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A Preliminary Embodiment Short Questionnaire

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Consumer virtual reality (VR) technologies have made embodying a virtual avatar during an immersive experience more feasible. The sense of embodiment toward that virtual avatar can be characterized and measured along three factors: self-location, agency, and body ownership. Some measures of embodiment have been previously proposed, but most have not been validated or do not measure the three individual factors of embodiment. In this paper, we present the construction and validation of a preliminary version of a short questionnaire that not only addresses these factors of embodiment but can also be used as an in-VR questionnaire, which we call the pESQ. By using and validating the pESQ, we provide results indicating that foot tracking significantly improves self-location and agency, and that an avatar significantly improves body ownership.

Keywords: embodiment, self-location, agency, body ownership, questionnaire, virtual reality

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INTRODUCTION

The prevalence of virtual reality (VR) becomes more apparent every year, as more consumer technologies become available and more academic research is published. One notable advancement in recent years is the increased feasibility of enabling the user to embody a full-body avatar through additional sensors, such as HTC Vive trackers, and consumer inverse kinematic (IK) solutions, such as the Final IK library by RootMotion. This advancement has naturally led to an increase in embodiment research.

Embodiment is the sense that emerges when the properties of a virtual body are processed as if they were the properties of one's own physical body (Kilteni et al., 2012a). Kilteni et al. (2012a) identified three structures underlying one's sense of embodiment: self-location, agency, and body ownership. *Self-location* is the localization of oneself within the spatial boundaries of a body representation (Arzy et al., 2006). *Agency* is the intention and execution of actions that includes the feelings of controlling one's own body movements, and through those actions, the events in the external environment (Tsakiris et al., 2006). *Body ownership* is the sense that one's own body is the source of any sensations felt (Tsakiris et al., 2006). Altogether, these three sensations contribute to one's overall sense of embodiment (Kilteni et al., 2012a).

Because embodiment is considered a personal experience or feeling, subjective self-report measures are a common method for capturing one's sense of embodiment. Most prior research studies have employed their own questionnaires to measure embodiment or one of its subfactors, such as body ownership (Gonzalez-Franco and Peck, 2018). There have been a few attempts toward establishing a standard embodiment questionnaire. Dobricki and de la Rosa (2013) published a 27-item questionnaire focused on self-identification, agency, and spatial presence—i.e., the cognitive feeling of being in a place (Skarbez et al., 2017)—which they validated using a third-person perspective, visuotactile experiment. Gonzalez-Franco and Peck (2018) published a

25-item questionnaire based on a review of more than 30 embodiment studies that focused on self-location, agency, body ownership, tactile sensations, external appearance, and response to external stimuli. Initially, Gonzalez-Franco and Peck (2018) did not empirically validate their questionnaire. However, during the review of this article, Peck and Gonzalez-Franco (2021) published a validated 16-item version of their questionnaire based on data collected from nine experiments and over 400 questionnaires. Also recently, Roth and Latoschik (2020) have presented the Virtual Embodiment Questionnaire (VEQ), which is a 12-item questionnaire focused on agency, body ownership, and change in the perceived body schema. Roth and Latoschik (2020) validated their VEQ through four studies that investigated the effects of immersion, personalization, tracking fidelity, and tracking latency. While the VEQ does address agency and body ownership, Roth and Latoschik (2020) acknowledge that it does not address the sense of self-location. Furthermore, they acknowledge that agency and body ownership are strongly correlated, while their new change dimension varies independently of the two traditional embodiment substructures.

The goal of this research was to construct and validate a sense of embodiment questionnaire that addresses self-location, agency, and body ownership. In addition to addressing all three factors of embodiment, we aimed to develop a short questionnaire that could be reasonably administered within VR at the end of an experience, as opposed to through a web form or paper version outside of VR. Alexandrovsky et al. (2020) have recently compared administering questionnaires in VR to outside VR in the physical world and found comparable questionnaire results. More interestingly, they also found that the majority of their participants enjoyed the in-VR questionnaires more and preferred them to the out-of-VR questionnaires. Furthermore, as "in the wild" VR studies become more prevalent, in which data is collected from VR devices owned by consumers in uncontrolled settings (Steed et al., 2016), it will become more important that any questionnaires, such as embodiment, can be easily administered in VR.

In this paper, we present the construction and validation of a preliminary embodiment short questionnaire (pESQ), based on data from two recently published studies focused on the effects of IK solutions on embodiment as a whole (Eubanks et al., 2020). The 10-item embodiment questionnaire used in these IK studies, which served as the initial pool of questions for the construction of the pESQ, consisted of three self-location, three agency, and four body ownership questions. Using exploratory factor analysis methods on the results of the first IK embodiment study, we discovered major reliability and validity issues with three of the four body ownership questions, which have all been previously used and recommended (Gonzalez-Franco and Peck, 2018). Interestingly, the results of another recent study echoes these reliability issues (Peck and Tutar, 2020). Ultimately, we were able to derive and validate a preliminary five-item embodiment questionnaire that address all three factors of embodiment (i.e., two self-location items, two agency items, and the sole remaining body ownership item). Using this pESQ, we have found new results from the previously published IK studies, which indicate that foot tracking significantly improves self-location and agency while the presentation of an avatar significantly improves body ownership. We conclude with discussions of these new findings, the problems with prior body ownership questions, and our plans for constructing and validating a final embodiment short questionnaire (ESQ) to be administered in VR for future "in the wild" VR studies.

RELATED WORK

In this section, we first discuss prior attempts to establish a standard embodiment questionnaire and the details of those efforts. We then provide an overview of prior embodiment studies and what factors have been previously investigated.

Prior Embodiment Questionnaires

Dobricki and de la Rosa (2013) published the first attempt to construct and validate an embodiment questionnaire. Their 27-item questionnaire addressed three factors: self-identification, agency, and spatial presence. Their self-identification factor combined the concepts of self-location and body ownership into a single factor, based on the classifications later presented by Gonzalez-Franco and Peck (2018). The spatial presence factor of their questionnaire, which addresses the feeling of "being there" (Skarbez et al., 2017), is generally considered to be independent of the sense of embodiment (Kilteni et al., 2012a; Gonzalez-Franco and Peck, 2018; Roth and Latoschik, 2020). The questionnaire also includes several items that assume the VR experience involves an incongruent avatar (i.e., a virtual body presented from a third-person perspective), which was the scenario employed in the two studies that Dobricki and de la Rosa (2013) used to construct and validate their questionnaire. These questions limit the general applicability of the overall questionnaire, especially since Maselli and Slater (2013) have identified first-person perspectives a necessary condition for the full-body ownership illusion.

Gonzalez-Franco and Peck (2018) reviewed over 30 embodiment studies that used questionnaires since 1998, when the first rubber hand illusion experiment was published by Botvinick and Cohen (1998). Through their review, they identified six main categories of questions that had been previously used: body ownership, agency and motor control, tactile sensations, location of the body (i.e., self-location), external appearance, and response to external stimuli. For each of these categories, Gonzalez-Franco and Peck (2018) selected a set of questions that was most often used in prior studies. This review-based approach yielded a 25-item questionnaire, which Gonzalez-Franco and Peck (2018) proposed as a possible standardized embodiment questionnaire. Originally, Gonzalez-Franco and Peck (2018) did not empirically validate their questionnaire. However, during the review of this paper, Peck and Gonzalez-Franco (2021) published a validated 16-item version of their questionnaire based on data collected from nine different experiments, with over 400 questionnaires. Their final questionnaire addresses 4 dimensions of embodiment: (external) appearance, response (i.e., motor control and agency), (body) ownership, and multi-sensory (location and tactile perception). Due to the timing of their publication, the validated Embodiment

Questionnaire of Peck and Gonzalez-Franco (2021) was not available to us when we conducted our current research.

Most recently, Roth and Latoschik (2020) have presented the construction and validation of the Virtual Embodiment Questionnaire (VEQ). The VEQ is a 12-item questionnaire that addresses agency, body ownership, and changes in the body schema (e.g., skin tone, height, weight). Roth and Latoschik (2020) used four studies to validate their VEQ, which controlled for the level of immersion—i.e., visual display fidelity (McMahan et al., 2012), user-performed personalization of the virtual body, the behavioral realism of the virtual body's movements, and the effects of tracking latency and jitter. It is important to note that while the VEQ does address agency and body ownership, it does not address the sense of self-location and being within the spatial boundaries of the virtual body. Due to how recent the publication of Roth and Latoschik (2020) became available, we were not aware of their VEQ when we started our current research.

In contrast to the prior efforts, our current work focuses on creating a short embodiment questionnaire that can be reasonably administered as an in-VR questionnaire, especially for "in the wild" VR studies (Steed et al., 2016) and addresses all three underlying factors (i.e., self-location, agency, and body ownership).

Evaluations of Embodiment Factors

To better understand the embodiment factors (i.e., self-location, agency, body ownership) and what they are affected by, we reviewed the prior embodiment studies identified by Gonzalez-Franco and Peck (2018) and newer studies that have since been published. We have identified six categories of experimental conditions that researchers have used to investigate one or more aspects of embodiment, including perspective, visuotactile, threat, visuomotor, avatar fidelity, and tracking fidelity. **Table 1** provides an overview of these studies and which experimental conditions and embodiment factors were investigated.

Numerous studies have employed or investigated the effects of visuotactile stimuli (i.e., receiving tactile sensations while viewing the virtual body being touched). Synchronous visuotactile sensations have been shown to significantly improve self-location (Ehrsson, 2007; Pomes and Slater, 2013), agency (Dobricki and de la Rosa, 2013; Maselli et al., 2016), and body ownership (Petkova and Ehrsson, 2008; Slater et al., 2010; Petkova et al., 2011). Closely related to visuotactile stimuli are external threats perceived to possibly cause harm to the virtual body. Researchers have investigated a wide range of threats, including moving objects (Kokkinara and Slater, 2014), fire (Lugrin et al., 2015), and even knives (González-Franco et al., 2014). Prior research indicates that a greater sense of body ownership leads to greater responses to threats (Pomes and Slater, 2013).

