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The Avatar as a Tool: The Critical Role of the First-Person Perspective in Linking Embodiment and Presence

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Abstract

In virtual reality, presence, (i.e. the feeling of being in a virtual environment), and embodiment, (i.e. the feeling of being an avatar within that environment), are closely related aspects of the user experience. Embodiment is thought to promote presence by providing a bodily reference through which users perceive and interact with the virtual environment. However, not all virtual bodies (or perspectives) affect embodiment and presence in the same way. Research suggests that a first-person perspective plays a key role in determining whether an avatar becomes integrated into the user's body representation and how strongly it influences presence compared to a third-person perspective. The present study investigated whether manipulating embodiment in a first-person avatar affects presence more strongly than in a third-person avatar. To test this, embodiment was manipulated by introducing varying levels of visuomotor delay in avatars viewed from either a first-person or a third-person perspective. Presence was continuously assessed using a by applying detrended fluctuation analysis (DFA) to velocity time-series derived from movement data. DFA identifies long-range correlations in movement dynamics that have been shown to respond to changes in presence. Results indicated that long-range correlations changed only when embodiment was manipulated in first-person avatars, while third-person manipulations produced stable patterns across delay levels. These findings suggest that perspective determines whether an avatar becomes integrated into the user's body representation, highlighting the central role of embodiment in shaping presence in virtual environments. We discuss how these results may inform design and development decisions of VR applications.

Keywords: *Virtual Reality; Body Representation; Presence; Embodiment; DFA; First-Person*

Introduction

When simulating experiences using virtual reality (VR) for training, entertainment, or therapy, the feeling of being in the virtual environment is considered a defining quality of the experience. One core aspect closely linked to presence is the feeling of experiencing a virtual body or avatar as the actual self, also called embodiment (Kilteni et al., 2012; K. M. Lee, 2004). The avatar serves as a virtual body and as a spatial reference within the larger virtual space,

influencing how users interact with and perceive the environment. Characteristics such as height (Van Der Hoort et al., 2011; Walker et al., 2019), ethnicity (J.-E. R. Lee et al., 2014; Peck et al., 2013), or the degree to which the avatar resembles the user (Waltemate et al., 2018), have been demonstrated to affect interaction inside and outside of virtual environments. For example, in a study by Reinhard et al. (2020), experiencing older avatars subsequently led to slower real-world walking speeds. These examples show that the extent to which an avatar becomes integrated into the user's internal body representation can influence behavior and shape the outcomes of simulated VR experiences (Ratan et al., 2020). In this paper we investigated the extent to which a key characteristic of an avatar, namely the user's first-person perspective, mediates whether an avatar becomes integrated into the body representation of the user.

Within the embodiment literature, the feeling of experiencing a virtual body as one's own is considered a subset (Forster et al., 2022), an integral component (Halbig & Latoschik, 2024), or even a prerequisite (Haans & Ijsselsteijn, 2012) for the emergence of presence.

To study the process of integrating the avatar into the user's body we focused on VR based frameworks that describe the intersection of embodiment and presence. Haans and Ijsselsteijn (2012) proposed a framework describing avatars as functional or phenomenological extensions of the body, based on the work of Blanke and Metzinger (2009), Gallagher (2005), and Metzinger (2003). They argue that avatars, like tools (Cardinali et al., 2009), can be integrated into the user's body representation, resulting in a temporary experience of a unified body that enables more fluent interaction.

Early research on the integration of functional extensions can be seen in the work of Biocca and Rolland (1998), who examined how participants adapted to viewing the world through a head-mounted display with cameras positioned above and in front of their eyes. After the devices were removed, participants continued to show pointing errors, suggesting a lasting adaptation to the new body representation. Similar aftereffects have been replicated in more recent virtual experiences (Nowak & Rauh, 2005; Seo et al., 2017) and have also been found to also result from phenomenological extensions, where changes in behavior extended to attitudes and self-perception, an effect known as the Proteus Effect (Yee & Bailenson, 2007).

Forster et al. (2022) argue in their Implied Body Framework that whether an avatar becomes integrated into the body representation depends largely on perspective. The framework suggests that users may embody different avatars, but that a first-person perspective is the strongest determinant of integration. According to this theory, for presence to occur, embodiment must exist at least in a minimal form to enable the active perception of the virtual environment, even if this only means that the user can explore the virtual world by turning their head while remaining a "ghost," without a visible avatar.

Building on this rationale, we investigated whether manipulating the embodiment of a first-person avatar influences presence more strongly than manipulating the embodiment of a third-person avatar. If the theory that first-person perspective mediates body integration is correct, manipulating an avatar associated with a first-person perspective should lead to a stronger change in presence than manipulating an avatar associated with a third-person perspective.

To capture this integration process, an adaptive and continuous method for assessing presence was applied which identifies shifts in presence during the embodiment of different

avatars in response to embodiment manipulations. Through this approach we identified the influence of manipulating embodiment associated with a first-person perspective avatar compared to embodiment associated with a third-person perspective avatar. In contrast to previous attempts to quantitatively capture tool embodiment in VR (Alzayat et al., 2019), this method provides a live and continuous output, making it potentially applicable to a wide range of future VR environments.

The present paper operationalized the assessment of presence as the measurement of the experience that emerges from the quality of interaction between the user and the environment. Grounded in complex dynamical systems analysis, this approach has previously been used to continuously and objectively measure presence (Harris, Van den Berg, et al., 2025; Renaud et al., 2007) as well as embodiment (Richardson & Chemero, 2010a), and tool integration (Dotov et al., 2010) but it has not yet been applied in contexts of integration an entire virtual avatar into the users body representation. At this point, we want to clarify that our use of the terms objective and subjective is meant to refer to the objective assessment as not being influenced by subjective self-reporting, rather than implying ground truth. At the same time, subjective explicitly refers to assessments that are affected by the biases and limitations associated with self-reporting.

