because I forgot that he could see me. […] I like that aspect" (P21).

Finally, as the fifth type of embodiment, a few participants described how they experienced their virtual bodies as extensions of themselves. One recalled that the virtual hand was an extension of his own hand because it moved realistically, and it was "around the same length" (P5). In this sense, VR's hand tracking enabled participants to experience virtual hands that were not replacements but augmentation of their real hands at a perceptual level.

4.2. Evaluation of the tracking technologies

To understand how users evaluate the importance of individual body tracking technologies in their embodiment experience (RQ2), participants were first asked to guess what tracking technologies were involved in their VR experience. Some participants mentioned eye tracking, body motion tracking, and facial recognition. Some others coined new terms, such as spatial tracking, hand coordination, and joint coordination.

Then each dyad was provided with a list of tracking technologies involved in their VR experience along with their definitions (available in supplemental materials: https://osf.io/yjxdh/?view_only=767c47ccc40d4a83a895e3e9795dfcd2). They were asked to discuss the importance of each technology based on their VR experience and achieve consensus on the rankings of the technologies. Results from 16 dyads suggested that overall, head tracking was perceived as the most important, followed by hand tracking and body motion tracking. Boundary space sensing, facial expression recognition, and eye tracking were deemed less essential in users' experience. Results of the rankings of each technology was shown in Fig. 2.

During each dyad's discussion, some participants explained why certain technologies were rated as more important than others. One mentioned that even if their bodies could not move, they still could look around, inferring that the 360-degree view (i.e., head tracking) was more essential than motion flexibility (i.e., body tracking). Two participants had the following conversation:

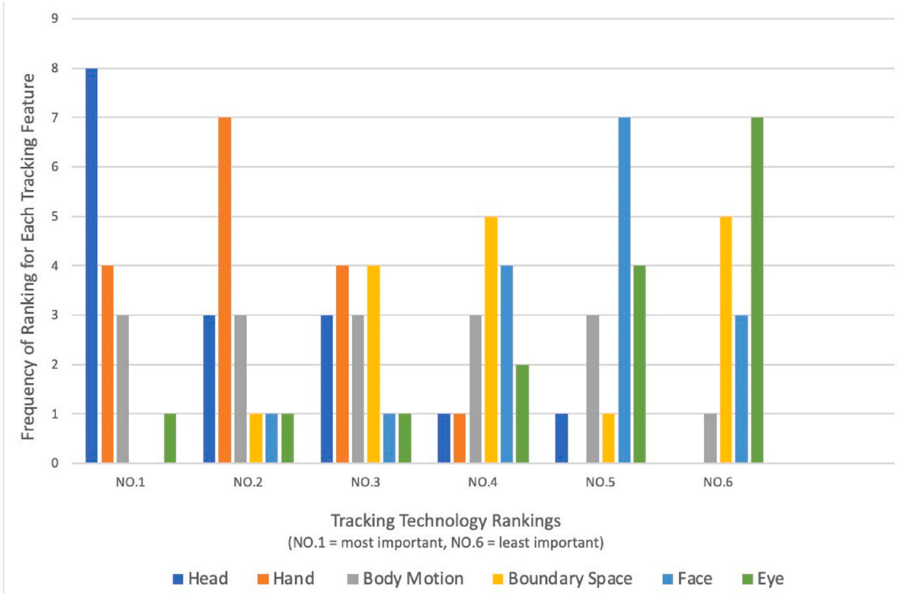

Fig. 2. Rankings of the tracking technologies by participants
Note. Each dyad ranked the importance of each tracking feature in their VR experience. Times for each technology placed in each rank were summed. For example, head tracking was ranked as the most important tracking technology in users' VR experience eight times.

> P4: I thought about voting for the motion because you can't really see your head.

> P3: I was gonna say that [motion] was the second one. […] I would say eye tracking and head tracking are the top two because that's what I used to ground myself and take into the world.

Another participant also endorsed the importance of head tracking: "If you only could keep your head one way, [it's] like you're looking at a computer screen" (P29).