Several studies have investigated the effects of the user's perspective of the virtual body on the embodiment factors. Third-person perspectives have been found to significantly reduce self-location (Maselli and Slater, 2014; Kokkinara et al., 2016), agency (Falconer et al., 2014; Maselli and Slater, 2014; Kokkinara et al., 2016), and body ownership (Petkova and Ehrsson, 2008; Slater et al., 2010; Petkova et al., 2011). Recently, Fribourg et al. (2020) have also found that users consistently prefer first-person perspectives over third-person perspectives. Similarly, numerous studies have used visuomotor synchrony, in which the user's movements control the movements of the virtual body, to investigate embodiment, including self-location (Piryankova et al., 2014; Padrao et al., 2016; Peck and Tutar, 2020), agency (Banakou and Slater, 2014; Osimo et al., 2015; Latoschik et al., 2016), and body ownership (Kilteni et al., 2012b; Bourdin et al., 2017).

A number of studies have investigated the effects of avatar fidelity, including embodying symbolic avatars (Lugrin et al., 2015), non-human avatars like mannequins and robots (Roth et al., 2017), personalized human avatars (Waltemate et al., 2018), human avatars differing form the user in terms of race (Peck et al., 2013) or gender (Kilteni et al., 2013), or not embodying an avatar at all (Peck and Tutar, 2020). Embodying some type of avatar has been demonstrated to significantly improve self-location and body ownership (Peck and Tutar, 2020). However, the effects of the avatar's appearance seems to be influenced by the uncanny valley phenomenon (Mori et al., 2012). In some studies, moderate-fidelity avatars have led to greater reports of body ownership than "higher" fidelity version (Lugrin et al., 2015; Jo et al., 2017). On the other hand, personalized avatars based on scans of the individual users have been shown to significantly increase body ownership (Waltemate et al., 2018).

Recently, a number of studies have also investigated the influence of tracking fidelity on embodiment. Tracking fidelity issues, such as latency and tracking noise, have been found to significantly decrease agency (Jeunet et al., 2018; Koilias et al., 2019; Roth and Latoschik, 2020), body ownership (Roth and Latoschik, 2020), and embodiment in general (Toothman and Neff, 2019). Outside of tracking latency and errors, Roth et al. (2016) compared a 5-point (head and extremities) IK tracking solution to a full-body motion capture system, but found no significant differences between the two tracking fidelity conditions in terms of agency and body ownership. Recently, Fribourg et al. (2020) found that users significantly preferred full-body motion capture to a six-point (pelvis included) IK tracking solution, but they did not directly measure self-location, agency, or body ownership.

The work presented in this paper is based on recently published research, in which we investigated the effects of avatar fidelity and three levels of tracking fidelity for controlling the movements of an IK-based avatar with visuomotor synchrony (Eubanks et al., 2020). In this recent work, we focused on the effects of avatar fidelity and tracking fidelity on the sense of embodiment as a whole. In the current work, we present an exploratory factor analysis of the same data, in an attempt to construct and validate a preliminary embodiment short questionnaire that individually measures all three embodiment factors: self-location, agency, and body ownership.

EMBODIMENT STUDIES

In order to pursue our goal of constructing and validating an embodiment short questionnaire that addresses self-location,

TABLE 1 | Comparison of experimental conditions and embodiment factors in related work.

References	Experiment						Factors		
	Visuotactile	Threat	Perspective	Visuomotor	Avatar Fidelity	Tracking Fidelity	Self-Location	Agency	Body Ownership
Latoschik et al. (2016)				X	X			X	
Normand et al. (2011), Heydrich et al. (2013)	X								X
González-Franco et al. (2014)		X							X
Petkova and Ehrsson (2008), Slater et al. (2010), Petkova et al. (2011)	X	X	X						X
Kilteni et al. (2012b)	X			X					X
Bourdin et al. (2017)	X	X	X	X					X
van der Hoort et al. (2011)	X				X				X
Kilteni et al. (2013), Jo et al. (2017)				X	X				X
Botvinick and Cohen (1998), IJsselsteijn et al. (2006), Lenggenhager et al. (2007), Slater et al. (2008), Lopez et al. (2010)	X						X		X
Ehrsson (2007), Pomes and Slater (2013)	X	X					X		X
Banakou and Slater (2014), Osimo et al. (2015)				X				X	X
Falconer et al. (2014)			X	X				X	X
González-Franco et al. (2010)		X		X				X	X
Peck et al. (2013), Steptoe et al. (2013), Banakou et al. (2016), Latoschik et al. (2017), Roth et al. (2017), Waltemate et al. (2018)				X	X			X	X
Maselli et al. (2016)	X			X	X			X	X
Argelaguet et al. (2016)		X		X	X			X	X
Roth et al. (2016)				X		X		X	X
Roth and Latoschik (2019)				X	X	X		X	X
Dobricki and de la Rosa (2013)	X						X	X	X
Maselli and Slater (2014)	X		X				X	X	X
Piryankova et al. (2014), Padrao et al. (2016), Peck and Tutar (2020)				X			X	X	X
Kokkinara et al. (2016)			X	X			X	X	X
Satyavolu et al. (2014)	X			X			X	X	X
Kokkinara and Slater (2014), Kondo et al. (2018)	X	X		X			X	X	X
Lugrin et al. (2015)		X		X	X		X	X	X
Toothman and Neff (2019)				X		X	X	X	X
Fribourg et al. (2020)			X	X	X	X	X	X	X
Eubanks et al. (2020)				X	X	X	X	X	X

agency, and body ownership, we set out to conduct an exploratory factor analysis and validation on the questionnaire data from two recently published studies (Eubanks et al., 2020). Specifically, we planned to conduct the exploratory factor analysis on the data from the first study and then use the results from both studies to validate the questionnaire. In this section, we briefly describe the experimental design of our two embodiment studies, including the materials, experimental conditions, embodiment activities, procedure, and participants. For further information regarding the studies and our original interpretation of their results, we recommend reading the recent publication in full detail (Eubanks et al., 2020).

Materials

For both studies, we used an HTC Vive Pro system consisting of the head-mounted display (HMD), two handheld controllers, and three additional Vive trackers to run our VR application. The Vive Pro HMD provided a 110° diagonal field of view with a display resolution of 1,440 × 1,600 pixels per eye and a 90 Hz refresh rate. The additional trackers were attached to the participants using straps at the arch of each foot and at the waist. The application was developed using Unity, and a framerate of 90 frames per second (fps) was maintained throughout the conditions to match the HMD refresh rate. The SteamVR plugin for Unity was used to process the Vive input data, and the RootMotion Final IK library was used to implement the full-body IK avatar.

Experimental Conditions

In both studies, we investigated the effects of avatar fidelity and tracking fidelity within subject. Across the studies, we investigated a total of four experimental conditions: No-Avatar, Complete, Head-and-Extremities, and Head-and-Hands. To avoid lengthy procedures and possibly introducing fatigue as a confounding variable, we only investigated three of our four experimental conditions in each study. We employed the No-Avatar and Complete conditions in both studies as lowest and highest-fidelity control conditions, as prior research indicates that the Complete condition should provide a greater sense of embodiment than the No-Avatar condition (Maselli and Slater, 2013). We investigated the moderately high-fidelity Head-and-Extremities condition in our first study (see **Figure 1**) and the moderately low-fidelity Head-and-Hands condition in our second study (see **Figure 2**). For both studies, the within-subject conditions were counterbalanced between subjects, using the full-factorial permutation, to negate potential ordering effects.

No-Avatar (Study 1 and Study 2)

In the No-Avatar condition, participants were only able to see the two virtual handheld controllers and were not provided with an avatar representation (see **Figures 1A**, **2A**).

Complete (Study 1 and Study 2)

In the Complete condition, participants were provided a gender-matched, full-body IK avatar representation that was fully controlled by the tracking data from the head, hands, feet, and pelvis (see **Figures 1C**, **2C**). Note, in order to avoid known issues with race during embodiment (Peck et al., 2013), our avatars were designed with winter gloves to conceal any indication of race and no virtual mirrors were present within the virtual environment. To help participants rationalize why their avatars were wearing gloves, we placed a frosty window with a view of a snowy outdoor scene within the virtual office environment used for the studies.

Head-and-Extremities (Study 1)

In the Head-and-Extremities condition, participants were also provided the full-body IK avatar, except it was controlled by the tracking data from the head, hands, and feet (see **Figure 1B**). Hence, the IK solver controlled the positioning of the avatar's pelvis.

Head-and-Hands (Study 2)

In the Head-and-Hands condition, participants were also provided the full-body IK avatar, except it was controlled by the tracking data from only the head and hands (see **Figure 2B**). In this condition, the IK solver controlled the positioning of the avatar's feet and pelvis based on the tracked movements of the avatar's head and hands.

Embodiment Activities

For each embodiment condition, participants completed two different tasks—adjusting subtle parameters of the virtual avatar body using a 3D floating window (LaViola et al., 2017), followed by collecting coins placed around the virtual environment. For the first task, the VR application presented the participants with a 3D floating window with a set of sliders, within a 4 × 4 m virtual office environment. The sliders controlled subtle aspects of the virtual avatar's IK parameters, including the elbow positioning, knee positioning, arm length, and leg length. Note, these body parameters only affected the movements of the interior joints of the avatar and had no effects on the end-effectors of the IK algorithm, and the handheld controllers directly controlled the positions of the avatar's hands. Hence, no interaction artifacts were produced as a result of adjusting these parameters. Participants were encouraged to change each slider to experience what each slider changed on the virtual avatar and then select a "Next" button to start the second task when ready.

The second task was a short, 1 min, coin collection game in which the participant was encouraged to collect as many coins as possible in the same virtual office environment (see **Figure 3**). The coins appeared every 5 s with spatial audio cues to aid discovery. Coin placement was varied to provide a wide range of movements for the participant to experience different avatar movements including walking, reaching, crouching, leaning, and standing. Coin placement was also randomly varied to avoid potential learning effects through the course of the study. This task's intention was to provide varied movement for the participant to observe how their virtual body is moving in the virtual environment.