Complex dynamical systems analysis evaluates the quality of coordination in biological systems, including those biological systems that have been augmented or extended with biological and non-biological systems or tools. The approach considers different determinants of a well-coordinated system. In well-coordinated (also referred to as interaction-dominant) systems, behavior is said to emerge from the interplay of components, agents, and situational factors or constraints rather than from fixed functions (Den Hartigh et al., 2017; Diniz et al., 2011; Richardson & Chemero, 2010a; Van Orden et al., 2003). Such a system, if unperturbed, produces emergent states that are temporarily bound through “soft assembly,” described as structural elements acting as a coherent unit (Kelso, 2009; Richardson & Chemero, 2010b). The user's experience of presence when interacting with VR, and by extension embodiment, can be understood as a softly assembled state that emerges from the interaction between the avatar, the virtual environment, and the VR hardware (Harris, Van den Berg, et al., 2025).

Research by Dotov and colleagues (2010, 2017) shows that the integration of tools into the body representation can be assessed using complex dynamical systems analysis. Their experiments demonstrate how tools can become softly assembled into a coherent, interaction-dominant system, turning “transparent” as attention shifts from movement coordination to task performance. This approach highlights how augmentations or extensions, whether functional or phenomenological, can become integrated into the user’s body representation. When integrated, avatars as virtual extensions become transparent or “non-mediated,” a concept originating in early presence literature that describes how the medium fades and the user experiences the illusion of perceiving the environment directly (Lombard & Ditton, 2006). In this state, users can focus on the task rather than on coordination. In this regard, we propose that complex dynamical systems analysis can be used to identify whether a first-person perspective facilitates the integration of the avatar into the user’s body representation by revealing when shifts in presence occur.

Adjacent embodiment research has focused on identifying subcomponents (Kilteni et al., 2012; Longo et al., 2008) and defining the quantitative and qualitative thresholds required for embodiment to emerge (Ismail & Shimada, 2016; Jeunet et al., 2018). Common frameworks describe the subcomponents of agency, ownership, and location (Guy et al., 2023; Kilteni et al., 2012; Nostadt et al., 2020), which have also been linked to specific brain regions in neuroimaging studies (De Borst et al., 2020; Seghezzi et al., 2019; Segil et al., 2022; Tsakiris, 2010). Key measures advancing the study of embodiment include proprioceptive drift to assess self-location (Botvinick & Cohen, 1998; Guy et al., 2023) and skin conductance responses (SCR) to assess ownership (Ma & Hommel, 2013).

Our focus was on manipulating embodiment through agency, as this subcomponent has been shown to be particularly effective compared to other subcomponents in how strongly it affects the experience of embodiment (Guy et al., 2022; Kilteni et al., 2012; Peck & Gonzalez-Franco, 2021). The experience of agency is described as arising from correctly predicted outcomes of actions in the visual, motor, or tactile domain. Users thereby perceive themselves as the causal factor of the actions, experienced through the control of their own body (Seghezzi et al., 2019).

An assessment method specific to agency is attentional (also referred to as intentional) binding, which captures how actions and their outcomes are perceived as more voluntary when they occur close together rather than delayed (Marasco et al., 2018). A related but distinct measure is sensory attenuation, which refers to the reduced perceptual intensity of sensory feedback when it results from one's own actions rather than from an external source (Fritsch et al., 2021). Similar to proprioceptive drift or threat responses mentioned above, these approaches have advanced the study of embodiment but remain limited to controlled, discrete tasks and are somewhat less suited to dynamic VR environments. Specifically, these approaches provide snapshots rather than continuous measures that capture how experiences evolve over time.

To bridge this methodological gap, the present study applied complex dynamical systems analysis, following the rationale used in studies of tool embodiment to capture the integration of virtual avatars through changes in interaction-dominant dynamics. By examining these dynamics, the study tested whether manipulating embodiment in a first-person avatar influences presence, revealing whether the avatar is integrated into the user's body representation. Observing a change in presence would indicate that the avatar was experienced as the user's own body, showing successful integration of the virtual body and the strong influence of perspective on presence.

Methods

Participants

The experiments were conducted at Utrecht University in Utrecht, the Netherlands between the 29th of April and the 27th of September 2024, involving students recruited via the university's participant recruitment system SONA Systems. Requirements included being fluent in English, having no cognitive impairments, having no mental illness or hearing difficulties, having normal or corrected acuity, and requiring no walking aid. Cognitive impairments and mental illnesses (i.e. presence of clinical/psychiatric diagnosis according to DSM-IV) were self-indicated and screened formally.

We collected data from *n* = 53 participants who each experienced all delay settings twice within the same experimental task. The average age of the sample was *M* = 21.8 (*SD* = 1.47) of which *n* = 13 were male, *n* = 39 were female, and *n* = 1 participant preferred not to indicate their gender. Of all the participants, *n* = 1 person owned a VR headset, *n* = 25 tried VR at least once, and the rest never tried VR (*n* = 28). This characterized our sample as comparatively inexperienced, particularly when contrasted with a similar online sample (*N* = 34) in one of our previous studies in which participants used their own headsets and reported an average of *M* = 2.83 hours of play per week (*SD* = 2.27) and *M* = 1.50 years of VR experience (*SD* = 1.07) (Harris, Van den Berg, et al., 2025). Finally, while we did not control for sex, we expected little to no effect on motor coordination (Stanney et al., 2020). For this reason, inter-pupillary distance (IPD) was not recorded, as it is influenced by gender but gender-related effects were not the focus of this study.

This study was reviewed and approved by the Ethics Committee of the Faculty of Social and Behavioural Sciences of Utrecht University (Approval Number: 24-0123), dated April 1, 2024 and realized following the ethical principles outlined in the Declaration of Helsinki ("World Medical Association Declaration of Helsinki," 2013). All participants gave their informed consent for inclusion before they participated in the study.

Materials

The virtual environment was developed with Unity 3D game engine software, by the company ImproVive, and was adapted for research purposes in close collaboration with Utrecht University. The visual elements in the virtual environment were all specifically 3D-modeled to be used in the experiment. To present the virtual stimuli, a Meta Quest 2 VR headset was used which has an LCD with a resolution of 1832 x 1920 pixels and a refresh rate of 72 Hz, a Snapdragon XR2 CPU chip, 6 GB of RAM, 256 GB of storage and a 85 - 97 degree field of view (FOV) depending on the eyes proximity to the lenses. The headset also allows for 6 degrees of freedom (DOF) and uses controllers for user interaction. The application that ran the virtual environment was installed on the headset via a third-party software called SideQuest. To run the application, the headset needed to be tethered to a PC via a USB Type-C cable. The PC itself ran a second companion application enabling the starting and stopping of the data recording, selecting the experimental condition, and reading configuration and saving raw data files. Settings for each condition, including the amount of delay, could be adjusted via a JSON script file. Finally, the application also mirrored the participant's headset display allowing the researcher to see the participant's perspective in real-time. The input for the later analysis was a time-series defined by a sequence of successive three-dimensional (x, y, z) positional coordinates stemming from the headset and controller movements over time. The raw movement data was collected at a frequency of 72 Hz and automatically saved to a CSV file on the PC's internal storage.