Boundary space sensing was regarded as less important than hand tracking probably because participants were restricted in the lab space and their experience of trespassing the virtual boundaries was limited. One participant compared hand tracking and space sensing and indicated that grabbing was more immersive than just not hitting a virtual wall. The reasons why participants regarded facial expression recognition as less important in their VR experience were addressed below when they discussed privacy risks.

4.3. Managing the benefits and privacy concerns over tracking technologies

To understand how users perceived the benefit of embodiment and privacy risks associated with these tracking technologies in VR (RQ3), we focused on participants' perceptions of privacy after being explicitly informed about the tracking technologies involved in their VR experience. Overall, most participants did not feel excessive intrusion of privacy because of their limited concerns over the collection of biometric data, their desire for elevated use experience, and desensitization to data collection. Yet, participants questioned the potential exploit of their data in VR, especially facial information. They also imagined other technologies to be added to their future VR experiences, including those that provide more sensorimotor, olfactory, or tactile feedback.

4.3.1. Limited privacy intrusion

Most participants believed the information collected by tracking technologies was not sensitive enough to be alarming. One participant felt that he did not provide anything revealing:

> If it was anything serious, they would have done it already, like stealing money from your account or track your family down. […] what would eye tracking or facial recognition do? Clone me? I don't worry about that, honestly. (P3)

Participants' responses also implied that they did not consider biometric information as important as other personal information: "Unless it's really important information like my address or social security number. I genuinely don't care companies have my [body] information" (P23).

Beyond the perception that their biometric information was not sensitive, participants indicated that an enhanced VR experience would be worth some loss of privacy. One participant felt that tracking technology offered a more "accurate and genuine" VR experience (P19). Another participant remarked that privacy compromises were inevitable and should be accepted to the point where simply wearing the headset could be granted as user consent.

While participants expressed their willingness to exchange privacy for better experience, their responses manifested a sense of powerlessness and desensitization: "[Body tracking] doesn't bother me. So much information is already being recorded about us. I mean, what's one more" (P1)? Some participants echoed and commented that they were already used to eye tracking, geo-location tracking, and face detection because of the use of smartphones.

4.3.2. Deactivating facial expression recognition for privacy protection

All participants were asked which tracking technology they would deactivate to safeguard privacy if given a chance. A few participants mentioned their concerns over boundary space sensing or hand tracking, but most participants were inclined to shut off facial expression recognition, which they regarded as more intrusive than other tracking technologies. In particular, the potential institutional abuse of the facial data and the stress of maintaining social norms in VR spaces emerged as two driving reasons.

Participants questioned how technology companies would use their facial data without consent: "If they had a reverse software where they were looking for my face, [what] would they be able to do with the information" (P30)? Another participant remarked that some companies could use facial information to access personal laptops and other devices in the future.

Related to the abusive use of facial data, some participants were concerned that technology companies may use their body information to create digital clones without their consent. One participant remarked, "I don't really know how it tracks, but if they can get an image of my eye or an image of my face, that would show identity" (P18). Similarly, another participant imagined the potential improper exploit of his facial data:

> They would be able to run an AI on [facial information] and read people's emotions so easily. [...] They could know, if you've had a bad day, if you had a good day. [...] It could start knowing what you like, what you don't like, what you're interested in, what you're passionate about, just because you're smiling more at some stuff. (P6)

Finally, several participants preferred to deactivate facial expression recognition, as it was mentally onerous to conform to the social norms in VR: "Because you have to keep up this whole etiquette of not looking annoyed, or not laughing too obnoxiously" (P28). Likewise, participants were afraid of offending others if they had to show their facial expressions: "My face will say something before my mouth does. If they see my face like 'I'm not interested,' they will get offended" (P22). Several other participants shared similar sentiments. They felt embarrassed when other users at *Venues* told them that they were smiling. In these cases, participants desired control over what others can find about them in VR settings.

4.3.3. *Tracking technologies to add for better experience*

Participants were further asked what novel technologies they wished to have in their future experience of virtual selves. Overall, participants anticipated tracking technologies that provide more sensorimotor, olfactory, haptic, and thermoreceptive feedback. For example, they preferred a greater level of body agency, such as being able to walk freely in VR without using controllers: "If you want to walk up to somebody and meet them, you can actually physically walk there" (P29). Related to free motion, participants also liked the possibility of having their legs tracked, which would augment their sense of body ownership.

Apart from more sensorimotor feedback, participants showed interest in more diverse haptic feedback via controllers or wearable devices like gloves. Participants brought up the potential of feeling pain or hugs, which they believe could improve their experience of virtual bodies in VR. Additionally, participants mentioned the possibility of feeling wind, temperature, and smells during VR use. Notably, a couple of participants wished their virtual selves could stick their tongues out, implying they were hoping for more accurate facial expression recognition in future VR experience.

5. Discussion

This study investigates how body tracking technologies can forge individuals' VR experience through SoE and how individuals weigh perceived privacy risks against the sensory stimuli provided by these tracking technologies. Our findings suggest that participants reported a range of bodily experiences afforded by tracking technology, including body agency, body ownership, body location, body encounters, and body extension. Additionally, participants regarded head tracking and hand tracking as important contributors to their sensations in VR, while facial expression recognition and eye tracking were perceived as less necessary. Even though participants' privacy concerns over body tracking were generally limited, they preferred to deactivate facial expression recognition due to the potential institutional misuse and the stress of complying with social norms in VR settings.

5.1. *Sense of embodiment*

This study first discovered that via body tracking features, participants reported five types of embodiment experience. Specifically, sense of body agency refers to users' subjective experience of actions (Kilteni et al., 2012). It was through action possibilities that participants became aware of their virtual bodies. This theme is aligned with the theory of embodied cognition, which suggests that individuals' mind must be understood in relation to their bodies and the interactions between their bodies and the environment (Wilson, 2002).

Body ownership refers to individuals' feeling that the virtual bodies belong to themselves. This theme is consistent with Döllinger et al.'s (2022) finding that body ownership is positively related to one's body awareness. In our study, body ownership was primarily reflected in individuals' feeling that their avatars acted in concert with, or at odds with, their actual movements, which indicated that real-time tracking and detection of users' characteristics, including facial expressions, body motion, and eye blinks were essential in leading to SoE. It also demonstrates that sense of body ownership may be closely connected to body agency. Lack of certain tracking features compromised users' body ownership and impaired users' experience of virtual selves (e.g., users' "ghost wandering" and "floating" experiences due to lack of leg tracking).

Apart from body agency and ownership, body location, body encounters, and body extension emerged as three embodiment experiences that were previously understudied. Specifically, sense of body location was related to but different from Kilteni et al.'s (2012) sense of self-location. Sense of self-location was referred to as a feeling of being inside an avatar's body (Kilteni et al., 2012). However, we found that some participants experienced their virtual selves through being aware of the space where they were immersed. With the help of head tracking, the more participants felt immersed in a virtual environment, the more they wanted to try different action possibilities, which heightened their sense of body agency and consequently their self-presence experience.

Individuals' encounters with other users in VR also reinforced their experience of virtual selves. For instance, some participants did not realize that their facial expressions and eye movements were presented by their avatars until pointed out by other users. Some also noticed the social distance that other users kept from their avatars. This is in line with Cooley's (1964) concept of looking-glass self, which indicates that humans understand themselves through interactions with others. Social spaces in VR enables users to reflect on their virtual bodies through observing other avatars' verbal and non-verbal reactions.

Finally, feeling extensions of participants' own physical bodies in VR is another important addition to the framework of SoE. It should be noticed that the sense of body extension does not necessarily mean body ownership. Rather, it denotes that individuals treat their virtual bodies as virtual tools they could act upon. Research on homuncular flexibility has corroborated that humans use technological artifacts such as virtual tails and virtual legs to extend their perceptual and sensorimotor functions (Haans & IJsselsteijn, 2012). Riva and Mantovani (2012) also proposed the concept of second-order mediated action and suggested that during VR interactions, individuals can use a proximal tool (e.g., controllers, joysticks) to control a distant tool (e.g., virtual hands, virtual rackets) in the virtual space and hence exert influence upon virtual objects (e.g., grabbing balls, playing tennis). Thus, despite the similarities between body ownership and body extension, a distinction should be made here that body extension is more related to users' perception of their virtual bodies as supplements to rather than replacements of their physical bodies in VR.

5.1.1. *Theory contribution to embodiment*

Two theory contributions can be discussed here based on the five types of SoE fostered by VR's tracking technologies. First, compared to the original framework of SoE (Kilteni et al., 2012), this study not only validated the roles of body agency and body ownership but also expanded users' embodiment experiences to sense of body location, body encounters, and body extension. These three new dimensions suggest that VR users experience themselves through interacting with their surroundings, socializing in virtual spaces, and treating their virtual bodies as tools in virtual environments. Along with body agency and ownership, all five types of bodily experiences reflect multi-layered embodiment experiences afforded by tracking technologies and constitute a strong explanatory component underlying individuals' self-presence experience.

Second, distinct from the previous framework that left the relationships among body agency, body ownership, and self-location undefined (Kilteni et al., 2012), through the investigation into the effects of tracking technologies, our findings partially illustrated the relationships among these different constructs. For example, based on interviewees' responses, body agency could evoke body ownership, as users' action possibilities can help them understand the morphology of their virtual bodies. Body ownership may also reinforce body agency via users' conscious control over their virtual bodies. Furthermore, combining participants' experiences and lens of looking glass, encounters with other users may lead to a greater sense of body ownership, as participants may realize their own facial expressions and eye movements via interactions with others. Such encounters with others may also evoke the sense of body location through the observation of the social etiquettes (e.g., social distance) in VR. Additionally, sense of body location can intensify users' sense of body agency, as our findings suggest that adapting to and feeling immersed in virtual spaces can motivate users to explore various action possibilities in VR. Overall, although participants' interview responses only implied some of the relationships among these embodiment experiences, these diverse senses of embodiment reflect how body tracking technologies can create complicated and interwoven bodily experiences in VR spaces. They mutually trigger each other and co-construct users' experience of their virtual selves in VR. Based on the qualitative findings, future research may accumulate additional empirical evidence to validate these different types of embodiment experiences and more systematically theorize the relationships among these experiences, as these relationships may help elucidate the psychological mechanism of individuals' self-presence experience. Fig. 3 presents the five embodiment experiences, the interrelationships among them, and their overall relationships with tracking technologies.

5.2. Balancing tracking technologies and networked privacy

Although tracking technologies facilitate different SoE in VR, it does not necessarily mean that users desire a full SoE at the cost of their body privacy. Based on participants' ranking of the contribution of individual tracking technologies to their experience, head tracking and hand tracking were generally perceived as more crucial than other technologies such as body motion tracking, facial expression recognition, and eye tracking, meaning that overall, inhabiting in a 360-degree immersive virtual space and using gestures for VR interactions were more important than being able to move around or present facial expressions. This also reflects that the visuomotor and visuospatial feedback provided by tracking technologies carried more weight in users' experience than other sensory feedback. However, it should be noted that the current study only factored in head tracking, hand tracking, body motion tracking, facial expression recognition, eye tracking, and boundary space sensing. Future research may include tracking technologies that could potentially redefine morphology (Murray & Sixsmith, 1999).

The reasons participants listed facial expression recognition as less necessary than other tracking features were addressed when participants expressed their privacy concerns. Most participants preferred to deactivate facial expression recognition because they had concerns over the institutional abuse of their personal data and the social norms they had to conform to in VR. For instance, participants were reluctant to show their faces because they did not want their faces to expose their emotions, thoughts, or reactions. This finding indicates that even in VR spaces, participants were still mindful of the facework they should manage. Consistent with Goffman's (1967) conceptualization of face as the positive social value, participants might have felt the pressure of managing their facework even when they were embodied in avatars that did not necessarily resemble their own appearances. Here, participants resisted showing facial expressions probably because, despite the anonymous avatars in which they were embodied, their avatars' facial reactions represented participants' authentic non-verbal behavior that could not be easily camouflaged in VR. Hence, disabling facial expression recognition became a shortcut to circumvent the social pressure and to hide their reactions in VR spaces.

Our findings also suggested that participants were afraid that technology institutions could use their facial information to create deepfakes or use their facial data as part of the machine learning procedures to understand people's emotions. The findings corroborated prior literature on individuals' discomfort with facial expression recognition when it was used to build individual profiles (Paik et al., 2022). They also

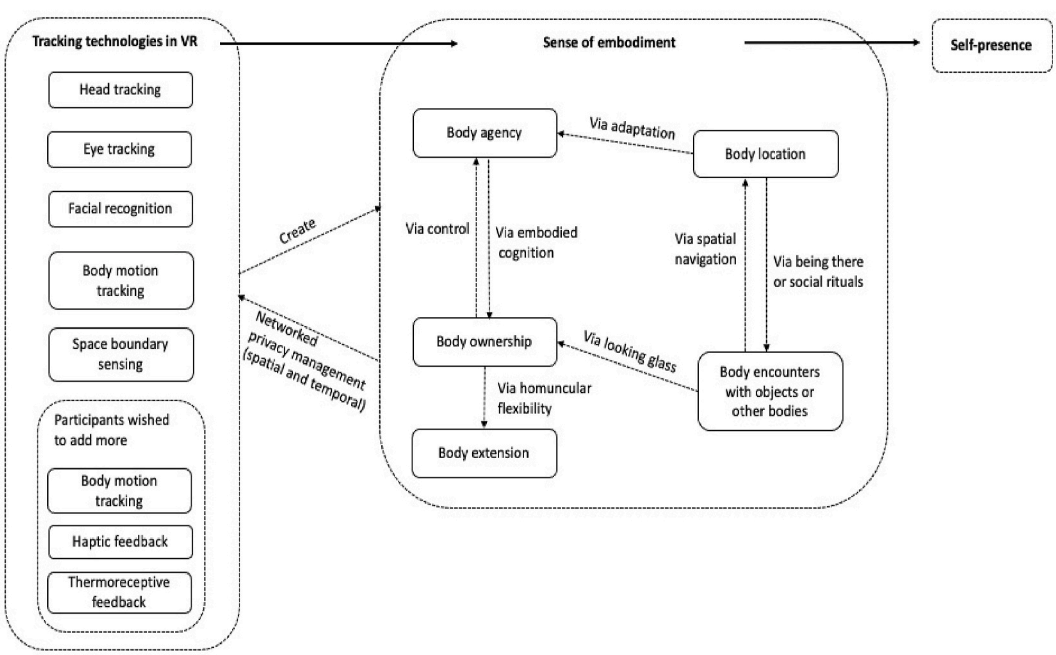

Fig. 3. Relationships among tracking technologies, sense of embodiment, and self-presence.

resonate with the assumption of networked privacy that individuals might no longer fully understand the social context and track the flow of their private information (Marwick & Boyd, 2014). Rather, their privacy becomes part of a network featuring all users' data for algorithmic training and recommendation purposes.

5.2.1. Theory contribution to networked privacy

The findings can contribute to the theorization of networked privacy, as they implied that users generally rely on two dimensions to consider privacy risks. The first dimension highlights the significance of spatiality when users realize the risks of disclosing their attitudes and emotions through untended facial expressions or eye gaze in VR. Such possibilities lead users to navigate the affordances of virtual spaces in order to manage their facework and self-presentation to avoid the disclosure of their bodily information.

The second dimension highlights the importance of temporality, which stresses how users base their sense of insecurity on past privacy intrusion instances (e.g., smartphones' facial recognition) and the likely improper use of their biometric data in the future (e.g., algorithmic recommendations). This dimension has also been elaborated in Palen and Dourish's (2003) research, where they argued that individuals orient not only to immediate circumstances, but also to future privacy intrusion situations. Both the spatiality and temporality dimensions can lay the foundation for users' networked privacy interpretation when they are exposed to body tracking technologies (see Fig. 3 for the role of privacy in the relationship between tracking and embodiment). Future work could revolve around these two dimensions to advance the theory construction of networked privacy, especially given that VR environments can situate users within various spatial and temporal contexts.

Whereas individuals were conservative about the use of facial recognition, it should be noted that overall participants' privacy concerns were limited, which is consistent with the past finding that individuals did not feel much discomfort when using wearable tracking technologies (Zimmer et al., 2020). Participants in our study were willing to sacrifice their privacy in return for enhanced experience. Meanwhile, they felt desensitized to massive privacy collection by technology institutions. What merits note is that participants considered their biometric data, including facial expressions and eye movements, as less important than other personal information, such as addresses or social security numbers. However, these interpretations could be risky, as biometric information can indeed carry even more personal information than addresses or social security numbers, possibly leading to disclosure of physiological data and behavioral data, such as medical, travel, and health records (Lin et al., 2022; Prabhakar et al., 2003). Moreover, a recent study has suggested that AI systems can identify 95 % of users correctly based on less than 5 min of their personal body tracking data (Miller et al., 2020). All these findings confirmed the challenges of managing networked privacy in that individuals may not have sufficient AI literacy to fully understand how body tracking technologies collect and utilize biometrics and motion data.

5.3. Practical implications

The findings in our study can present some practical and managerial implications. For example, head tracking and hand tracking were ranked by participants as more important contributors compared to other features such as eye tracking and facial expression recognition, which implies that when empowering users to have a positive embodiment experience in VR spaces, head tracking and hand tracking could be prioritized among various other tracking technologies. Furthermore, to allow for a range of different embodiment experiences, in addition to body agency and body ownership (Kilteni et al., 2012), developers may consider elevating social experiences in VR and creating more immersive spaces to enrich individuals' embodiment experiences, as our findings suggest that encounters with users and virtual objects per se could augment such experiences.

Moreover, understanding the different dimensions of embodiment has implications for health and clinical research. Studies indicate that individuals with depersonalization-derealization disorder experience a sense of detachment from their body, self, and external world (Tanaka, 2018). Understanding embodiment experiences in VR may provide insights into the underlying mechanisms of this dissociative disorder and offer strategies to use emerging technologies to help these individuals reintegrate with their physical self.

Finally, as tracking data may disclose personal identity (Miller et al., 2020), developers or marketers should inform users of the potential privacy threats when providing users with different options for body tracking. This practice may not only enhance the transparency of various tracking technologies used in VR devices but also offer users the opportunities to balance the benefits and costs of using these technologies.

6. Conclusions and limitations

Overall, body tracking technologies, built with computer vision and machine learning techniques, can fulfill users' sensory needs for embodiment in VR. Yet, a paradox may exist between users' desire for smooth, intuitive, and realistic sensory experience of their virtual selves and their concerns over disclosing sensitive bodily information via unexpected biometrics tracking. Given the potential trade-off between individuals' embodiment experience and their perceived privacy risks, this study profiles how individuals interpret and reflect on the double-edged impact of body tracking technologies and adds new theoretical dimensions to both the SoE and the networked privacy frameworks.

This study has some limitations. First, as participants in this study only experienced two Meta-based apps in the lab space, their responses might have been based on their limited VR interactions in a restricted setting. Future studies can include participants with extensive VR experiences to more systematically understand their attitudes toward tracking technologies. Second, in our study, participants experienced embodiment via the tracking technologies as a whole. Future research may draw on lab experiments to empirically investigate the discrete effect of each tracking technology and aim to elucidate the granular linkage between different types of tracking features and individuals' embodiment experiences. Finally, the interviewees in this study were college students recruited from a large public university. Given their identities and their limited age range, future research could include VR users with more diverse cultural, economic, and social backgrounds. For instance, age differences, or even generational differences may be considered, as prior research has shown that older adults tend to experience greater difficulties with emerging devices and demand more cognitive effort to learn to use headsets and controllers (Bohdanowicz et al., 2020). These factors can provide deeper understanding of how users navigate the promises and perils of VR tracking technologies.

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CRediT authorship contribution statement

Kun Xu: Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Yunxiao Chen:** Writing – review & editing, Methodology, Formal analysis. **Jiayue Li:** Writing – review & editing, Methodology, Investigation, Formal analysis. **Tony Liao:** Writing – review & editing, Conceptualization. **Sylvia Chan-Olmsted:** Writing – review & editing, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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