The two tasks described above were repeated 3 times for each embodiment condition. These repetitions allowed participants to re-evaluate their virtual body parameters and gave each participant more experiences with each embodiment condition. At the end of each condition, after the third repetition, participants were prompted with another window to indicate which of the three iterations of body parameter selections they thought was most realistic. This process was repeated 3 times, once for each condition, for a total of 9 trials (3 conditions × 3 repetitions).

Procedure

The following procedure was reviewed and approved by the University of Texas at Dallas Institutional Review Board (IRB).

Each study consisted of a single session that lasted up to 1 h for each participant. Participants were informed that the purpose of the study was to "increase our understanding of how full-body avatars may be represented in VR" during informed consent. Participants were not told of the nature of the condition during the experiment because they donned all the wearable equipment in all conditions.

After informed consent, we assigned each participant to one of the full-factorial condition orderings to counterbalance the potential effects of ordering. Each participant experienced three of the four experimental conditions: No-Avatar, Complete, and one of the partial tracking conditions: Head-and-Extremities (Study 1) or Head-and-Hands (Study 2). We began the study with a background survey on the participant's gender, age, height, weight, education, and technology experiences. The participant was then helped with donning the trackers, straps, controllers, and HMD. The experimenter then calibrated the full-body IK avatar to match the participant's gender and height provided by a standard T-pose. The experimenter then explained the two tasks described in section Embodiment Activities and started the participant on their first experimental condition, based on their assigned presentation ordering. After completing the VR tasks successfully, each participant completed the Simulator Sickness Questionnaire (SSQ) (Kennedy et al., 1993), the Spatial Presence Experience Scale (SPES) (Hartmann et al., 2015), and the initial pool of 10 embodiment questions, as described in section Initial

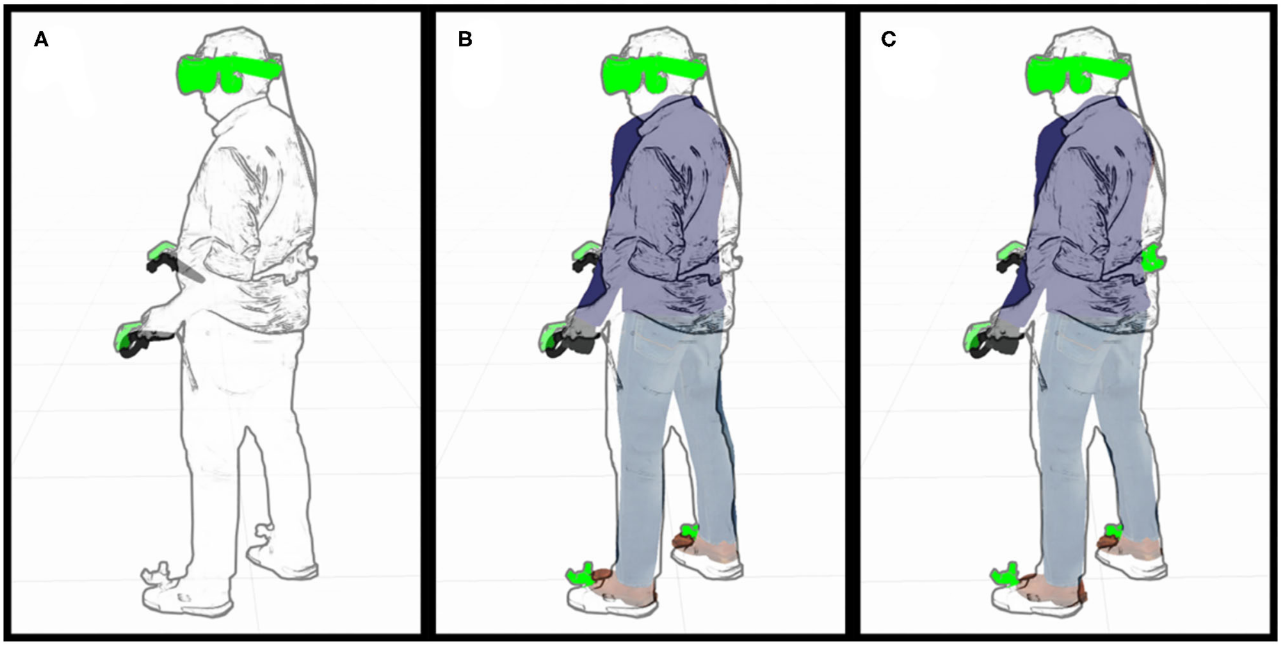

FIGURE 1 | The three experimental conditions investigated in our first study: **(A)** No-Avatar, **(B)** Head-and-Extremities, and **(C)** Complete. Active IK trackers are highlighted green.

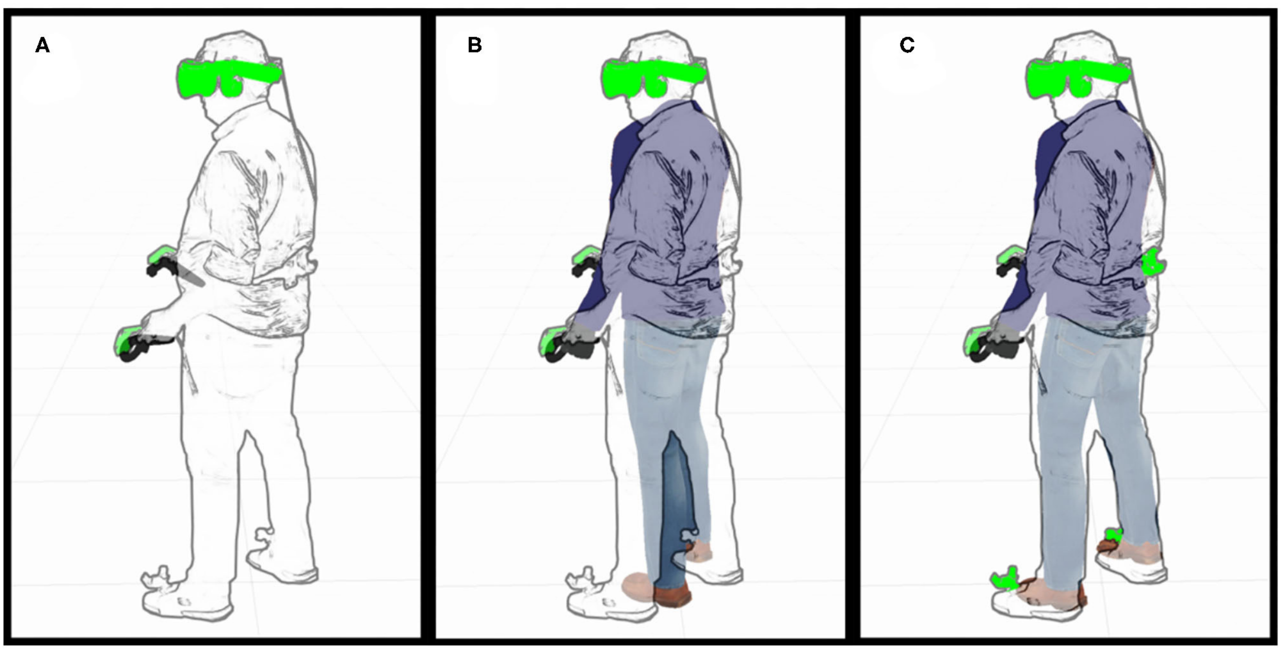

FIGURE 2 | The three experimental conditions investigated in our second study: **(A)** No-Avatar, **(B)** Head-and-Hands, and **(C)** Complete. Active IK trackers are highlighted green.

Item Pool. After completing the first condition, the participant repeated this process for the remaining two experimental conditions. Each condition took about 20 min to complete. The study concluded with each participant completing an exit survey with open-ended responses regarding their study experience.

Participants

A parametric a priori power analysis for a medium effect size ($f = 0.25$) revealed that a total sample size of 28 participants would be needed to obtain statistical power at a 95% confidence level with the three repeated measures for two groups (males

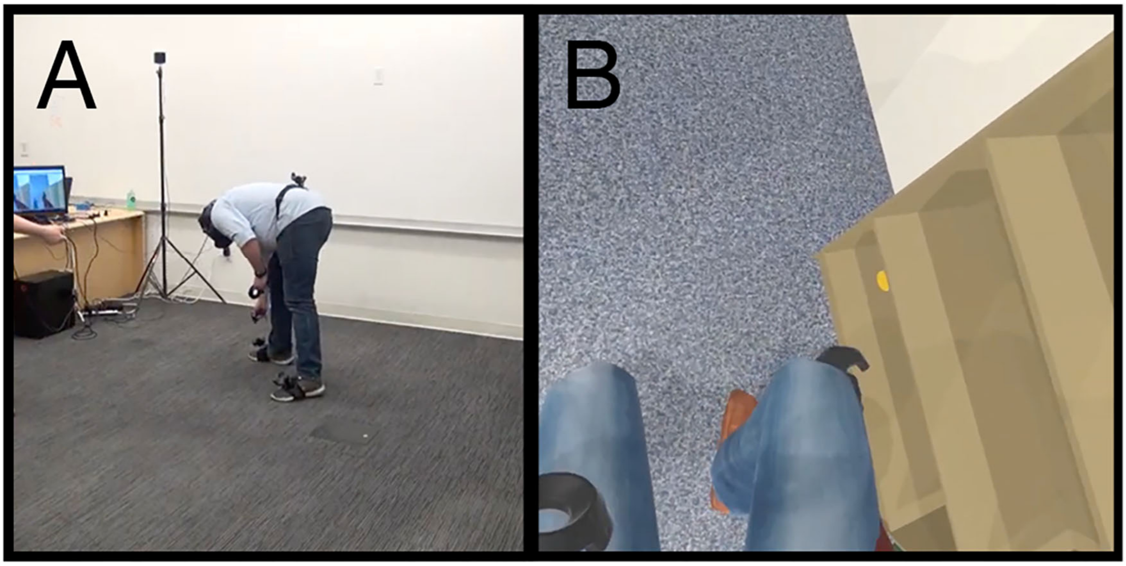

FIGURE 3 | The coin game used as an embodiment activity: **(A)** the user reaching down within the physical tracked space, and **(B)** the user's perspective of reaching toward a coin within the virtual office environment.

and females). Because larger samples are recommended for non-parametric tests, such as those often used for analyzing questionnaires, we intended to recruit 48 participants (24 males, 24 females) for each study, using the six full-factorial permutations to counterbalance. These target numbers also exceeded the recommendation of having at least a 5:1 ratio of measurements to items factored (MacCallum et al., 1999; Kline, 2014).