Demographic data was collected via the online survey platform Qualtrics. All the above data was then analyzed using MATLAB (version 2022b) and IBM SPSS Statistics (version 28.0.0.0.). The subjective rating of embodiment was performed using the software CARMA, developed by Girard (2014). The application works as a modernized version of the "continuous assessment methodology" or "affect rating dial" (Ijsselsteijn et al., 1998; Ruef & Levenson, 2007). It lets participants watch a video of their VR experience while they continuously rate how

they remembered their experience along a chosen dimension. The method has been found to demonstrate construct validity when used in VR related assessments including cybersickness (Kim et al., 2020; McHugh et al., 2019). Audio instructions played during the experimental task were generated using a free text-to-speech tool provided by the website www.naturalreader.com. An iPad was used to collect questionnaire data.

Procedure

The experiment followed a 2 x 6 design with two experimental groups (see Figure 1). The groups were defined by whether the third-person avatar shown in the virtual mirror (mirror delay condition) or the first-person avatar (avatar delay condition) (see Figure 2a) was manipulated in its embodiment through agency by applying various delay settings. To test whether embodiment affects presence stronger when a first-person avatar is manipulated, DFA exponents were defined as the outcome measures for presence and dependent variables. These were expected to vary with the degree of delay applied to the avatar's movements depending on the perspective in relationship to the avatar.

The procedure began with participants signing up for the study through the online participant platform SONA. The platform provided an initial description of the study, its duration of 1 hour in total, and possible negative effects, namely nausea. If participants met the inclusion criteria, they were invited to participate. On the testing day, all participants were welcomed, accompanied from the waiting room to the lab, and asked to read the information letter before signing the informed consent form. They then completed a few initial questions and afterwards received instructions on how to use the VR hardware and perform the task. The researcher prepared the headset by starting the screen recording and launching the application before the participant mounted the headset with the researcher's assistance. If necessary, participants were able to adjust the IPD within the headset based on their liking by choosing one of three settings. Once inside VR, participants found themselves in a game lobby (see Figure 2a and 2b). Here they could get familiar with the look and feel of VR, experience having a virtual body, and ask the researcher questions if anything was unclear. After completing the practice room, participants pressed a virtual button (see Figure 2d) to teleport into the room where the experimental task was performed (from hereon called task room). The task room environment was identical for both mirror delay and avatar delay conditions, and up to this point all participants had been exposed to the same settings without experiencing any delay settings (see Figure 1).

In the task room, participants were assigned to one of the two conditions. In both conditions, they first listened to the same audio instructions, which explained the procedure, the trials, what to do between trials, and how the task ended. In the mirror delay condition, the participant's real-world body movements were synchronized with the avatar that was associated with the first-person perspective, while movements of the avatar in the mirror reflection (associated with the third-person perspective) were delayed relative to the participant's real-world movements. In the avatar delay condition, the settings were reversed. The avatar in the first-person perspective was delayed, and the avatar in the mirror reflection was synchronized (see Figure 1).

Figure 1

Schematic overview illustrating the participant's progression through the study procedure including the experimental conditions with the application of delay settings

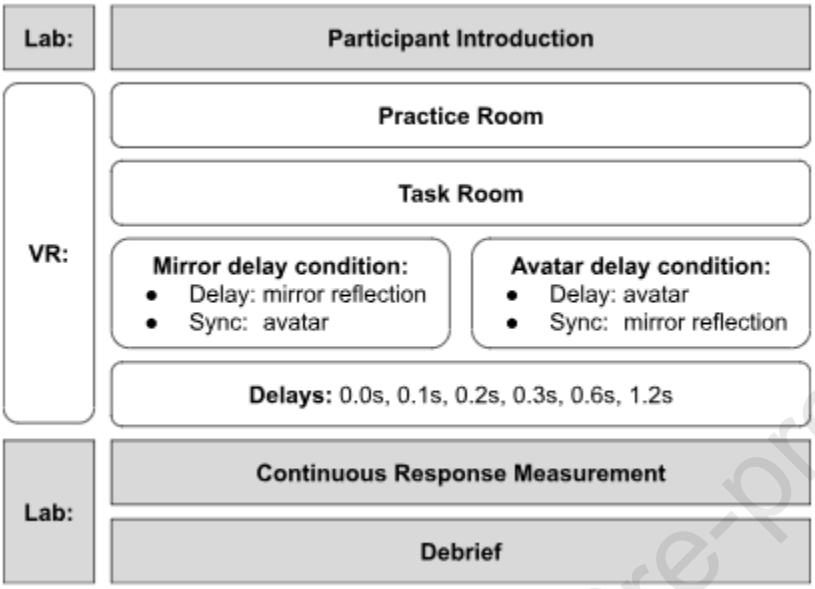
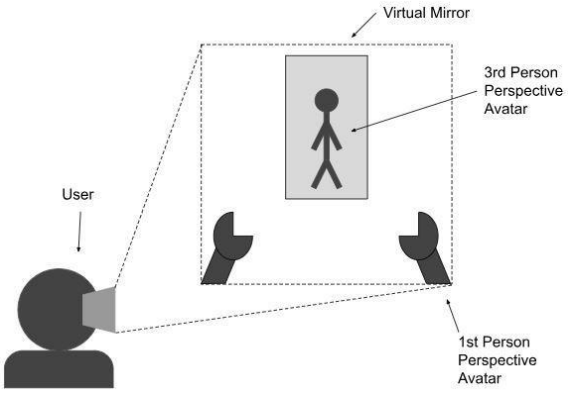