Due to the COVID-19 pandemic, we were unable to conduct all of the planned participants, as we were forced to stop conducting human subject studies due to university policies. However, before stopping the studies, we were able to successfully recruit and conduct a total of 30 participants for Study 1 and 14 participants for Study 2. Despite these low samples, we were able to construct a preliminary embodiment short questionnaire (see section Construction of the pESQ) and validate it with the significant results of both studies (see section Initial Validation of the pESQ). Clearly, more research is needed to construct and validate a final embodiment short questionnaire (ESQ), but we believe the current work is a solid step toward it.

In terms of demographics, Study 1 included 23 males and 7 females, with a mean age of 20.3 years ($SD = 3.4$ years). Of the 30 participants, 24 had prior VR experience while 6 participants did not. For Study 2, the 14 participants included 11 males and 3 females, with a mean age of 25.9 years ($SD = 12.7$ years). Of the participants, 12 had prior VR experience and 2 participants did not.

CONSTRUCTION OF THE pESQ

Again, the goal of this research was to construct and validate a preliminary embodiment questionnaire that addresses all three factors of embodiment (i.e., self-location, agency, and body ownership) and is short enough to be reasonably administered in VR for future "in the wild" VR studies. The previous embodiment questionnaire presented by Dobricki and de la Rosa (2013) is too lengthy to be administered in VR with 27 items and the questionnaire was validated with studies employing a third-person perspective, which is questionable given other research identifying first-person perspectives as a necessary condition for the full-body ownership illusion (Maselli and Slater, 2013). The embodiment questionnaire presented by Gonzalez-Franco and Peck (2018) is also lengthy with 25 items, many of which address specific scenarios like virtual mirrors and tactile sensations, and it has not been formally validated. Finally, the VEQ presented by Roth and Latoschik (2020) could be administered in VR, but the questionnaire does not address the self-location factor, which is known to be important for embodiment (Gonzalez-Franco and Peck, 2018).

With regard to developing a short questionnaire, Alexandrovsky et al. (2020) have discussed that length is an important factor for administering a questionnaire in VR. Their research indicates that in-VR questionnaires yield results comparable to their traditionally administered counterparts, but that participants find the in-VR versions more enjoyable and prefer them to the traditional versions.

Initial Item Pool

Our initial set of items consisted of 10 questions scored on a 5-point Likert scale from 1 ("I do not agree at all") to 5 ("I fully agree"). See **Table 2** for all 10 initial questions. Items Q1 through Q5 were sourced from the questionnaire presented by Gonzalez-Franco and Peck (2018) and have commonly appeared in other virtual embodiment studies (Slater et al., 2008; Steptoe et al., 2013). We introduced items Q6 through Q10 as new embodiment questions, which we modeled after closely related

TABLE 2 | Our initial pool of self-location (SL), agency (A), and body ownership (BO) items, and our initial factor analysis.

Item	Factor	Question	*M*	*SD*	*p*	*MSA*	*F1–1 (SL)*	*F1–2 (A)*	*F1–3 (BO)*
Q1	SL	Overall, I felt as if my body was located where I saw the virtual body to be.	3.34	1.31	0.586	0.934	0.753	0.427	0.130
Q2	BO	Overall, I felt that the virtual body was my own body.	2.89	1.24	0.472	0.890	**0.823**	0.341	0.148
Q3	A	The movements of the virtual body were caused by my movements.	3.77	1.23	0.692	0.935	0.407	0.722	0.111
Q4	BO	It seemed as if I might have more than one body.	3.94	1.12	0.736	**0.411**			
Q5	BO	Overall, I felt that the virtual body belonged to someone else.	3.99	1.07	0.747	**0.595**			
Q6	SL	I felt like my body was actually there in the environment.	3.36	1.18	0.589	0.893	0.852	0.253	0.150
Q7	SL	I felt like my body appeared in the environment.	2.93	1.36	0.483	0.837	0.735	0.462	0.214
Q8	A	I felt like my bodily movements occurred within the environment.	3.64	1.06	0.661	0.922	0.420	0.728	0.050
Q9	A	I felt like my body affected the environment.	3.30	1.21	0.575	0.924	0.243	0.810	0.214
Q10	BO	I felt like the environment affected my body.	2.78	1.34	0.444	0.880	0.199	0.165	0.961

p indicates item difficulty. F1–1, F1–2, and F1–3 indicate the three forced factors from our initial factor analysis. Bold values indicate the basis for an item being dropped.

questions from the SPES (Hartmann et al., 2015). Of the 10 initial questions, three questions addressed self-location, three addressed agency, and four addressed body ownership. We felt this fairly balanced distribution would ultimately yield a similarly balanced distribution in the final short questionnaire.

Exploratory Factory Analysis

We used an exploratory factory analysis approach involving three steps to select the items for our pESQ (DeVellis, 2003; Hartmann et al., 2015; Clark and Watson, 2016). First, we analyzed the distributions of all the items from our responses to exclude any items that were strongly skewed, difficult, or had little variance. Second, we investigated the items using varimax-rotated principal component analysis (PCA) (Kline, 2014). Third, we confirmed the internal consistency of each of our factors through standard reliability criteria using corrected item-total correlation and Cronbach's alpha. **Tables 2**, **3** provide a summary of the results obtained.

Item Distribution and Item Difficulty

As suggested by Clark and Watson (2016), we identified and eliminated items that had highly skewed and unbalanced distributions. Items that are strongly unbalanced provide little information. Our analysis of the distributions obtained in Study 1 showed that all items had reasonable variance ($1.06 \leq SD \leq 1.36$). All our items avoided a strong ceiling or bottom effect ($2.78 \leq M \leq 3.99$). None of our initial items showed a normal distribution (all K-S tests ≥ 0.20; $p < 0.001$). Instead, all the response distributions were skewed toward "no agreement" ($-0.81 \leq$ skewness ≤ 0.31). However, none of our items were skewed strongly enough to warrant being dropped for their skewness (Hartmann et al., 2015). Finally, we computed the item difficulty p for each item by dividing the item's mean minus 1 by the maximum value (5) minus 1, so that p was normalized to a range between 0 and 1. It is preferrable for the p-value of all items to be in the range of 0.2 and 0.8 to be retained (Hartmann et al., 2015). All of our items fell within this range. See **Table 2**.

Factor Structure and Factor Loadings

When determining how suited our items were for factor analysis, our initial overall portion of common variance was high [Kaiser–Meyer–Olkin (KMO) = 0.87], but two of our items showed poor measures of sampling adequacy (MSA). Q4 (MSA = 0.411) and Q5 (MSA = 0.595) both had poor adequacy, so we dropped them from our subsequent analysis. These two questions have recently been shown to have low reliability in other research (Peck and Tutar, 2020). We calculated our overall suitability for factor analysis again (KMO = 0.92) and individual adequacy ($0.90 \leq$ KMO ≤ 0.96) and found that all our remaining items were adequate for factor analysis. Additionally, our response to item ratio for the sample was 9:1 (30 participants × 3 measures: 10 items), exceeding the recommendation of at least five responses per item (MacCallum et al., 1999; Kline, 2014).

We conducted a forced 3-factor PCA with varimax rotation as recommend on our remaining eight items (Hartmann et al., 2015). In our first PCA, we found that one of our questions loaded under a factor different than it has historically been categorized. Specifically, Q2 was expected to load alongside Q10 as a body ownership factor (Gonzalez-Franco and Peck, 2018), but it instead loaded under the self-location factor with items Q1, Q6, and Q7 (see **Table 2**). Hence, we decided to drop Q2 at this point and re-conducted the forced 3-factor PCA with varimax rotation.

The three factors obtained from our second PCA accounted for 80.20% of the shared variance (Factor 1: 33.21%, Factor 2: 31.50%, Factor 3: 15.49%). See **Table 3** for our factor loadings. Our agency items loaded strongly on the first factor, all but one of the self-location items loaded strongly on the second factor, and our sole remaining body ownership item loaded very strongly on the third factor. We retained items if they loaded higher than 0.3 on their primary factor and if this loading was at least 0.2 higher than any of the cross-loadings, as done in prior research (Hartmann et al., 2015). Q7

TABLE 3 | Results of our second factor analysis, internal consistency tests, and our final factor analysis for the pESQ.

Item	Factor	Question	*F2–1 (SL)*	*F2–2 (A)*	*F2–3 (BO)*	r_{itc}	*F3–1 (SL)*	*F3–2 (A)*	*F3–3 (BO)*	pESQ
Q1	SL	Overall, I felt as if my body was located where I saw the virtual body to be.	0.770	0.438	0.131	0.718	0.811	0.400	0.147	**SL**
Q3	A	The movements of the virtual body were caused by my movements.	0.344	0.761	0.124	0.667	0.368	0.779	0.158	**A**
Q6	SL	I felt like my body was actually there in the environment.	0.887	0.267	0.147	0.718	0.886	0.273	0.161	**SL**
Q7	SL	I felt like my body appeared in the environment.	0.695	**0.508**	0.223					-
Q8	A	I felt like my bodily movements occurred within the environment.	0.348	0.778	0.065	0.651	0.268	0.871	0.109	**A**
Q9	A	I felt like my body affected the environment.	0.265	0.769	0.215	**0.622**				-
Q10	BO	I felt like the environment affected my body.	0.182	0.170	0.964	N/A	0.172	0.150	0.973	**BO**

F2–1, F2–2, and F2–3 indicate the three forced factors from our second factor analysis. r_{itc} indicates corrected item-total correlations. F3–1, F3–2, and F3–3 indicate the three forced factors from our final factor analysis. Bold values indicate the basis for an item being dropped. Bold letters indicate the final pESQ items.

was dropped because it failed to meet these criteria, leaving 6 items.