Figure 2

Stimuli of the practice room and the task room including interactive elements, mirror, and views of the first-person avatar and third-person avatar used for both the mirror delay and avatar delay condition

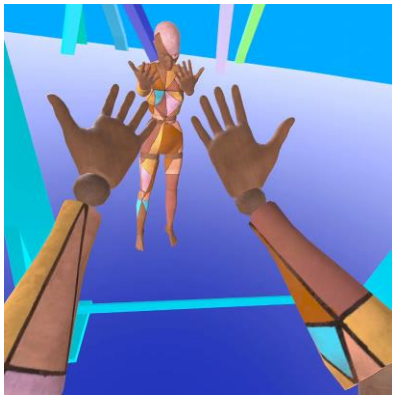
(a)

Schematic visualization showing the user experience and the manipulation of the avatars in relation to the virtual elements in the mirror delay and avatar delay condition



(b)

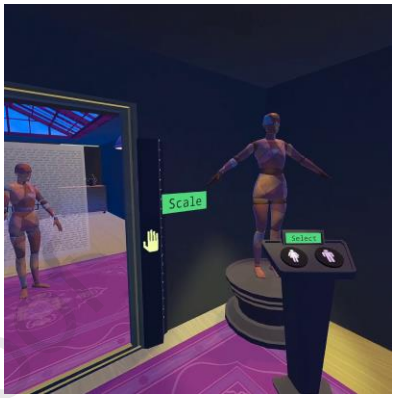
A first-person view of the mirror in the task room with tracked hands/arms and the reflection of the entire avatar



(c)
A view of the task room with the first-person avatar on the left and the third-person avatar on the right side

(d)
The start button to get from the practice room to the task room

(e)
Practice room with a mirror and a kiosk to change the appearance from male to female



The experimental task lasted about 13 minutes and consisted of 12 trials. Each trial lasted 30 seconds, followed by a 30 second pause. Prior to the first trial and after the last trial, participants received instructions on how to position themselves and how to remove the headset with the help of the researcher. During the pauses, the instructions were repeated and participants were asked to remain still until the next trial began. The 12 trials were randomly assigned to six different delay settings, resulting in two trials per delay setting within each condition.

At the end of the task, a final 10 second countdown signaled completion. The researcher then assisted the participant in removing the controllers and instructed them to take off the headset, sit down, and read the instructions for using the CARMA software. During this time, the researcher connected the headset to the PC and saved the video file and movement data. The video recording was split into two separate files, one containing footage from the practice room and the other from the task room.

The first video file was loaded into the CARMA software and prepared using the following settings. The axis labels were defined as “Strong Agency/Control” (upper label) and “Weak Agency/Control” (lower label). The axis maximum and minimum values were set to 100 and -100, with a starting value of 0. The color map and bin size (1 second) were left at default, and the sampling rate was set to the maximum of 30 Hz. After reading the instructions, participants completed a practice round using footage from the practice room. Once finished, the researcher saved the CARMA output file and then loaded the second video containing the task room. Participants repeated the rating procedure for the experimental task. After completion, the researcher saved the output file and debriefed the participant.

Stimuli

The virtual environment was designed to test the hypothesis by manipulating embodiment through a delayed mirror setup. As demonstrated by Ismail & Shimada (2016) and Latoschik et al. (2016), a delayed response introduces a precise delay between the participant’s

movements and the corresponding visual feedback, also referred to as multisensory correlation. The first-person avatar provided users with a first-person view of a virtual body that mirrored their own movements. In contrast, the mirror reflection also mirrored the user's movements but was positioned at a distance (see Figure 2a and 2b). Using the reflection as a stimulus, participants could directly observe these visuomotor correlations in the context of full-body reflections.

The setup allowed for independent manipulation of delay in either the mirror reflection or the avatar experienced from a first-person perspective. By comparing the effects of delaying the avatar's reflection (mirror delay condition) with delaying the avatar itself (avatar delay condition), we examined the role of first-person perspective in linking embodiment and presence. All other aspects of the stimulus, including progression through the virtual environment, remained identical.

Participants first appeared in the practice room, which included a virtual mirror, a virtual kiosk to adjust the avatar's height and appearance, and a button to launch the task room (see Figure 2). The avatar had a humanoid form with abstract colors (see Figure 2d and 2e). Using the controllers, participants could move and teleport freely in the practice room. In the task room, teleportation was disabled, and participants stood in front of a mirror in a large, empty space. Here, they remained stationary and listened to audio instructions presented through the headset's built-in speakers.

Because the arms, torso, legs, and feet of the participants were not tracked, these movements were inferred through inverse kinematics (IK). IK predicted the untracked parts of the body using data from the tracked headset and hand controllers. This process could introduce small inaccuracies; therefore, participants were asked to avoid overt leg movements, as misalignment between the virtual and real body could affect the experience of embodiment in unpredictable ways (Porssut et al., 2021). In the task room, participants had a few moments to prepare before a countdown appeared, signaling the start of the task.

Task

In the task room, a computer-generated voice instructed participants to use their controllers to spell out the words "Utrecht University" or "The Netherlands" in the space in front of them. This task was repeated 12 times, with half of the trials randomly assigned to "Utrecht University" and the other half to "The Netherlands". These phrases were chosen because they were familiar and easy to spell for all participants, who were students of the university. Participants were asked to trace the words in the air with their dominant hand while keeping the mirror in view and to spell each word without mistakes. Randomization helped minimize boredom and repetition effects, ensuring that participants remained attentive and engaged throughout the task. The variation in phrases was not introduced as an experimental factor but rather as a means to sustain motivation and reduce potential artifacts from fatigue or disengagement, as participants could not anticipate which word would appear next.

In the avatar delay condition, the instructions were slightly adjusted to emphasize focusing on the hand of the first-person avatar, as the relevant movements occurred closer to the participant (see Figure 2a and 2b). To direct attention toward the manipulated first-person avatar, participants were told that the researcher would be checking their spelling. In the mirror delay condition, the manipulated avatar appeared as a reflection in the mirror, centered and

positioned farther away, while in the avatar delay condition, the manipulated avatar was visible from the participant's own viewpoint, showing their arms, torso, and legs (see Figure 2c). These adjustments ensured that participants attended to the correct avatar in each condition rather than simply looking straight ahead at the mirror reflection.

Manipulations

To manipulate embodiment in this study, we focused on agency, a well-defined subcomponent of embodiment (Guy et al., 2022; Seghezzi et al., 2019; Tsakiris et al., 2006), we use the term agency to include all sensations related to the experience of controlling one's movements and their effects in the environment. Agency was manipulated by varying the degree of multisensory correlation between the participants' movements and the corresponding visual feedback. Reducing this correlation through visuomotor delay has been shown to disrupt agency and, in turn, embodiment (Jeunet et al., 2018; Waltemate et al., 2018).

While we acknowledge the implications of focusing on a single subcomponent, we found this choice justified to ensure a precise and controlled manipulation. Agency was selected because it has a strong influence on other subcomponents, particularly ownership (Guy et al., 2023; Tsakiris et al., 2006), and because it can be reliably controlled through delay. This made agency an effective means to manipulate embodiment within the scope of this study. In this paper, we use the term agency when referring to specific manipulations and outcome measures, and the term embodiment when referring to its broader relationship to presence.

The agency participants experienced over the avatar was tested under different delay settings. All participants experienced all delay settings, which were sequentially randomized for each participant. The exact settings were 0.0, 0.1, 0.2, 0.3, 0.6, and 1.2 seconds of delay relative to the participant's real movements. The 0.0 seconds setting acted as a control and similar to the 0.1 seconds setting it was below the noticeable threshold (Tsakiris et al., 2006). The 0.2 and the 0.3 seconds settings were on the barely noticeable or noticeable threshold (Ismail & Shimada, 2016; Waltemate et al., 2018), while the 0.6 and 1.2 seconds settings were overtly noticeable (Ismail & Shimada, 2016; Jeunet et al., 2018). During the pauses, the delay was kept at 0.0 seconds. These settings ensured the inclusion of two levels for below noticeable, noticeable, and overly noticeable delays, making sure to capture potential individual differences in how participants experienced delays. Delay settings were applied to either the avatar in the mirror reflection (mirror delay condition) or the avatar associated with the first-person perspective (avatar delay condition).

Data Analysis

To assess the presence outcome measure, movement data was continuously recorded throughout the entire task at a sampling rate of 72 Hz. The data sources included the head and both the left and right controllers, each represented by three coordinates, resulting in a total of nine positional coordinate variables (dimensions x, y, z). The raw movement time-series was then segmented to include only the 12 trials, excluding pauses, transitions, and practice room data. Outlier detection was performed on each time-series, with values exceeding three median absolute deviations being removed on a case-wise basis. Ultimately, for each participant, 12 (2 x 6) time-series, each lasting 30 seconds, were retained from the initial raw data, representing the different delay settings.

Next, we extracted the degree to which the participants volitionally interacted with the virtual environment by assessing their active control over movement. Active motor control was operationalized in terms of changes in velocity. Motor control requires the careful coordination of applied force, which are contributed by patterns of activation in the neuromuscular organizations across the body (Dotov et al., 2010). In the literature, studies have applied a similar approach to running (Simperingham et al., 2016), walking (Auvinet et al., 2002), and balancing (Montull et al., 2023).

While assessing the quality of motor control in volitional movements has traditionally remained in the realm of movement science it has also been shown to be applicable in research surrounding presence and related concepts (Harris, Van den Berg, et al., 2025; Maneuvrier et al., 2023; Renaud et al., 2002, 2007). This operationalization served as a key step in translating the 12 raw data time-series from positional coordinates into meaningful movement dynamics (changes in velocity over time) that were suitable for complex dynamical systems analysis.

By calculating velocity, we calculated the key indicator of active motor control. As velocity is calculated based on changes in distance, we used the head as a dynamic reference point, measuring distances from the head to the left and right hands. This yielded two velocity time-series per trial, reflecting participants' volitional interactions through hand movements. These time-series were subjected to Detrended Fluctuation Analysis (DFA), a method for quantifying the temporal structure in time-series data and identifying long-range correlations. Long-range correlations statistically describe how values in a time-series can remain structurally related even when separated by long intervals. This property helps distinguish between purely random noise, where values are independent, and structured dynamics, where dependencies across time suggest a coordinated system with memory that evolves as a result of dynamic interaction with internal and environmental constraints. In virtual reality research, changes in long-range correlations have been linked to head-tracking and eye tracking behaviors indicative of changes in presence and related concepts such as cybersickness (Harris, Van den Berg, et al., 2025; Maneuvrier et al., 2023; Renaud et al., 2002, 2007).

The relevance of long-range correlations extends beyond presence research, as they are a hallmark of interaction-dominant systems in both physiological and behavioral contexts (Den Hartigh et al., 2015, 2018; Grönlund et al., 2012; Mansfield et al., 2001; Peng et al., 1995; Werner, 2010; Wijnants et al., 2012). Hence, DFA is well-suited for our aim of analyzing the temporal structure in the movement time-series in this experiment, and is an effective method for assessing how movement dynamics changed across the different delay settings.

The DFA outcome measures, DFA exponents (α), which describe the strength of long-range correlations, were calculated separately for the right and left hands and then averaged for each delay setting and participant. This averaging was necessary given the small sample size, as relying on a single hand's data would not provide sufficient statistical power. DFA exponents typically range between $\alpha = 0.5$ and $\alpha = 1.5$. Values near $\alpha = 0.5$ (white noise) indicate random, unstructured patterns of variations, while values approaching $\alpha = 1.5$ (Brownian noise) reflect rigid, overly-structured patterns. Values around $\alpha = 1.0$ (pink noise) are produced by complex dynamic systems with long-range correlations, characteristic of interaction-dominant behavior. In calculating the DFA exponent values, we aimed to assess whether variations in movement dynamics related to presence coincided with changes in agency across the different delay settings. Using the DFA exponents together with the CRM outcome measures, we performed a

repeated measures analysis of variance (RM-ANOVA). The two factors were the avatar perspectives in which agency was manipulated, and the within-subject levels were defined by the delay settings applied to the avatars in each condition. To test the assumptions of the RM-ANOVA, we used Mauchly's Test of Sphericity. If this assumption was violated ($p < .05$), we applied corrections using the Huynh-Feldt method. Normality was assessed with Shapiro-Wilks. Where appropriate, we conducted equivalence tests, reporting effect sizes and 90% confidence intervals to evaluate whether statistically significant differences were negligible or meaningful. We defined negligible differences as smaller than one fifth of the typical variability (a commonly used 'small effect' threshold) (Lakens, 2017).