Internal Consistency

In order to first test the internal consistency of our remaining items, we examined the corrected item-total correlation r_{itc}. The remaining two self-location items (Q1 and Q6) and the remaining three agency items (Q3, Q8, and Q9) were analyzed separately. The single body ownership item remaining (Q10) is naturally consistent with itself. Items were required to have an acceptable r_{itc} value of at least 0.5 (Hartmann et al., 2015). All items met this criterion.

To continue our examination of internal consistency, we examined values for Cronbach's alpha. For self-location, Q1 and Q6 yielded a satisfactory internal consistency (Cronbach's alpha = 0.834). For agency, we removed Q9 to maximize internal consistency for only two items. The remaining agency questions, Q3 and Q8, also yielded a satisfactory consistency (Cronbach's alpha = 0.751). Hence, our preliminary embodiment short questionnaire consisted of two self-location items (Q1 and Q6), two agency items (Q3 and Q8), and one body ownership item (Q10). It is interesting to note that despite starting with four body ownership questions (out of 10 total), our exploratory factor analysis resulted in only one suitable body ownership question.

INITIAL VALIDATION OF THE pESQ

As discussed in section Embodiment Studies, we used data collected from two studies investigating the effects of avatar fidelity and tracking fidelity on overall embodiment to develop the pESQ. We used the embodiment data from Study 1, which included our entire initial pool of questions, to construct the pESQ, as described in section Construction of the pESQ. In this section, we describe how we have initially validated the pESQ by comparing its results to the results of the initial question pool for both Study 1 and Study 2.

Study 1 Validation

As described in section Experimental Conditions, our first study investigated three within-subject experimental conditions: No-Avatar (head and hands trackers; only controllers visible), Head-and-Extremities (hand, hands, and feet trackers with the full-body IK avatar), and Complete (head, hands, feet, and pelvis trackers with the full-body IK avatar). See **Figure 1** for visual depictions of these conditions. The No-Avatar and Complete conditions served as lowest-fidelity and highest-fidelity experimental controls, respectively, with prior research indicating that the Complete condition should provide a greater sense of embodiment than the No-Avatar condition (Maselli and Slater, 2013; Gonzalez-Franco and Peck, 2018; Peck and Tutar, 2020).

In our original analysis of the results (Eubanks et al., 2020), we found that the Complete and Head-and-Extremities conditions induced significantly more embodiment than the No-Avatar condition. We also did not find a significant difference between the Complete and Head-and-Extremities conditions.

For our new analyses, we conducted Friedman tests at 95% confidence levels, as non-parametric alternatives to one-way, repeated-measures ANOVAs, to investigate the effects of the three experimental conditions on self-location, agency, and body ownership. Wilcoxon signed-ranked tests were used to identify significantly different conditions when a significant main effect was found with Bonferroni corrections applied to correct for Type I errors in the repeated measures. We conducted these analyses for both the initial question pool (i.e., all 10 questions based on their original factor assignments) and our constructed pESQ.

Self-Location

For the initial question pool, we found a significant main effect of condition on self-location, $\chi^2(2) = 20.786$, $p < 0.001$, $W = 0.346$, based on the average of the three self-location items (Q1, Q6, and Q7). The *post-hoc* tests showed that the Complete condition ($Z = -3.822$, $p < 0.001$) and the Head-and-Extremities condition ($Z = -3.830$, $p < 0.001$) afforded significantly more self-location than the No-Avatar condition. However, there was not a significant difference between the Complete and Head-and-Extremities conditions ($Z = -0.322$, $p = 1.000$).

For the pESQ, based on the average of our two self-location pESQ items (Q1 and Q6), we found a significant main effect of condition on self-location, $\chi^2(2) = 15.453$, $p < 0.001$, $W = 0.258$. The *post-hoc* tests showed that the Complete condition ($Z = -3.573$, $p < 0.001$) and the Head-and-Extremities condition ($Z = -3.396$, $p = 0.003$) afforded significantly more self-location than the No-Avatar condition. However, there was not a significant difference between the Complete and Head-and-Extremities conditions ($Z = -0.659$, $p = 1.000$).

Hence, the self-location results of the pESQ were comparable to those of the initial question pool.

Agency

For the initial question pool, we found a significant main effect of condition on agency, $\chi^2(2) = 17.442$, $p < 0.001$, $W = 0.291$, based on the average of the three agency items (Q3, Q8, and Q9). The *post-hoc* tests showed that the Complete condition ($Z = -3.620$, $p < 0.001$) and the Head-and-Extremities condition ($Z = -3.576$, $p < 0.001$) afforded significantly more agency than the No-Avatar condition. However, there was not a significant difference between the Complete and Head-and-Extremities conditions ($Z = -0.734$, $p = 1.000$).

For the pESQ, based on the average of our two agency pESQ items (Q3 and Q8), we found a significant main effect of condition on agency, $\chi^2(2) = 16.231$, $p < 0.001$, $W = 0.271$. The *post-hoc* tests showed that the Complete condition ($Z = -3.343$, $p = 0.003$) and the Head-and-Extremities condition ($Z = -2.899$, $p = 0.012$) afforded significantly more agency than the No-Avatar condition. However, there was not a significant difference between the Complete and Head-and-Extremities conditions ($Z = -0.914$, $p = 1.000$).

Hence, the agency results of the pESQ were comparable to those of the initial question pool.

Body Ownership

For the initial question pool, we did not find a significant main effect of condition on body ownership, $\chi^2(2) = 5.685$, $p = 0.058$, $W = 0.095$, based on the normalized average of the four body ownership items (Q2, Q4 inverted, Q5 inverted, and Q10).

For the pESQ, based on our single body ownership pESQ item (Q10), we found a significant main effect of condition on body ownership, $\chi^2(2) = 11.400$, $p = 0.003$, $W = 0.190$. The *post-hoc* tests showed that the Complete condition ($Z = -2.658$, $p = 0.024$) and the Head-and-Extremities condition ($Z = -2.975$, $p = 0.009$) afforded significantly more body ownership than the No-Avatar condition. However, there was not a significant difference between the Complete and Head-and-Extremities conditions ($Z = -0.699$, $p = 1.000$).

Hence, the body ownership results of the pESQ provided significant differences while the initial question pool results did not.

Overall Embodiment

For the initial question pool, we found a significant main effect of condition on overall embodiment, $\chi^2(2) = 14.672$, $p < 0.001$, $W = 0.245$, based on the average of the three factors above. The *post-hoc* tests showed that the Complete condition ($Z = -3.692$, $p < 0.001$) and the Head-and-Extremities condition ($Z = -3.406$, $p = 0.003$) afforded significantly more overall embodiment than the No-Avatar condition. However, there was not a significant difference between the Complete and Head-and-Extremities conditions ($Z = -0.864$, $p = 1.000$).

For the pESQ, based on the average of our three pESQ factors (SL, A, and BO), we found a significant main effect of condition on overall embodiment, $\chi^2(2) = 16.053$, $p < 0.001$, $W = 0.268$. The *post-hoc* tests showed that the Complete condition ($Z = -3.775$, $p < 0.001$) and the Head-and-Extremities condition ($Z = -3.691$, $p < 0.001$) afforded significantly more overall embodiment than the No-Avatar condition. However, there was not a significant difference between the Complete and Head-and-Extremities conditions ($Z = -0.732$, $p = 1.000$).

Hence, the overall embodiment results of the pESQ were comparable to those of the initial pool.

Study 2 Validation

Our second study investigated three within-subject experimental conditions: No-Avatar, Head-and-Hands (head and hands trackers with the full-body IK avatar), and Complete. See **Figure 2** for visual depictions of these conditions. Again, the No-Avatar and Complete conditions served as lowest-fidelity and highest-fidelity experimental controls, respectively.

In our original analysis of the results (Eubanks et al., 2020), we found that the Complete condition induced significantly more embodiment than both the Head-and-Hands and No-Avatar conditions. However, we did not find any significant differences between the Head-and-Hands and No-Avatar conditions, in terms of embodiment.

For our new analyses using the pESQ, we again conducted Friedman tests to investigate main effects and used Wilcoxon signed-ranked tests with Bonferroni corrections to identify significantly different conditions. Again, we conducted these analyses for both the initial question pool (i.e., all 10 questions based on their original factor assignments) and our constructed pESQ.

Self-Location

For the initial question pool, we found a significant main effect of condition on self-location, $\chi^2(2) = 14.873$, $p = 0.001$, $W = 0.531$. The *post-hoc* tests showed that the Complete condition afforded significantly more self-location than both the Head-and-Hands condition ($Z = -3.151$, $p = 0.006$) and the No-Avatar condition ($Z = -3.084$, $p = 0.006$). There was not a significant difference between the Head-and-Hands and No-Avatar conditions ($Z = -1.358$, $p = 0.522$).

For the pESQ, we found a significant main effect of condition on self-location, $\chi^2(2) = 14.880$, $p = 0.001$, $W = 0.531$. The *post-hoc* tests showed that the Complete condition afforded significantly more self-location than both the Head-and-Hands condition ($Z = -3.078$, $p = 0.006$) and the No-Avatar condition ($Z = -2.919$, $p = 0.012$). There was not a significant difference between the Head-and-Hands and No-Avatar conditions ($Z = -0.671$, $p = 1.000$).

Hence, the self-location results of the pESQ were comparable to those of the initial question pool.

Agency

For the initial question pool, we found a significant main effect of condition on agency, $\chi^2(2) = 12.286$, $p = 0.002$, $W = 0.439$. The *post-hoc* tests showed that the Complete condition afforded significantly more agency than both the Head-and-Hands condition ($Z = -2.999$, $p = 0.009$) and the No-Avatar condition ($Z = -2.809$, $p = 0.015$). There was not a significant difference between the Head-and-Hands and No-Avatar conditions ($Z = -1.056$, $p = 0.873$).