The goal was to determine whether the presence outcome measure, as indicated by DFA exponent values, differed across the six delay settings, thereby suggesting that changes in embodiment influenced presence. We report F, p, partial η^2p, and 95% or 90% confidence intervals.

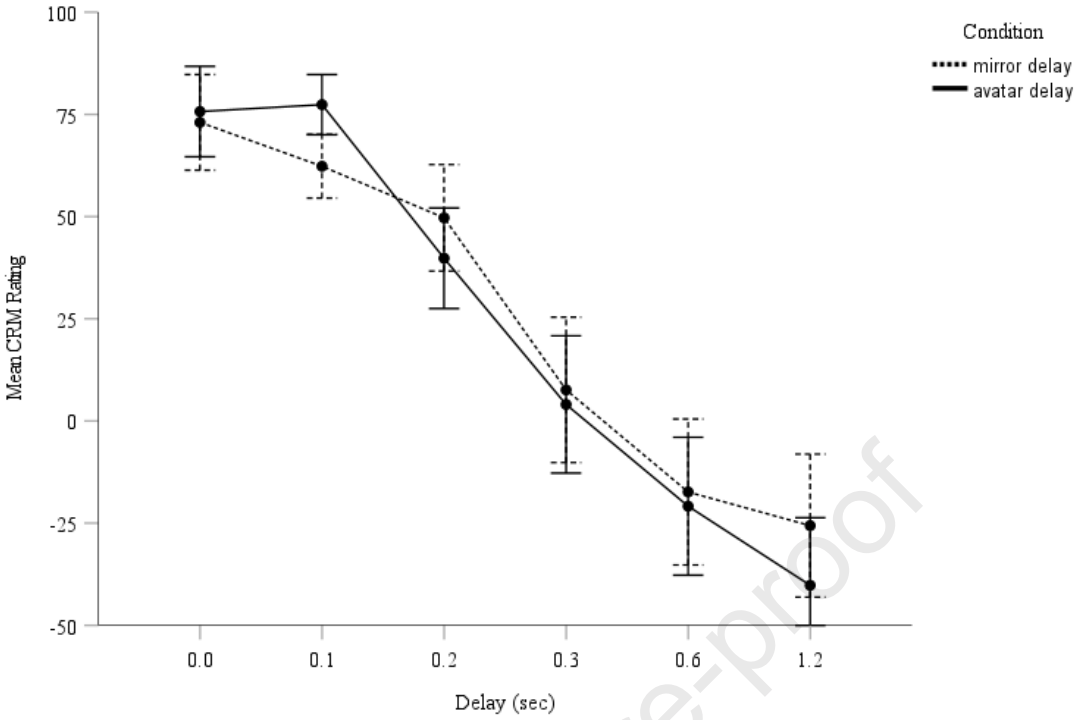
Results

Participants did not report meaningful differences in agency between first-person and third-person avatars, $F(1, 51) = .125$, $p = .725$, $\eta^2p = .002$, and the interaction effect also failed to reach significance, $F(2.552, 255) = 1.481$, $p = .227$, $\varepsilon = .510$, $\eta^2p = .028$. These results led us to deduce that increasing delays reduced agency, but they did so in almost the same way regardless of perspective. This pattern is reflected in the parallel lines in Figure 3, which suggest that the effect of delay was consistent across conditions. To test this further, we checked whether the absence of significance could be interpreted as equivalence. Comparing mirror delay and avatar delay condition means showed only a small difference, $M = 2.302$, $SD = 6.520$, $p = .725$, CI [-10.787, 15.392], but the confidence intervals extended well beyond our negligible difference range (±1.304). The same held for the pairwise comparison at the highest delays, where the difference also failed to reach significance and again fell outside the equivalence range ($M = -14.602$, $SD = 12.032$, $p = .230$, CI [-38.758, 9.553]).

These findings carry two implications. First, the self-reported reductions in agency appear robust to perspective, with both avatars affected similarly by increasing delays. Second, the lack of significance does not automatically imply that the mirror delay and avatar delay conditions are equivalent. The equivalence tests show that the evidence is inconclusive. The reason for this being that while the data do not support a perspective-specific significant effect, they also do not rule one out as the confidence interval falls outside of the negligible difference range. This suggests that more data or different manipulations may be needed to establish whether perspective plays a role in shaping how agency links to presence.

Figure 3

Mean embodiment outcome measure (CRM rating) per delay setting compared between mirror delay and avatar delay conditions



The main effect of condition was not significant, $F(1, 51) = 3.036$, $p = .087$, $\eta^2p = .056$, but the interaction effect, which was the focus of this investigation, was, $F(3.991, 203.549) = 6.907$, $p < .001$, $\varepsilon = .798$, $\eta^2p = .037$. This specific effect demonstrated that differences between the conditions emerged only at certain delay levels (see Figure 4), suggesting that the within-subject effect of delay depended on which avatar was manipulated.

Figure 4 illustrates this pattern. At lower delays, presence was similar across conditions, but at higher delays the amount of presence associated with the first-person avatar (avatar delay condition) changed more strongly than presence associated with the third-person avatar (mirror delay condition). In line with the CRM ratings shown in Figure 3, delays reduced self-reported agency only in the mirror delay condition, whereas in the avatar delay condition, delays affected both agency and presence, as reflected in changes in self-reported agency and coordination dynamics. This suggests that the connection between embodiment and presence is stronger when the avatar body is experienced as one's own, likely because the virtual avatar is integrated into the body representation. This proposed state of integration infers the link between presence and embodiment via the first-person perspective.

To follow up these findings, we tested for equivalence. For the between-subject effect, the mirror delay condition ($M = .838$, $SD = .019$) and avatar delay condition ($M = .885$, $SD = .018$) differed by $M = –.049$, $SD = .027$, $p = .087$, CI [–.100, –.007]. Since this interval extended beyond the negligible range of ±.005, the results were not considered equivalent.