For the pESQ, we found a significant main effect of condition on agency, $\chi^2(2) = 11.870$, $p = 0.003$, $W = 0.424$. The *post-hoc* tests showed that the Complete condition afforded significantly more agency than both the Head-and-Hands condition ($Z = -2.831$, $p = 0.015$) and the No-Avatar condition ($Z = -2.764$, $p = 0.018$). There was not a significant difference between the Head-and-Hands and No-Avatar conditions ($Z = -0.876$, $p = 1.000$).

Hence, the agency results of the pESQ were comparable to those of the initial question pool.

Body Ownership

For the initial question pool, we found a significant main effect of condition on body ownership, $\chi^2(2) = 18.038$, $p < 0.001$, $W = 0.644$. The *post-hoc* tests showed that the Complete condition afforded significantly more body ownership than both the Head-and-Hands condition (Z = −3.192, p = 0.003) and the No-Avatar condition (Z = −2.506, p = 0.036). There was not a significant difference between the Head-and-Hands and No-Avatar conditions (Z = −1.927, p = 0.162).

We found a significant main effect of condition on body ownership, $\chi^2(2) = 11.854$, $p = 0.003$, $W = 0.423$. Interestingly, the *post-hoc* tests showed that the Complete condition ($Z = -2.705$, $p = 0.021$) and the Head-and-Hands condition ($Z = -2.122$, $p = 0.034$) afforded significantly more body ownership than the No-Avatar condition. Additionally, there was not a significant difference between the Complete and Head-and-Hands conditions ($Z = 0.000$, $p = 1.000$).

Hence, the body ownership results of the pESQ provided different and more-intuitive significant differences (i.e., the Head-and-Hands condition afforded more body ownership than the No-Avatar condition) than the results of the initial question pool.

Overall Embodiment

For the initial question pool, we found a significant main effect of condition on overall embodiment, $\chi^2(2) = 17.127$, $p < 0.001$, $W = 0.612$. The *post-hoc* tests showed that the Complete condition afforded significantly more overall embodiment than both the Head-and-Hands condition ($Z = -3.297$, $p = 0.003$) and the No-Avatar condition ($Z = -3.110$, $p = 0.006$). There was not a significant difference between the Head-and-Hands and No-Avatar conditions (Z = −0.628, p = 1.000).

We found a significant main effect of condition on overall embodiment, $\chi^2(2) = 16.333$, $p < 0.001$, $W = 0.583$. The *post-hoc* tests showed that the Complete condition afforded significantly more overall embodiment than both the Head-and-Hands condition ($Z = -2.977$, $p = 0.009$) and the No-Avatar condition ($Z = -3.181$, $p = 0.003$). Though not significant, there was also a statistical trend that the Head-and-Hands condition afforded more overall embodiment than the No-Avatar condition ($Z = -1.855$, $p = 0.064$).

Hence, the overall embodiment results of the pESQ were comparable to those of the initial pool.

DISCUSSION

In this section, we first discuss the implications of our new results based on the pESQ with regard to the embodiment literature. We then discuss problems with prior body ownership questions and how those issues affected our construction of the pESQ. Finally, we discuss our future plans for constructing and validating a final embodiment short questionnaire (ESQ) to be administered as an in-VR questionnaire.

Avatar Fidelity Increases Body Ownership

In our first study, we found that both the Complete condition and the Head-and-Extremities condition afforded significantly more body ownership than the No-Avatar condition. Likewise, in our second study, we found that the Complete condition and the Head-and-Hands condition afforded significantly more body ownership than the No-Avatar condition. This last result is particularly interesting, as body ownership was the only embodiment factor that we found a significant difference for between the Head-and-Hands and No-Avatar conditions. Overall, these results support the concept that the presentation of an avatar increases body ownership, which is also supported by prior research (Maselli and Slater, 2013; Gonzalez-Franco and Peck, 2018; Peck and Tutar, 2020). Hence, for those researchers and developers interested in affording body ownership to their users, it is imperative that an avatar, and not just virtual controllers, is presented.

Foot Tracking Increases Self-Location and Agency

In our second study, we found that the Completing tracking condition afforded significantly more self-location and agency than the Head-and-Hands condition. However, in our first study, we did not find any significant differences between the Complete and Head-and-Extremities conditions. Furthermore, while we found that the Head-and-Extremities condition afforded significantly more self-location and agency than the No-Avatar condition in our first study, we did not find any significant differences in terms of self-location and agency between the Head-and-Hands and No-Avatar conditions in our second study. These results indicate that foot tracking, the only objective difference between the Head-and-Extremities and Head-and-Hands conditions, significantly increases users' sense of self-location and agency. To the best of our knowledge, this is the first research to indicate the effects of foot tracking on self-location and agency.

However, this result is not surprising considering the nature of the full-body IK avatar. When foot tracking is not available, the IK solver must use a distance threshold to auto-step the avatar's feet, in order to keep them under the torso and to avoid sliding the avatar's feet across the ground. As a result, when the user steps forward with their left foot, the IK solver may respond by auto-stepping the avatar's right foot forward instead. This type of incongruency clearly impacts self-location and agency in a negative manner.

Finally, considering these results, we recommend that VR researchers and developers should include foot tracking when using a full-body IK avatar and attempting to afford self-location, agency, and embodiment in general.

Pelvis Tracking Warrants More Research

As mentioned, in our first study, we did not find any significant differences between the Complete and Head-and-Extremities conditions. However, this lack of differences could have been due to participants not observing their pelvises and torsos during the coin collection game, particularly considering the limited field of view (110° diagonal) of the HMD. Hence, more research is necessary to fully understand how pelvis tracking affects embodiment. In particular, we suggest that future studies involving a virtual mirror may better determine this issue.

Issues With Body Ownership Questions

In our research, we started with four questions that addressed body ownership (Q2, Q4, Q5, and Q10). Three of these questions (Q2, Q4, and Q5) were previously recommended by Gonzalez-Franco and Peck (2018) and have commonly appeared in other virtual embodiment studies (Slater et al., 2008; Steptoe et al., 2013). During the construction of the pESQ, we found that Q4 and Q5 yielded poor measures of sampling adequacy despite all of our other questions yielding suitable sampling adequacies. Very recently, Peck and Tutar (2020) also found that these two questions yielded poor reliability and ultimately decided to drop them from their analysis. These poor qualities are likely the result of these two questions addressing negative aspects of embodiment (i.e., having more than one body, or the virtual body belonging to someone else, respectively).

During the construction of our short questionnaire, we also found that Q2 loaded under the self-location factor instead of the body ownership factor, as classified by Gonzalez-Franco and Peck (2018). If we reconsider the definitions of self-location (i.e., the localization of oneself within the spatial limits of a body) and body ownership (the sense that one's own body is the source of any sensations felt), it is not difficult to understand why Q2 ("Overall, I felt that the virtual body was my own body") would load with other self-location items, such as Q1 ("Overall, I felt as if my body was located where I saw the virtual body to be"), as opposed to the remaining body ownership item, Q10 ("I felt like the environment affected my body"). Furthermore, it is clear that Q10 is the most closely related to the concept of body ownership, referencing a potential source of sensations.

Toward the Embodiment Short Questionnaire (ESQ)

In the current work, we have presented the construction and validation of a preliminary embodiment short questionnaire (pESQ) that addresses all three factors of embodiment (i.e., self-location, agency, and body ownership) and is short enough to be suitable as an in-VR questionnaire, especially for "in the wild" VR studies. However, despite starting with an initial pool that includes four body ownership questions, our pESQ includes only a single body ownership question, due to the reasons discussed above in section Pelvis Tracking Warrants More Research. While this is acceptable for a preliminary version of a questionnaire, the final version should include more than one item per factor and the proportion of items devoted to each factor should be proportional to the importance of each factor (Clark and Watson, 2016).

In the future, to achieve our goal of establishing a short questionnaire that addresses all three factors—self-location, agency, and body ownership—we plan to conduct new embodiment studies in order to construct and validate a final ESQ. We plan to explore an initial pool of questions that include those from our current pESQ (Q1, Q3, Q6, Q8, and Q10), those questions removed during our second factor analysis (Q7 and Q9), questions from other embodiment questionnaires (Dobricki and de la Rosa, 2013; Gonzalez-Franco and Peck, 2018; Roth and Latoschik, 2020), and new body ownership questions that better capture the source of any sensations felt.

In addition to constructing the final ESQ to address self-location, agency, and body ownership, we also plan to incorporate external appearance questions into the ESQ. As indicated by Gonzalez-Franco and Peck (2018), the sense of embodiment also involves the acceptance of the external appearance of the virtual avatar. While the current pESQ does not address external appearance, we plan to explore a pool of external-appearance questions for the final ESQ.

Another potential issue for future investigation is the use of our current 5-point scale, which ranges from 1 ("I do not agree at all") to 5 ("I fully agree"). We adopted this 5-point scale from the SPES questionnaire (Hartmann et al., 2015) because we felt the choices were clear and would keep our questionnaire short by limiting the options for participants to consider. Prior research indicates that using a 7-point scale would provide more sensitivity (Finstad, 2010), but there are conflicting recommendations in the literature with regard to using 5, 7, or 10-point scales (Dawes, 2008). Hence, more research is needed to determine how the sensitivity of the scale affects the usefulness of the ESQ, which is intended for "in the wild" VR studies, as opposed to more-rigorous and more-sensitive questionnaires.

Limitations of the Preliminary Embodiment Short Questionnaire

While we consider the current work a major step toward establishing a short questionnaire for measuring embodiment and its factors, we acknowledge and warn other researchers that there are limitations of our work and further research is necessary to construct and validate the questionnaire.

First, we were forced to stop recruiting and conducting participants for our studies prematurely due to the COVID-19 pandemic and resulting university policies regarding human-subject studies. As a result, we were only able to successfully conduct 30 total participants for our first study and 14 participants through our second study, as opposed to the originally intended 48 participants each. Despite this limitation, we were still able to successfully construct the pESQ from the first study's data using standard exploratory factor analysis methods (Hartmann et al., 2015), and we successfully validated the preliminary questionnaire on our limited data, finding expected significant differences between our lowest-fidelity and highest-fidelity experimental controls and additional significant differences among our other conditions (e.g., Head-and-Hands afforded more body ownership than the No-Avatar condition).

Second, our samples have a disproportionate number of males to females in both studies (23 to 7 in the first study, and 11 to 3 in the second study). This was due to more males volunteering to participant in our studies before the COVID-19 pandemic. Hence, the pESQ and our results should be further validated with a more-representative sample of the general population. In the near future, we are planning to re-launch our studies to establish these more-representative samples and to further investigate the effects of gender on self-location, agency, and body ownership.

Finally, in addition to the study limitations mentioned above, it is important to note that the pESQ (and eventually the ESQ) will not provide as much sensitivity as longer embodiment questionnaires. With short questionnaires, such as our pESQ, there are only one or two questions addressing each factor. As a result, these questions may not sufficiently address subtle differences between similar conditions. Hence, more-sensitive questionnaires, such as those presented by Peck and Gonzalez-Franco (2021) and Roth and Latoschik (2020), should be employed for more-rigorous studies involving subtle variables.

CONCLUSION AND FUTURE WORK

In recent years, research on the sense of embodiment and its factors (i.e., self-location, agency, and body ownership) has increased with the availability of consumer VR technologies. While there have been prior attempts to establish questionnaires for measuring embodiment, we have identified potential issues with each one. In this paper, we present the construction and validation of the pESQ, a preliminary short questionnaire for measuring embodiment and its factors. In addition to providing an embodiment questionnaire focused on self-location, agency, and body ownership, we also aimed to create a short measurement tool that could be readily administered as an in-VR questionnaire for future "in the wild" VR studies that involve remote participants using their own VR hardware. Using the data from two embodiment studies, we were able to construct the pESQ as a five-item questionnaire that addresses self-location, agency, and body ownership. By using and validating the pESQ on the results of our studies, we have found that foot tracking significantly increases self-location and agency while the presentation of a full-body avatar is necessary to afford higher degrees of body ownership.

In the near future, we hope to re-launch our studies as originally planned, recruiting larger, gender-balanced samples and investigating a larger pool of questions, with specific focus on finding better body ownership questions. Furthermore, we hope to control for the presentation format of our eventual ESQ to evaluate whether an in-VR version yields results statistically equivalent to a conventional out-of-VR version, using the TOST procedure (Lakens, 2017).

DATA AVAILABILITY STATEMENT

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

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by University of Texas at Dallas Institutional Review Board (IRB). The participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

JCE contributed to the design, implementation, conduct, analysis, and presentation of this work. AGM contributed to the design and implementation of this work. PAF contributed to the presentation of this work. RPM contributed to the design, analysis, and presentation of this work. All authors contributed to the article and approved the submitted version.

REFERENCES

Alexandrovsky, D., Putze, S., Bonfert, M., Höffner, S., Michelmann, P., Wenig, D., et al. (2020). "Examining design choices of questionnaires in VR user studies," in *CHI '20: Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI), 1–21. doi: 10.1145/3313831.3376260

Argelaguet, F., Hoyet, L., Trico, M., and Lecuyer, A. (2016). "The role of interaction in virtual embodiment: effects of the virtual hand representation," in *2016 IEEE Virtual Reality (VR)* (Greenville, SC), 3–10. doi: 10.1109/VR.2016.7504682

Arzy, S., Thut, G., Mohr, C., Michel, C. M., and Blanke, O. (2006). Neural basis of embodiment: distinct contributions of temporoparietal junction and extrastriate body area. *J. Neurosci.* 26, 8074–8081. doi: 10.1523/JNEUROSCI.0745-06.2006

Banakou, D., Hanumanthu, P. D., and Slater, M. (2016). Virtual embodiment of white people in a black virtual body leads to a sustained reduction in their implicit racial bias. *Front. Hum. Neurosci.* 10:601. doi: 10.3389/fnhum.2016.00601

Banakou, D., and Slater, M. (2014). Body ownership causes illusory self-attribution of speaking and influences subsequent real speaking. *Proc. Natl. Acad. Sic. U.S.A.* 111, 17678–17683. doi: 10.1073/pnas.1414936111

Botvinick, M., and Cohen, J. (1998). Rubber hands 'feel' touch that eyes see. *Nature* 391:756. doi: 10.1038/35784

Bourdin, P., Barberia, I., Oliva, R., and Slater, M. (2017). A virtual out-of-body experience reduces fear of death. *PLoS ONE* 12:e0169343. doi: 10.1371/journal.pone.0169343

Clark, L. A., and Watson, D. (2016). "Constructing validity: basic issues in objective scale development," in *Methodological Issues and Strategies in Clinical Research, 4th Edn,* ed A. E. Kazdin (Washington, DC: APA), 187–203. doi: 10.1037/14805-012

Dawes, J. (2008). Do data characteristics change according to the number of scale points used? an experiment using 5 point, 7 point and 10 point scales. *Int. J. Mark. Res.* 51, 61–104. doi: 10.1177/147078530805000106

DeVellis, R. F. (2003). *Scale Development: Theory and Applications, 3rd Edn*. Thousand Oaks, CA: SAGE publication Ltd.

Dobricki, M., and de la Rosa, S. (2013). The structure of conscious bodily self-perception during full-body illusions. *PLoS ONE* 8:e83840. doi: 10.1371/journal.pone.0083840

Ehrsson, H. H. (2007). The experimental induction of out-of-body experiences. *Science* 317, 1048. doi: 10.1126/science.1142175

Eubanks, J. C., Moore, A. G., Fishwick, P. A., and McMahan, R. P. (2020). "The effects of body tracking fidelity on embodiment of an inverse-kinematic avatar for male participants," in *2020 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)* (Recife: IEEE), 54–63. doi: 10.1109/ISMAR50242.2020.00025

Falconer, C. J., Slater, M., Rovira, A., King, J. A., Gilbert, P., Antley, A., et al. (2014). Embodying compassion: a virtual reality paradigm for overcoming excessive self-criticism. *PLoS ONE* 9:e111933. doi: 10.1371/journal.pone.0111933

Finstad, K. (2010). Response interpolation and scale sensitivity: evidence against 5-point scales. *J. Usability Stud.* 5, 104–110.

Fribourg, R., Argelaguet, F., Lécuyer, A., and Hoyet, L. (2020). Avatar and sense of embodiment: studying the relative preference between appearance, control and point of view. *IEEE Trans. Vis. Comput. Graph.* 26, 2062–2072. doi: 10.1109/TVCG.2020.2973077

Gonzalez-Franco, M., and Peck, T. C. (2018). Avatar embodiment. towards a standardized questionnaire. *Front. Robot. AI* 5:74. doi: 10.3389/frobt.2018.00074

González-Franco, M., Peck, T. C., Rodríguez-Fornells, A., and Slater, M. (2014). A threat to a virtual hand elicits motor cortex activation. *Exp. Brain Res.* 232, 875–887. doi: 10.1007/s00221-013-3800-1

González-Franco, M., Pérez-Marcos, D., Spanlang, B., and Slater, M. (2010). "The contribution of real-time mirror reflections of motor actions on virtual body ownership in an immersive virtual environment," in *2010 IEEE Virtual Reality Conference (VR)* (Boston, MA), 111–114. doi: 10.1109/VR.2010.5444805

Hartmann, T., Wirth, W., Schramm, H., Klimmt, C., Vorderer, P., Gysbers, A., et al. (2015). The spatial presence experience scale (SPES). *J. Media Psychol.* 28, 1–15. doi: 10.1027/1864-1105/a000137

Heydrich, L., Dodds, T., Aspell, J., Herbelin, B., Buelthoff, H., Mohler, B., et al. (2013). Visual capture and the experience of having two bodies – evidence from two different virtual reality techniques. *Front. Psychol.* 4:946. doi: 10.3389/fpsyg.2013.00946

IJsselsteijn, W. A., de Kort, Y. A. W., and Haans, A. (2006). Is this my hand i see before me? The rubber hand illusion in reality, virtual reality, and mixed reality. *Presence Teleoper. Virt. Environ.* 15, 455–464. doi: 10.1162/pres.15.4.455

Jeunet, C., Albert, L., Argelaguet, F., and Lécuyer, A. (2018). "Do you feel in control?": towards novel approaches to characterise, manipulate and measure the sense of agency in virtual environments. *IEEE Trans. Vis. Comput. Graph.* 24, 1486–1495. doi: 10.1109/TVCG.2018.2794598

Jo, D., Kim, K., Welch, G. F., Jeon, W., Kim, Y., Kim, K.-H., et al. (2017). "The impact of avatar-owner visual similarity on body ownership in immersive virtual reality," in *Proceedings of the 23rd ACM Symposium on Virtual Reality Software and Technology* VRST '17 (New York, NY: ACM), 77:1–77:2. doi: 10.1145/3139131.3141214

Kennedy, R. S., Lane, N. E., Berbaum, K. S., and Lilienthal, M. G. (1993). Simulator sickness questionnaire: an enhanced method for quantifying simulator sickness. *Int. J. Aviat. Psychol.* 3, 203–220. doi: 10.1207/s15327108ijap0303_3

Kilteni, K., Bergstrom, I., and Slater, M. (2013). Drumming in immersive virtual reality: the body shapes the way we play. *IEEE Trans. Vis. Comput. Graph.* 19, 597–605. doi: 10.1109/TVCG.2013.29

Kilteni, K., Groten, R., and Slater, M. (2012a). The sense of embodiment in virtual reality. *Presence Teleoper. Virt. Environ.* 21, 373–387. doi: 10.1162/PRES_a_00124

Kilteni, K., Normand, J.-M., Sanchez-Vives, M. V., and Slater, M. (2012b). Extending body space in immersive virtual reality: a very long arm illusion. *PLoS ONE* 7:e40867. doi: 10.1371/journal.pone.0040867

Kline, P. (2014). *An Easy Guide to Factor Analysis*. London: Routledge. doi: 10.4324/9781315788135

Koilias, A., Mousas, C., and Anagnostopoulos, C.-N. (2019). The effects of motion artifacts on self-avatar agency. *Informatics* 6:18. doi: 10.3390/informatics6020018