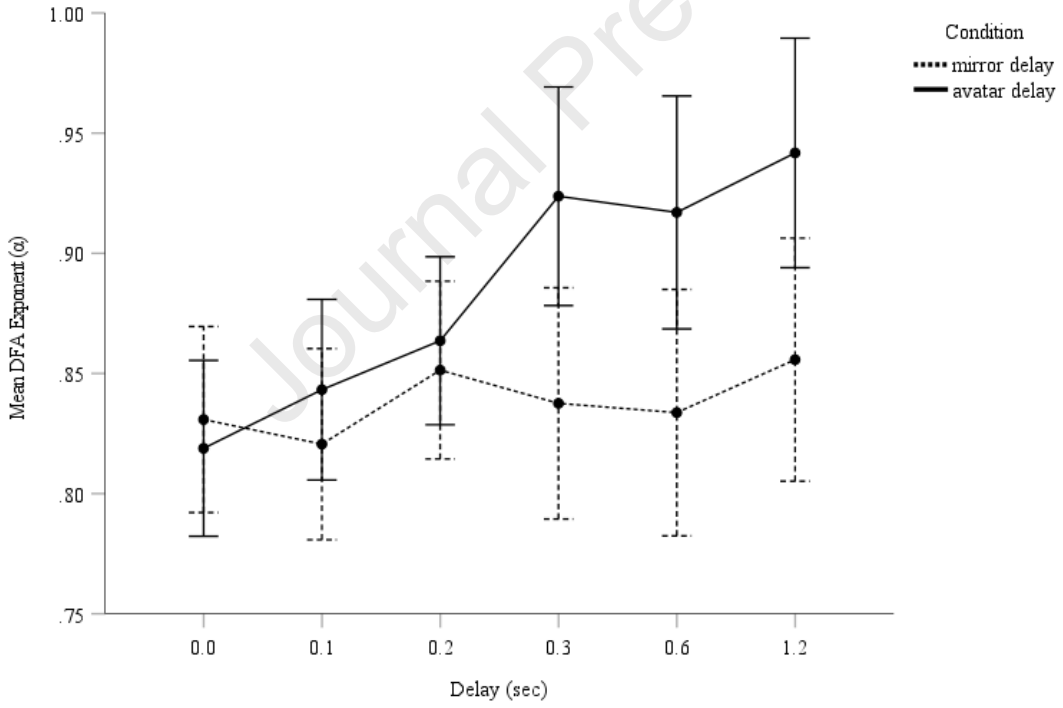
At the highest delay, the mirror delay condition had a mean DFA exponent of $M = .856$ ($SD = .025$), while the avatar delay condition had a higher value of $M = .942$ ($SD = .024$). The mean difference was significant, $M = –.086$, $SD = .035$, $p = .017$, CI [.016, .156], and here again the confidence interval fell outside the negligible range of ±.007. Both the significance and equivalence tests point to the same conclusion that the differences are meaningful. This

suggests that the two diverging presence outcome measures for each condition likely reflect the influence of perspective on the relationship between embodiment and presence.

Further analysis showed that in the avatar delay condition, most pairwise comparisons between increasing delay steps were not significant ($p > .05$). The only exception was the step between 0.2 seconds ($M = .864$, $SD = .017$) and 0.3 seconds ($M = .924$, $SD = .023$), where the difference was $M = –.060$, SD = .018, $p = .021$, CI [–.110, –.010], a value near the threshold of being a noticeable delay. The lack of differentiation at stronger delays suggests that participants may have adapted once the delay was becoming more obvious. Even so, the overall pattern was captured by a strong linear contrast, $F(1, 51) = 35.664$, $p < .001$, $\eta^2p = .412$, showing a clear trend in presence that was absent when the third-person avatar was manipulated (see Figure 4). This underscores the unique role of the first-person perspective in linking embodiment to presence and thereby affecting the integration of the avatar into the body representation.

Figure 4

Mean presence outcome measure via DFA exponent per delay setting compared between mirror delay and avatar delay conditions



In summary, presence assessed through interaction-dominant dynamics remained stable in the mirror delay condition, where the third-person avatar was delayed, even though agency changed. This pattern suggests that the third-person avatar was not fully integrated into the body representation, so the link between embodiment and presence did not emerge as strongly. In contrast, delaying the first-person avatar produced systematic, delay-dependent changes in the presence outcome measure, indicating that presence was affected by embodiment manipulations in this condition. Overall, the results indicate a key distinction,

namely that embodiment contributes measurably to presence only when the avatar is presumably integrated into the body representation. This integration held specifically for the first-person perspective but not for the third-person perspective.

Discussion

In this study, we examined whether manipulating the sense of agency through introducing delays can reveal whether an avatar becomes integrated into a user's body representation by assessing how strongly the manipulation affected the experience of presence. Increasing delays reduced reported agency in both the mirror delay and avatar delay conditions, but only the avatar delay condition also produced changes in presence. In the mirror delay condition, delays influenced subjective agency but left interaction dynamics unaffected. This suggests that avatars viewed from a third-person perspective were not fully integrated into the body representation, as the link between embodiment and presence was weaker.

The first-person perspective appeared to act as a key factor linking embodiment and presence. Increasing delay systematically affected both self-reported agency and DFA exponents, suggesting that the avatar body was more strongly integrated into the body representation from the outset. These results indicated that manipulating agency through delay influenced not only the user's sense of embodiment but also their sense of presence when the embodied avatar was experienced from the first-person perspective.

These findings aligned with the Implied Body Framework (Forster et al., 2022), which proposes that while multiple avatars can be embodied, only those considered plausible, based on multisensory correlations, become integrated into the body representation and thereby also affect presence. According to this framework, first-person avatars are most likely to pass this check and to drive presence, while third-person avatars are less likely to do so. Our results supported this assumption, as measurable changes in coordination dynamics and presence occurred only when the embodied avatar was experienced from the first-person perspective (De Borst et al., 2020; Forster et al., 2022; Gorisse et al., 2017).

To implement these findings in a practical way, designers and developers of VR applications should consider using first-person perspectives for their avatar when the aim is to give users the sense that their own body is experiencing the virtual environment rather than a disconnected or abstract avatar. This may not be necessary for all use cases, but for those that seek to affect the users' bodily responses to virtual or real environments, the first-person perspective is likely a crucial design choice.