Kokkinara, E., Kilteni, K., Blom, K. J., and Slater, M. (2016). First person perspective of seated participants over a walking virtual body leads to illusory agency over the walking. *Sci. Rep.* 6:28879. doi: 10.1038/srep28879

Kokkinara, E., and Slater, M. (2014). Measuring the effects through time of the influence of visuomotor and visuotactile synchronous stimulation on a virtual body ownership illusion. *Perception* 43, 43–58. doi: 10.1068/p7545

Kondo, R., Sugimoto, M., Minamizawa, K., Hoshi, T., Inami, M., and Kitazaki, M. (2018). Illusory body ownership of an invisible body interpolated between virtual hands and feet via visual-motor synchronicity. *Sci. Rep.* 8:7541. doi: 10.1038/s41598-018-25951-2

Lakens, D. (2017). Equivalence tests: a practical primer for t tests, correlations, and meta-analyses. *Soc. Psychol. Personal. Sci.* 8, 355–362. doi: 10.1177/1948550617697177

Latoschik, M. E., Lugrin, J.-L., and Roth, D. (2016). "FakeMi: a fake mirror system for avatar embodiment studies," in *Proceedings of the 22nd ACM Conference on Virtual Reality Software and Technology* VRST '16 (New York, NY: Association for Computing Machinery), 73–76. doi: 10.1145/2993369.2993399

Latoschik, M. E., Roth, D., Gall, D., Achenbach, J., Waltemate, T., and Botsch, M. (2017). "The effect of avatar realism in immersive social virtual realities," in *Proceedings of the 23rd ACM Symposium on Virtual Reality Software and Technology* VRST '17 (New York, NY: Association for Computing Machinery). doi: 10.1145/3139131.3139156

LaViola, J. J., Kruijff, E., McMahan, R. P., Bowman, D., and Poupyrev, I. (2017). *3D User Interfaces: Theory and Practice, 2nd Edn*. Boston, MA: Addison-Wesley Professional.

Lenggenhager, B., Tadi, T., Metzinger, T., and Blanke, O. (2007). Video ergo sum: manipulating bodily self-consciousness. *Science* 317, 1096–1099. doi: 10.1126/science.1143439

Lopez, C., Lenggenhager, B., and Blanke, O. (2010). How vestibular stimulation interacts with illusory hand ownership. *Conscious. Cogn.* 19, 33–47. doi: 10.1016/j.concog.2009.12.003

Lugrin, J.-L., Latt, J., and Latoschik, M. E. (2015). "Avatar anthropomorphism and illusion of body ownership in VR," in *2015 IEEE Virtual Reality (VR)* (Arles), 229–230. doi: 10.1109/VR.2015.7223379

MacCallum, R. C., Widaman, K. F., Zhang, S., and Hong, S. (1999). Sample size in factor analysis. *Psychol. Methods* 4, 84–99. doi: 10.1037/1082-989X.4.1.84

Maselli, A., Kilteni, K., López-Moliner, J., and Slater, M. (2016). The sense of body ownership relaxes temporal constraints for multisensory integration. *Sci. Rep.* 6:30628. doi: 10.1038/srep30628

Maselli, A., and Slater, M. (2013). The building blocks of the full body ownership illusion. *Front. Hum. Neurosci.* 7:83. doi: 10.3389/fnhum.2013.00083

Maselli, A., and Slater, M. (2014). Sliding perspectives: dissociating ownership from self-location during full body illusions in virtual reality. *Front. Hum. Neurosci.* 8:693. doi: 10.3389/fnhum.2014.00693

McMahan, R. P., Bowman, D. A., Zielinski, D. J., and Brady, R. B. (2012). Evaluating display fidelity and interaction fidelity in a virtual reality game. *IEEE Trans. Vis. Comput. Graph.* 18, 626–633. doi: 10.1109/TVCG.2012.43

Mori, M., MacDorman, K. F., and Kageki, N. (2012). The uncanny valley [from the field]. *IEEE Robot. Automat. Magaz.* 19, 98–100. doi: 10.1109/MRA.2012.2192811

Normand, J.-M., Giannopoulos, E., Spanlang, B., and Slater, M. (2011). Multisensory stimulation can induce an illusion of larger belly size in immersive virtual reality. *PLoS ONE* 6:e16128. doi: 10.1371/journal.pone.0016128

Osimo, S. A., Pizarro, R., Spanlang, B., and Slater, M. (2015). Conversations between self and self as sigmund freud—a virtual body ownership paradigm for self counselling. *Sci. Rep.* 5:13899. doi: 10.1038/srep13899

Padrao, G., Gonzalez-Franco, M., Sanchez-Vives, M. V., Slater, M., and Rodriguez-Fornells, A. (2016). Violating body movement semantics: neural signatures of self-generated and external-generated errors. *Neuroimage* 124, 147–156. doi: 10.1016/j.neuroimage.2015.08.022

Peck, T. C., and Gonzalez-Franco, M. (2021). Avatar embodiment. A standardized questionnaire. *Front. Virt. Real.* 1:44. doi: 10.3389/frvir.2020.575943

Peck, T. C., Seinfeld, S., Aglioti, S. M., and Slater, M. (2013). Putting yourself in the skin of a black avatar reduces implicit racial bias. *Conscious. Cogn.* 22, 779–787. doi: 10.1016/j.concog.2013.04.016

Peck, T. C., and Tutar, A. (2020). The impact of a self-avatar, hand collocation, and hand proximity on embodiment and stroop interference. *IEEE Trans. Vis. Comput. Graph*. 26, 1964–1971. doi: 10.1109/TVCG.2020.2973061

Petkova, V., Khoshnevis, M., and Ehrsson, H. H. (2011). The perspective matters! multisensory integration in ego-centric reference frames determines full-body ownership. *Front. Psychol.* 2:35. doi: 10.3389/fpsyg.2011.00035

Petkova, V. I., and Ehrsson, H. H. (2008). If I were you: perceptual illusion of body swapping. *PLoS ONE* 3:e3832. doi: 10.1371/journal.pone.0003832

Piryankova, I. V., Wong, H. Y., Linkenauger, S. A., Stinson, C., Longo, M. R., Bülthoff, H. H., et al. (2014). Owning an overweight or underweight body: distinguishing the physical, experienced and virtual body. *PLoS ONE* 9:e103428. doi: 10.1371/journal.pone.0103428

Pomes, A., and Slater, M. (2013). Drift and ownership toward a distant virtual body. *Front. Hum. Neurosci.* 7:908. doi: 10.3389/fnhum.2013.00908

Roth, D., and Latoschik, M. E. (2019). Construction of a validated virtual embodiment questionnaire. *arXiv preprint* arXiv:1911.10176.

Roth, D., and Latoschik, M. E. (2020). Construction of the virtual embodiment questionnaire (VEQ). *IEEE Trans. Vis. Comput. Graph*. 26, 3546–3556. doi: 10.1109/TVCG.2020.3023603

Roth, D., Lugrin, J.-L., Büser, J., Bente, G., Fuhrmann, A., and Latoschik, M. E. (2016). "A simplified inverse kinematic approach for embodied VR applications," in *2016 IEEE Virtual Reality (VR)*, 275–276. doi: 10.1109/VR.2016.7504760

Roth, D., Lugrin, J.-L., Latoschik, M. E., and Huber, S. (2017). "Alpha IVBO - construction of a scale to measure the illusion of virtual body ownership," in *Proceedings of the 2017 CHI Conference Extended Abstracts on Human Factors in Computing Systems* CHI EA '17 (New York, NY: Association for Computing Machinery), 2875–2883. doi: 10.1145/3027063.3053272

Satyavolu, S. K., Creem-Regehr, S. H., Stefanucci, J. K., and Thompson, W. B. (2014). "Pointing from a third person avatar location: does dynamic feedback help?," in *Proceedings of the ACM Symposium on Applied Perception* SAP '14 (New York, NY: Association for Computing Machinery), 95–98. doi: 10.1145/2628257.2628272

Skarbez, R., Brooks, F. P. Jr., and Whitton, M. C. (2017). A survey of presence and related concepts. *ACM Comput. Surv*. 50:96. doi: 10.1145/3134301

Slater, M., Pérez Marcos, D., Ehrsson, H., and Sanchez-Vives, M. (2008). Towards a digital body: the virtual arm illusion. *Front. Hum. Neurosci.* 2:6. doi: 10.3389/neuro.09.006.2008

Slater, M., Spanlang, B., Sanchez-Vives, M. V., and Blanke, O. (2010). First person experience of body transfer in virtual reality. *PLoS ONE* 5:e10564. doi: 10.1371/journal.pone.0010564

Steed, A., Frlston, S., Lopez, M. M., Drummond, J., Pan, Y., and Swapp, D. (2016). An "in the wild" experiment on presence and embodiment using consumer virtual reality equipment. *IEEE Trans. Vis. Comput. Graph*. 22, 1406–1414. doi: 10.1109/TVCG.2016.2518135

Steptoe, W., Steed, A., and Slater, M. (2013). Human tails: ownership and control of extended humanoid avatars. *IEEE Trans. Vis. Comput. Graph*. 19, 583–590. doi: 10.1109/TVCG.2013.32

Toothman, N., and Neff, M. (2019). "The impact of avatar tracking errors on user experience in VR," in *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)* (Osaka), 756–766. doi: 10.1109/VR.2019.8798108

Tsakiris, M., Prabhu, G., and Haggard, P. (2006). Having a body versus moving your body: how agency structures body-ownership. *Conscious. Cogn*. 15, 423–432. doi: 10.1016/j.concog.2005.09.004

van der Hoort, B., Guterstam, A., and Ehrsson, H. H. (2011). Being barbie: the size of one's own body determines the perceived size of the world. *PLOS ONE* 6:e20195. doi: 10.1371/journal.pone.0020195

Waltemate, T., Gall, D., Roth, D., Botsch, M., and Latoschik, M. E. (2018). The impact of avatar personalization and immersion on virtual body ownership, presence, and emotional response. *IEEE Trans. Vis. Comput. Graph*. 24, 1643–1652. doi: 10.1109/TVCG.2018.2794629

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