One can imagine this approach implemented for emergency training scenarios where users may need to train coordinated movements in highly realistic and stressful situations, such as catastrophe aid training. At other times, when the focus primarily lies on performing the correct procedural steps or if the focus lies exclusively on dexterity, such as with remote-controlled robotic arms, this may not necessarily be the case. A different way to use these findings may be during scenarios when users are supposed to control an avatar and interact with a virtual environment, but the sense of presence needs to be decreased to avoid overwhelming them. Examples may be therapy settings for persons with severe trauma or PTSD, such as veterans, or phobics, who experience certain virtual reality environments as too intense. Third-person perspective avatars could be a valuable in-between step that provides users with a certain degree of agency and the ability to interact with the virtual world, while at

the same time reducing the impact of presence. This strategy could make it easier to approach certain sensitive scenarios without having to exclude the use of VR technology altogether.

A possible explanation of why perspective appears to be a strong determinant lies in the importance of the user's location and orientation relative to other elements in the visual scene including the avatar and the reflection of the avatar in the virtual mirror. The broader sense of self-location, defined by Kilteni et al. (2012, p. 375) as the “determinate volume in space where one feels to be located,” may not have extended to the mirror’s location, resulting in a disconnect. If the avatar was perceived as too distant, or if its orientation was misaligned with the self, the avatar could have been categorized as belonging to another body or in a broader sense belonging to the virtual environment. Prior work on the rubber-hand illusion and related paradigms shows that such misalignment can disrupt ownership and self-attribution (Ehrsson, 2007; Gallagher, 2005; Kilteni et al., 2012; Tsakiris et al., 2006). Therefor there is a possibility that spatial and temporal misalignment may have prevented the third-person avatar from being integrated. Future experiments should address this limitation and examine how factors such as self-location and orientation interact with perspective, specifically when manipulated through delay, to shape the process of integrating the avatar into the virtual body.

From the results we conclude that DFA can serve as an indirect assessment of whether an avatar has been integrated into the body representation by determining if presence has been influenced by embodiment manipulations. However, DFA has also been used to examine other aspects of VR experience, including cybersickness, which frequently correlates negatively with presence (Weech et al., 2019). Therefore, DFA should not be interpreted as a direct measure of presence but as a measure of coordination dynamics that reflect underlying presence states amongst other things.

Furthermore, the DFA measure, and particularly the DFA exponent, have a relative range and directionality that determine the quality of interaction dynamics, making absolute conclusions more difficult. In our previous study (Harris, Van Den Berg, et al., 2025), we found that during breaks in presence the DFA exponent increased, which led us to predict a similar pattern here. However, the increase in DFA with longer delay remained below $\alpha = 1.0$, suggesting a shift toward pink noise rather than an overall move toward more rigid, Brownian-like dynamics ($\alpha = 1.5$). This indicated that the argument of a more rigid organization with higher delay would only apply if the DFA exponent moved beyond $\alpha = 1.0$, reflecting increased temporal correlations typical of Brown noise. Since this was not the case, the current findings may instead point to a transition toward more structured but still adaptive dynamics. It is also possible that task demands changed with increasing delay, perhaps making the task easier to perform, which could have overridden the expected presence-related effects. At present, we do not have a conclusive explanation for this pattern. However, given these uncertainties, the pattern observed here differs from what has been reported in motor control studies (Ravi et al., 2020) and warrants further investigation in future work.

It is important to also note the limitations of the experimental design. Subjective ratings of embodiment and objective measures of presence represent abstract constructs that are not always directly comparable. Agency also represents only one subcomponent of embodiment, while other subcomponents can also strongly influence the user experience. Future research should examine how these interact in the context of the approach used here. Finally, another limitation concerns the possibility that participants anticipated the delay manipulation, which

may have influenced coordination and presence measures. Future studies should work to offset possible anticipatory behavior, for example by including longer breaks between trials, temporarily removing the VR headset to reset the user experience, or introducing additional subcomponent manipulations to reduce predictability.

Taken together, our findings demonstrate that the integration of an avatar into the users body representation can be evaluated similarly to tool embodiment, an approach already established in prosthetics (Segil et al., 2022) and human-machine interaction (Bennett et al., 2022; Favela et al., 2021). This highlights the value of DFA within a complex dynamical systems framework (Diniz et al., 2011; Van Orden et al., 2003) and its applicability. To our knowledge, this was the first study to show that entire avatars can exhibit integration behavior similar to tools when they are embodied and serve as sensory extensions. If this perspective generalizes, it could reshape our understanding of body representation by unifying tools, prosthetics, and virtual bodies within a single dynamical framework. Adjacent fields such as VR, prosthetics, and robotics may therefore share a common foundation in the interaction between tools and users, marking a step toward identifying universal principles of embodiment and presence across domains.

Supplements

Table 1

Descriptive Statistics for Presence (DFA) and Embodiment (CRM) Across Delays and Conditions

Condition	Delay	DFA			CRM		
		M	SD	CI	M	SD	CI
Mirror delay	0	.831	.020	.790, .872	73.065	4.119	64.564, 81.567
	0.1 s	.821	.019	.782, .860	62.328	4.825	52.370, 72.287
	0.2 s	.851	.020	.811, .892	49.726	4.593	40.246, 59.206
	0.3 s	.838	.023	.790, .885	7.624	9.495	-11.972, 27.221
	0.6	.834	.025	.783, 885	-17.360	9.343	-36.642, 1.923
	1.2 s	.856	.019	.816, 896	-25.584	9.317	-44.814, -6.355
Avatar delay	0	.819	.018	.782, .856	75.374	6.653	61.724, 89.024
	0.1 s	.843	.020	.803, .883	77.166	2.700	71.625, 82.706
	0.2 s	864	.016	.830, .897	40.041	7.404	24.849, 55.232
	0.3 s	.929	.024	.879, .979	4.009	7.862	-12.123, 20.141
	0.6	.917	.025	.866, .968	-21.285	8.064	-37.831, -4.739
	1.2 s	.942	.028	.885, .999	-39.448	7.776	-55,403, -23.492

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the author(s) used ChatGPT, Gemini, Consensus, and Elicit in order to perform deep research. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

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Declaration of interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: