Does Random Movements mean Random Results? Why Asynchrony in Experiments on Body Ownership does not Work as Intended

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Abstract

Effects of embodying virtual avatars are routinely validated experimentally by comparing synchronous and asynchronous movements between virtual and real bodies. This experimental paradigm, however, lacks justification, validation, and standardization. Asynchrony is implemented in numerous ways, such as through delayed, dislocated, or prerecorded movements, and these may impact embodiment and user experience distinctively. An online study ($N = 202$) revealed that variations of asynchrony cause disparate responses to embodiment and user experience, with prerecorded movements distorting embodiment the most. A think-aloud study ($N = 16$) revealed that asynchronous conditions lead to peculiar and oftentimes negative experiences. Furthermore, asynchronous conditions in some cases maintain, rather than break the body ownership illusion, as participants imitate the virtual body. Our results show that asynchrony in experiments on embodiment entails profound validity issues and should therefore be used with caution.

CCS Concepts

• **Human-centered computing → Virtual reality**; **Empirical studies in HCI**; *HCI design and evaluation methods*; HCI theory, concepts and models.

Keywords

virtual reality, embodiment, body ownership illusions, experiments, confounds, validity

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1 Introduction

Research in virtual reality (VR) has shown that participants experience that their actual body is replaced by a virtual one [68], when a virtual body moves synchronously with their real movements. This phenomenon, where the properties of a virtual body are perceived as properties of one's physical body, is called the "Sense of Embodiment" [45]. The ability to evoke the sense of embodiment has inspired numerous explorations into the intricacies of body-mind connections. Experiments have demonstrated that embodying a virtual body distinct from one's own can affect behavior and attitudes [e.g., 4, 69, 73, 77]. For example, owning a healthy virtual body effectively reduced symptoms of anorexia nervosa [63]; owning Einstein's body showed improvements in cognitive abilities [6]; and owning the body of an out-group member resulted in reduction in social biases [77].

To validate the effects attributed to the characteristics of the virtual body, embodiment experiments in VR commonly include an *asynchronous condition*—a scenario in which the movements of the virtual body are not in synchrony with the participant's real movements. The asynchronous condition is designed to disrupt the integration between visual perception and motor actions, and thereby diminish the sense of embodiment over the virtual body [68]. When the primary effect under investigation does not manifest in the asynchronous condition, it is concluded that the documented effect arises from the embodiment of the virtual body [68]. Banakou et al. [4], for instance, showed that ownership of a virtual child body causes an overestimation of object sizes. Participants did not overestimate the sizes of objects when the virtual child's body was asynchronous, and the authors concluded that the embodiment of the virtual child's body was the cause of the size overestimations.

The practice of using asynchronous conditions in VR experiments was developed ad hoc. Therefore, the use of asynchronous conditions in VR experiments has never been formally justified or standardized, which undermines its intended function. Further skepticism regarding whether asynchrony truly achieves its intended goal arises from the wide range of implementations, where important details are often left unreported. For instance, some studies operationalize asynchrony as a delay between the participant's movements and the virtual avatar's movements [88, 98], others as a reversal of the avatar's movements [71]. Furthermore, other studies have implemented asynchrony by prerecording the avatar's motions, rendering the virtual body completely independent of that of the participant [49]. These variations represent conceptually distinct approaches, in which users are left with varying degrees of control over the avatar and ability to predict its actions. These implementations may consequently result in distinct experiences and effects on embodiment.

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Despite the widespread employment of asynchronous conditions in VR research, the rationale provided for the specific implementations is missing from embodiment scholarship. We argue that the use of the asynchronous condition in embodiment experiments warrants critical examination, because of its central role in research design, and as numerous questions about its application remain unanswered. First, it is unclear whether different implementations of asynchrony are equally effective in disrupting the embodiment illusion. Second, the experience of an asynchronous body is unlike the normal experience of having a body, and little is known about how participants experience asynchronous bodies or whether such experiences involve effects beyond the disruption of embodiment. Finally, there is no justified standard for implementing asynchronous conditions, which introduces uncertainty into what from a distance appears to be a standardized approach for conducting embodiment research.

To address these questions, we conducted two studies that quantitatively and qualitatively investigate common implementations of asynchronous conditions used in VR experiments. In a between-participants crowdsourced study ($N = 202$), participants experienced common implementations of asynchrony and subjectively rated their embodiment, user experience, and virtual sickness. We found that the implementations led to divergent responses regarding embodiment and user experience. To investigate the reason behind these distinctive ratings, and how participants perceive asynchronous bodies, we conducted a second, within-participants laboratory study ($N = 16$). In this study, participants described their experience and perception of the implementations of asynchrony using a think-aloud protocol. We revealed that behind the guise of numerical embodiment scores, more complex experiences are untold, making the interpretation of embodiment questionnaire results complicated. In light of our empirical findings, we discuss the implications of using asynchrony in experiments on body ownership. Our results suggest that asynchrony does not function as intended and should be employed with caution.

2 Background

In this section, we review how the use of asynchronous conditions emerged in classical non-VR embodiment experiments, how this practice was adopted for VR research, and why this adaptation is problematic. Mottelson et al. [68] indicated that the embodiment literature is fraught with terminological confusion, with central concepts often used interchangeably to refer to distinct constructs. This paper employs concepts that are prone to such ambiguity. To prevent divergent understanding, we clarify how we define the central concepts of the paper in Table 1.

2.1 Origins of the asynchronous condition

The use of the asynchronous condition in research concerning virtual bodies is rooted in studies on body ownership in cognitive science [20], neuroscience [22], and psychology [10]. The rubber hand illusion (RHI) [10] emerged as evidence to support that it is possible to experience ownership of fake limbs. In the RHI, Botvinick and Cohen [10] demonstrated that when participants receive synchronous brush strokes on a visible rubber hand and their real hand, they report a sense of ownership over the fake hand, a sensation of touch, and a shift in their perceived hand position (i.e., proprioceptive drift). The results from the RHI are interpreted as reflecting the mechanisms of multisensory integration [11, 83], where congruence of visual perception and tactile stimulation leads to the sensation of ownership over the fake limb. To ensure that the illusion was caused by multisensory integration, the authors conducted the experiment with a control group, where participants' hands and the fake rubber hand were brushed asynchronously. Crucially, the strokes on the real hand were *delayed* relative to the strokes on the rubber hand. Participants in the asynchronous condition reported a lower prevalence of the illusion. The authors thus concluded that visuo-tactile multisensory integration plays a central role in embodiment, and fundamental aspects of selfhood can be disrupted by sensory conflicts.

The paradigm is a cornerstone of research on embodiment, serving as the basis for an expansive literature that utilizes body ownership illusions [e.g., 15, 22, 59, 61, 83, 94]. Correspondingly, the use of asynchrony as a control condition became a gold standard in verifying causal claims about alterations of limbs and bodies [61].

2.2 Asynchronous conditions in VR research

VR makes it possible to evoke a sense of embodiment over a full virtual body [4, 21, 79]. The possibility of creating such illusions has inspired multiple explorations of body-mind links, and illustrated the malleability of humans body representations [68]. It has been shown that through multisensory stimulation it is possible to create an illusion of owning a body that is noticeably different in shape, size, and morphology of one's real body [32, 46, 70, 87, 91, 96, 99]; such as the body of a child [4], an obese body [70], a historical figure [90], or a body with amputated limbs [44]. Moreover, research has shown that manipulating virtual bodies is an effective intervention for changing behavior and attitudes [64, 68]. For example, the illusion of having a black-skinned body can reduce racial bias [77], embodying a virtual child's body can affect the perception of size [4], and the illusion of owning an elderly's body can increase willingness to vaccinate [69].

Studies exploring body-mind links in VR rely on the assumption that participants experience the embodiment of the virtual body. As in RHI [10], researchers in VR conventionally use the asynchronous condition to validate that changes in the dependent variable, such as symptoms of eating disorder [63], racial bias [77], or size perception [4], are caused by the illusion of having the body unlike one's own [e.g., 4, 6, 50, 71, 73].

Adapting the use of the asynchronous condition from RHI to VR is problematic because multisensory integration in VR conceptually differs from classical, non-VR embodiment studies. In most classical non-VR embodiment studies, the illusion of ownership of a fake limb or mannequin body is induced through visuo-tactile integration, where visual stimulation of the fake body is synchronized with touch sensations on the real body [e.g., 10, 57, 75, 96]. A few studies employed visuo-motor stimulation in non-VR settings by synchronizing movements of the participants' index finger and a fake hand through a mechanical linkage [41, 82]. By comparison, VR allows to replace visuo-tactile stimulation with visuo-motor synchrony by synchronizing the movements of the participant's full real body and the full virtual body. Recent research highlighted

Term	Definition
Synchronous condition	*The synchronous condition in VR is an experimental condition in which the movements of the virtual body are synchronized with the real movements of participants.*
Asynchronous condition	*The asynchronous condition in VR is an experimental condition in which the movements of the virtual body are not synchronized with the real movements of participants.*
Visuo-motor integration	*Coordination between visual perception and motor actions. It reflects how the brain integrates visual input with motor outputs to produce purposeful movements, reinforcing the sense of one's own body.*
Visuo-tactile integration	*Combination of visual and tactile (touch) information to create a coherent perception of objects and the body in space. It reflects how the brain merges sensory inputs from sight and touch to maintain a unified and consistent experience of the body and its boundaries, contributing to the sense of one's own body.*
Sense of Embodiment	*The ensemble of sensations that arise in conjunction with being inside, having, and controlling a body, especially in relation to virtual reality applications [45]. Sense of Embodiment is the sense that emerges when the virtual body's properties are processed as if they were the properties of one's own biological body.*
Embodiment experiments in VR	*Studies that induce a sense of embodiment over a virtual body, and examine if the embodiment has an effect on a subsequent measure (e.g., behavior, attitudes, cognitive abilities, etc.)*
Reasoning behind asynchronous conditions	*Asynchronous conditions distort the sense of embodiment in VR studies. If an effect tested in an experiment is present in the synchronous, but not in the asynchronous condition, it is concluded that effect is caused by embodiment of the virtual body.*

Table 1: Explanations of the central concepts used in the paper

that visuo-motor synchrony is in fact the most effective experimental manipulation for inducing embodiment and is of greater importance than other visual congruences (e.g., tactile, perspective, or realism [68]). Additionally, in contrast to visuo-tactile congruence, visuo-motor integration in VR allows participants to control the virtual body and interact with the environment closer to the experience of owning a real body.

Diminishing the embodiment illusion in visuo-motor studies is not as straightforward as in visuo-tactile experiments, where the tactile stimulation is simply delayed [10, 83]. The sense of embodiment in VR is complex and multidimensional [45]. It combines the perception of owning, controlling, and being in a body, and having the conscious presence of one's biological body at the same time. A well-established theoretical framework of embodiment, which is the basis of many VR studies, posits that the sense of embodiment is constituted by three subcomponents: the sense of body ownership, the sense of agency, and the sense of self-location [45]. Importantly, the specific contribution of each component to the sense of embodiment remains largely unknown, as is the question of whether any single element plays a dominant role.

In the reviewed literature, we did not find any explanation or reasoning for the specific way in which asynchrony was implemented. Non-VR studies that induced illusory ownership through mechanical linkage of participant's real and fake fingers introduced this effect by delaying movements [41, 82]. However, the motivation for such implementations was not explicitly discussed. Implementation of asynchrony as delay appears plausible given that the delay in movements was inconsistent, and the task was simple – limited to lifting the index finger with the rest of the body remaining static. In contrast to non-VR settings, full-body ownership illusions in VR enable unrestricted, complex movements that are not confined to a specific body part. Consequently, implementing delays in VR scenarios is more complex, as it requires accommodating a broader range of actions. For visuo-motor integration, distortions to the synchronization of an avatar can involve dislocating movements or making the avatar's movements completely independent of the participant's actions. This complexity is reflected in the variability of implementations of asynchronous conditions found in the literature. Such variability suggests that the method, despite appearing standardized, lacks consistency. What qualifies as asynchrony remains unclear, as the term may be used to describe fundamentally distinct phenomena. Below, we present a review of implementations of asynchronous conditions in VR studies on embodiment and discuss conceptual issues related to these implementations.

2.3 How asynchrony is typically done in VR

To identify how visuo-motor asynchrony is implemented in VR studies, we designed a query to target empirical VR research that dealt with embodiment, induced embodiment illusion through visuo-motor congruency, and had an asynchronous condition in the experimental design. We searched academic databases ACM Digital Library (34 papers), IEEE Xplore (6 papers), Science Direct (23 papers), PubMed (10 papers), Nature Scientific Reports (26 papers), and Frontiers in Virtual Reality (14 papers). We searched the relevant research databases (query: ("vr" OR "virtual reality") AND ("embodiment" OR "body ownership" OR avatar*) AND (async*) AND (visuomotor* OR visuo-motor* OR "visual motor" OR "visuo motor")) across the title, abstract, and full text of articles written in English, and identified 112 relevant papers.

Then, we scanned the articles and filtered out only those papers that presented an original empirical study, used a head-mounted VR display, and presented work in which participants had a virtual avatar. Removing duplicates and screening resulted in 31 papers meeting these criteria. Each paper was then coded based on how

Implementation	Description	Papers
Prerecorded movements	The movements of the virtual avatar are recorded prior to the experiment.	13 papers [14, 17, 43, 48, 49, 51–55, 70, 73, 91]
Delay	The movements of the virtual avatar are delayed in relation to the participant's real movements.	5 papers [25, 34, 78, 81, 98]
External guidance	The movements of the avatar are guided by the experimenter externally.	2 papers [1, 56]
Random	The movements of the avatar's *tail* are random within 5 intercept points.	1 paper [92]
Offsets	The avatar is moving with quasi-random offsets.	1 paper [24]
Partial generation	Automatic generation of lower body motion animation from upper body motion tracking.	1 paper [40]
Reversed	The movements of the avatar are reversed with respect to the participant's real movements.	1 paper [71]
No body	Removing visual feedback.	1 paper [39]
Not reported	No explanation is provided of how the asynchronous condition was implemented is provided.	6 papers [4, 19, 50, 74, 77, 84]

Table 2: The implementations of the asynchronous condition found in the literature

the asynchronous condition was implemented. The overview of the results is presented in Table 2. We identified eight ways in which asynchrony is implemented in current embodiment VR research.

2.3.1 Prerecorded and externally guided. The most common way (13 papers) to implement the asynchronous condition in VR research is through *prerecorded movements* [14, 17, 43, 48, 49, 51–55, 70, 73, 91]. Here, the movements of the virtual avatar are recorded before the experiment, and the virtual body moves independently of the participant's movements. Two additional studies implemented asynchrony in the form of *external guidance* [1, 56], that affords the same avatar independence. Here, an experimenter controls the movements of the participant's virtual body in real-time.

This method is well-suited for breaking the illusion of embodiment. The movements of the participants are not synchronized with the avatar in space or in time, and prerecording the movements also prevents participants from controlling the avatar. Yet, this method of asynchrony raises conceptual questions. First, there is no standardization for how random the movements should be relative to the participants' behavior in the experiment. If the movements are close to how participants move themselves, participants may accidentally match the prerecorded movements. Furthermore, a self-avatar follower effect can occur, where participants unconsciously follow the movements of the avatar viewed from the first-person perspective [9, 30], unintentionally underpinning embodiment.

Next, the prerecorded avatar might be perceived merely as a different person in the environment [e.g., 4, 5].

Such a perception of the asynchronous avatar can (1) shift attention and distract participants from the experimental task, (2) make participants hypothesize about why researchers designed it so, thereby inducing demand characteristics [38, 61], and (3) influence concepts such as social presence, as participants may believe that they are not alone in the scene [e.g., 4, 77].

The details about the implementation of prerecorded movements are, furthermore, usually not reported. Studies commonly omit details of the prerecorded avatars, in particular how participants' first-person view is realized, and how head rotations are aligned with the prerecorded body. If the head is aligned with the participant's real head movements, the participant could experience self-location with the virtual avatar, which can contribute to the sense of embodiment [45]. Emblematic of this issue, in a study by Peck et al. [77] where a small difference in body ownership between the synchronous and asynchronous conditions was observed, the authors noted: *"It is possible that simply seeing the dark-skinned avatar in the mirror, located at the correct place for a reflection, might have been enough to generate an illusion of body ownership"*.

2.3.2 Delayed. The second most common variant of asynchrony (five papers) is *delayed movements* [25, 34, 78, 81, 98]. In this variant, the virtual body is rendered with a temporal delay relative to the participant's real movements.

When the movements of the virtual body are delayed, participants retain some control of the avatar [95]. The model of the sense of embodiment suggests that agency is an integral component of embodiment [45]. Therefore, delayed movements might not break the illusion of having a body, but rather create the illusion of having a delayed body [2]. Participants can also adjust to delayed movements; this is used in motor learning research [e.g., 58]. Delays are known to cause sickness and disrupt the user experience, performance, and presence, which may confound participants' behavior and reports in the experiments [86]. Finally, delays affect participants' behavior and perception in VR inconsistently [97]. For example, when the delay is smaller than 75 ms, the motor performance, body ownership, and sense of agency are not affected; at the delay of 125 ms, they start to decline, but do not break down completely even at the delay of 350 ms [97].

2.3.3 Unique and unreported asynchronous implementations. Other variants of asynchrony only appear once. In a study by Steptoe et al. [92], the participants experienced a tail that moved randomly within five intercept points. Feuchtner and Müller [24] implemented asynchronous movements as a constantly changing offset between the positions of the virtual and real hands. Jang et al. [40] asynchronized only the lower part of the virtual body, using motion tracking of the upper body. In the study by Ogawa et al. [71], the movements of the virtual body were reversed in relation to the participant's real movements. Ito et al. [39] described the asynchronous condition as an absence of visual feedback, meaning that participants in the asynchronous condition did not see the virtual body. Six papers did not report details about how the asynchronous condition was implemented [4, 19, 50, 74, 77, 84].

The variability of implementations underlines the lack of standardization and straightforward way to implement asynchronous conditions in VR. It is evident that implementations of asynchrony are practically and conceptually diverse. Some of them, such as delays and spatial offsets, leave the user in control of the actions and retain the ability to predict the avatar's behavior, while prerecorded and externally guided implementations make the virtual body completely independent and unpredictable. These fundamental differences make studies with asynchronous conditions difficult to compare. The implementations can lead to peculiar user experiences, and perceptions of the usability of the virtual body, and can inconsistently influence the sense of embodiment. The studies where implementation details are left out, do not afford a critical assessment of the conclusions made in the paper, and make replicating the studies infeasible.

2.4 The conceptual scheme of asynchronously moving bodies in VR

Previous literature suggests a variety of implementations of asynchrony, which are conceptually incompatible, as some render the avatar independent of the participant, while others afford a distorted control of the avatar. To support the decision on independent variables in our study, we organized variations of asynchronizations of virtual and real bodies in a conceptual scheme (see Figure 1).

The body ownership illusion in VR is achieved by spatially and temporally synchronizing a participant's real and virtual body. Spatial synchronization involves matching the location of the real and virtual bodies in space, from the participant's perspective. The virtual body is thus rendered in the place where the participant expects to see their real body. Temporal synchronization refers to the timing of the participant's movements and those of their virtual avatar. It is thus the speed at which the virtual body reacts.

Asynchrony can therefore be achieved by distorting either the spatial or temporal synchrony, or both. As a result, we propose a simple scheme of asynchronously moving bodies in VR (Figure 1).

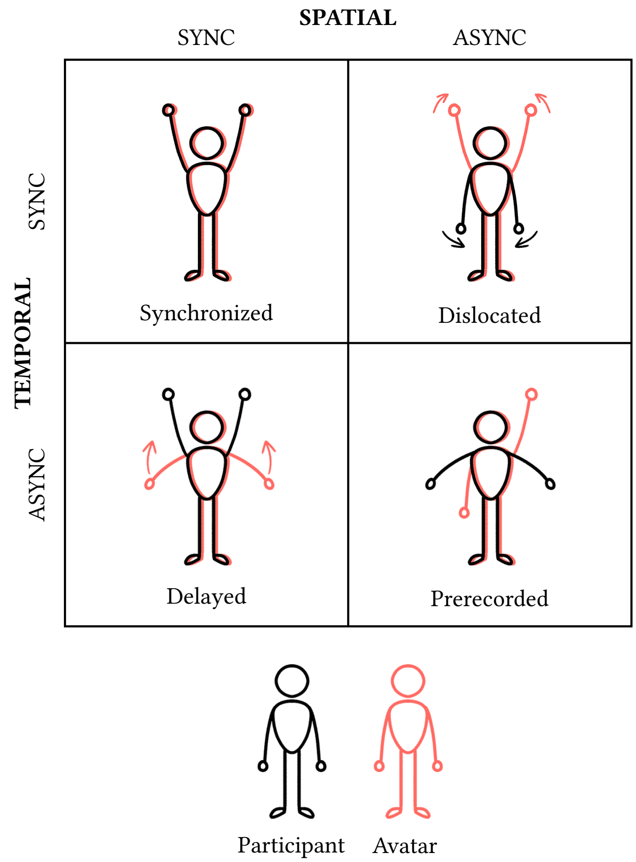

Figure 1: Conceptual scheme of asynchronously moving bodies in VR.

When the virtual body is synchronized with the participant's real body both temporally and spatially, the avatar is considered to be *Synchronized*. When the virtual body is synchronized spatially, but asynchronized temporally, the body is *Delayed*. If the body is temporally synchronized, but spatially asynchronized, the avatar is *Dislocated*. Finally, when the body is asynchronized both temporally and spatially, it means that the avatar is *Prerecorded* and moves fully independently of the participant. The presented scheme is grounded in the literature that employs asynchronous conditions in experiments. However, other implementations of asynchrony within the scheme are possible. For example, temporal-spatial asynchrony can be achieved through the simultaneous delaying of movements and their dislocation, or temporal asynchrony can be implemented as a prediction of movements rather than delaying them.

We argue that these variations of synchronizing movements are conceptually different, and speculate that they might lead to disparate experiences and yield differences in effects on embodiment.

2.5 Summary

The literature shows that the use of visuo-motor asynchrony in VR experiments was casually adopted from the rubber hand illusion [10]; a conceptually different, non-VR study. The fundamental difference between visuo-tactile and visuo-motor multisensory integrations has resulted in conflicting implementations of visuo-motor asynchrony that, to our knowledge, has never been justified or critically examined. In this paper, we raise the following issues related to the use of asynchronous conditions in VR experiments:

(1) We do not know whether there are foundational differences between asynchrony implementations, or whether they are equivalent and interchangeable in their effects on experimental outcomes. As such, we do not know if the conclusions made from papers using different implementations of asynchrony are comparable.

(2) We do not know how participants experience asynchronous bodies beyond subjective scales of embodiment. Having a body that moves not in synchrony with one's own movements is an atypical experience, dissimilar from the experience of having a normal body. Perhaps it can affect user experience, cause virtual sickness, or introduce effects we do not know about.

(3) There is no validated and theoretically justified implementation of the asynchronous condition, and we do not know which variation of possible implementations is the most effective and valid way to disrupt embodiment in visuo-motor embodiment studies.

To explore these issues, we conducted two studies that quantitatively and qualitatively investigate implementations of asynchronous conditions used in VR experiments. In study 1, we tackle issues (1) and (3), and explore how implementations of asynchrony influence commonly used subjective scales of embodiment. In study 2, we use a think-aloud protocol to explore issue (2) and explore how implementations of asynchrony are experienced beyond self-reported questionnaires.

3 Study 1: How asynchrony affects embodiment, user experience, and sickness

In the first study we aimed to identify how implementations of asynchrony quantitatively influence participants' reports on embodiment and its subcomponents (agency, appearance, self-location, and body ownership), virtual sickness, and user experience. The asynchronous condition is meant as a "neutral" condition, the sole purpose of which is to disrupt body ownership. If the implementations of asynchrony distinctively influence body ownership, or influence other constructs, that would constitute a potential confounding validity issue.

3.1 Method

The study employed a between-participants design with one independent variable. Participants were randomly assigned to one of the four implementations of movements (delayed, dislocated, prerecorded, or synchronized) and were asked to explore the possibilities of a virtual body. Following the experience, participants completed the Avatar Embodiment Questionnaire [76] which is a standardized and validated scale to assess embodiment (using a 7-point Likert scale from "never" to "always"), the Virtual Reality Sickness Questionnaire (VRSQ) [47] – a commonly used motion sickness questionnaire tailored to VR applications (using a 4-point Likert scale from "none" to "severe"), and the System Usability Scale (SUS) [12] – a common and universal scale to measure user experience (using a 5-point Likert scale from "strongly disagree" to "strongly agree").

3.2 Participants

We recruited 202 crowdsourced English-speaking participants who owned a Meta Quest headset (versions 2 or 3). Participants were reimbursed the equivalent of USD $10. Participants were recruited from advertisements on social media and through Prolific. Participants received information describing the study, data collection, and information on informed consent. The participants were 177 males, 24 females, and one non-binary, with a mean age of 32.9 years (SD = 9.3). We excluded the non-binary participant from the analysis as the possible gender mismatch with the virtual body could influence the embodiment scores. Participants were well represented across age groups (see Table 3). Most participants came from the US (77), the UK (47), and countries in the European Union (58).

Age	**18-22**	**23-27**	**28-32**	**32-37**	**38-42**	**43-47**	**48+**
	33 (16)	31 (15)	41 (20)	33 (16)	30 (15)	13 (6.4)	21 (10)
Gender	**F**	**M**	**NB**				
	24 (12)	177 (88)	1 (0.5)				

Table 3: Participant characteristics. Data are shown as n (%). Labels are: Female, Male, and Non-Binary.

3.3 Apparatus

The VR environment was developed in Unity 2022, deployed for Meta Quest 2 and 3. Text-to-speech software from Google[1] was used to verbalize stretching instructions and navigation through the experimental procedure. The posture of the avatar was computed using the inverse kinematics library VRIK[2]. We used Microsoft RocketBox's rigged models as avatars in the experiment [31], and the floor-to-HMD height to scale the avatar. Upon completion of the experiment, the application sent relevant participants metrics over HTTPS to a server application written in Python, hosted on Google App Engine.

To study how participants experience asynchronous bodies in VR, we implemented the four variants of asynchrony from our scheme (see Figure 1); based on how asynchronous conditions were realized in previous work (see Subsection 2.3). In all conditions, the camera view was synchronized with the participants' head movements. Participants viewed their body from a first-person perspective, in standing pose, with the asynchrony of movements affecting their upper bodies. We asked participants not to move their feet; the lower body was thus kept static. Below, we describe the implementation details of each condition.

[1] https://cloud.google.com/text-to-speech/
[2] http://www.root-motion.com/

(a) Female avatar **(b) Male avatar**

Figure 2: Virtual scene seen from the first-person perspective. (a) Female avatar. (b) Male avatar.

3.3.1 Delayed movements. Delayed movements were implemented by introducing a delay of 2000 ms between the participants' real movements and the movements of the avatar. We chose the delay of 2000 ms as this latency in multisensory incongruence was shown to be effective in disrupting the sense of agency and body ownership [13]. In this case, the temporal synchronization was distorted, while the spatial location of the virtual limbs corresponded to the location of the participants' limbs.

3.3.2 Dislocated movements. Dislocated movements were implemented by introducing Brownian noise to the arms' movements. Brownian noise was implemented by applying random offsets to the position and rotation of the arms within a fractal area, with a standard deviation of 15 cm for positional noise and 5° for rotational noise. In this condition, when the participant moved, the virtual body reacted temporally synchronously, but the spatial location of the virtual body did not correspond to the location of the participant's body. This spatial distortion resulted in movements that were continuously misaligned with the real body.

3.3.3 Prerecorded movements. Prerecorded movements were implemented by recording the avatar's movements prior to the experiment. These prerecorded movements did not follow the instructions given to participants during the experiment. In this case, the avatar's movements were independent of the participant's, resulting in the distortion of both temporal and spatial synchronization.

3.3.4 Synchronous movements. The synchronous condition was included as a control. In this condition, the movements of the avatar were synchronized with the participant's movements both temporally and spatially. This allowed us to observe participants' responses during alignment between their movements and the virtual avatar's movements.

3.4 Procedure

Participants installed the experimental APK on their own headset using SideQuest[3] and conducted the experiment at their own discretion. To control for the movement space, we asked participants to set a stationary boundary (1 × 1 m).

The participants were randomly assigned to one of the four experimental conditions at runtime. Participants were not aware of the existence of other experimental conditions to reduce the influence of demand characteristics on the experimental outcomes [38].

An introduction (text and voice) explained that the purpose of the study was to understand perceptions of virtual bodies in VR. Participants were then introduced to the procedure, and asked to put down the controllers and press the "Start" button when they felt ready to begin the experiment. Participants selected their gender and were assigned to a gender-matched adult avatar.

Upon initiating the experiment, participants were placed in a virtual room furnished with everyday items (Figure 2). A virtual screen on the wall reminded participants of the instructions. An audio recording guided participants to perform stretching exercises during the first minute of the study. These are commonly used to explore the possibilities of the virtual body and underpin the

[3] https://sidequestvr.com/

illusion of embodiment [e.g., 4]. After completing the stretching exercises, participants were free to move and explore the body as they wished, with no specific instructions. When a time limit of 120 s was reached, participants could no longer see the virtual body and were prompted to complete a questionnaire. The experiment was controllers-free, and used hands-tracking for inverse kinematics, but the questionnaire afterwards was completed with controllers. Upon finishing the questionnaire, the study concluded. The entire study took 15 minutes.

3.5 Analysis and results

We performed exploratory analyses of the collected data. Analyses were conducted in R (version 4.4.1). In the following, we present the highlights of our results. The main results are presented in Table 4. The full analysis report can be found at OSF[4].

Measure	Delayed N = 50	Dislocated N = 50	Prerecorded N = 50	Synchronized N = 51
Embodiment	-0.37 (1.06)	-0.78 (0.97)	-0.97 (1.22)	0.00 (0.98)
Ownership	-0.31 (1.18)	-0.82 (1.05)	-1.16 (1.37)	0.23 (1.17)
Appearance	-0.32 (1.06)	-0.84 (0.93)	-0.81 (1.12)	-0.19 (0.89)
Response	-0.60 (1.28)	-0.99 (1.21)	-1.11 (1.25)	-0.32 (1.16)
Multi-sensory	-0.24 (1.08)	-0.48 (1.05)	-0.79 (1.48)	0.28 (1.09)
Agency	-0.4 (2.5)	-2.0 (2.5)	-2.2 (3.2)	0.9 (2.6)
User experience	69 (19)	63 (20)	58 (20)	77 (18)
Sickness	43 (15)	48 (18)	43 (13)	50 (21)

Table 4: Mean and standard deviations of the collected measures across conditions. The red color denotes a significant difference with the synchronous condition found in a t-test (Bonferroni-adjusted $p < 0.05$).

3.5.1 *Main Embodiment.*
First, we analyze the main measurement *Embodiment*, as it denotes the overarching experience of having a body in VR, and is a mean of its four sub-scales [76].

Experiencing a synchronous virtual body, unsurprisingly, led to the highest degree of embodiment (Figure 3). A t-test with Bonferroni-correction showed significant differences to Dislocated and Prerecorded variants, and overall Asynchrony. These reports also serve as a manipulation validation of the experiment.

Of the asynchronous variants, the Prerecorded led to the lowest embodiment, then Dislocated, and then Delayed. The Prerecorded condition resulted in a high variance in embodiment, suggesting individual differences in participants' experience.

3.5.2 *Sub-scale analysis.*
The responses to the embodiment sub-scales 'Multi-sensory', 'Response', 'Appearance', 'Agency', and 'Ownership' followed the same pattern as 'Embodiment'; with the Synchronized condition resulting in the highest scores, followed by Delayed, Dislocated, and Prerecorded (see Table 4 and Figure 5). The Prerecorded and Dislocated conditions, as well as overall Asynchrony, were consistently significantly different from the Synchronized condition in all the sub-scales, as shown by the Bonferroni-adjusted t-tests. The Delayed condition was significantly different

[4] https://osf.io/cyp2r/

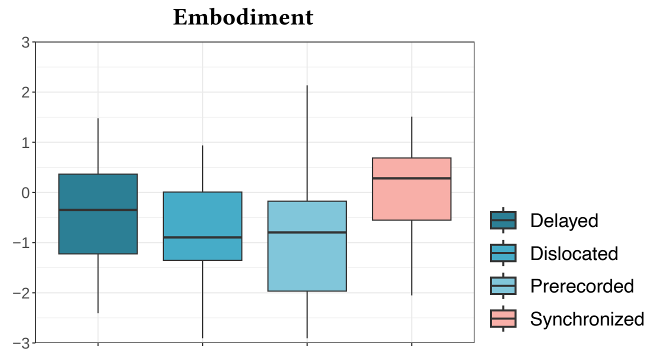

Figure 3: Distribution of embodiment scores.

only for 'Agency'. Sub-scale responses were distinguished by high variance, suggesting high contribution of individual participants' perception of the condition.

3.5.3 *User Experience.*
We observed the same pattern as embodiment for the user experience scores. Experience of the Prerecorded body was the worst for participants, followed by Dislocatedand Delayed. The Synchronized condition delivered the best user experience. The differences in user experience between Synchronous and Prerecorded, Synchronous and Dislocated, and Synchronous an overall Asynchrony were significant in Bonferroni-adjusted t-tests.

3.5.4 *Virtual sickness.*
We did not find any difference in virtual sickness across conditions, with virtual sickness scores being low for all the conditions (see Table 4).

3.5.5 *Correlation analysis.*
After observing similar distributions across scales, we computed correlations between embodiment, user experience and sickness. We found a positive Pearson correlation between embodiment and user experience $r(199) = 0.39,\ p < 0.0001$. We also observed a positive correlation between embodiment and sickness $r(199) = 0.17,\ p = 0.02$. User experience and sickness were negatively correlated $r(199) = -0.28,\ p < 0.0001$.

3.6 Summary

The descriptive statistics indicate distinct patterns in the results that emerged from the experiment. First, there is a clear division between the synchronous and asynchronous conditions in embodiment and its sub-scales that serve as a manipulation check and validation that asynchronous conditions indeed reduce embodiment. Also, albeit at a descriptive level, there is a systematic pattern of the implementations' effectiveness in breaking embodiment, with the Prerecorded condition diminishing the illusion the most, followed by the Disclocated condition. Notably, the Delayed condition appeared to be an ineffective manipulation in disrupting the body ownership illusion, yielding no significant difference from the Synchronized condition, except for agency. Surprisingly, the pattern of distribution of ratings also holds for the Appearance sub-scale, and we found that participants rated the appearance of the avatar differently across conditions, even though we used the same model in all the conditions of the experiment. This may suggest that different

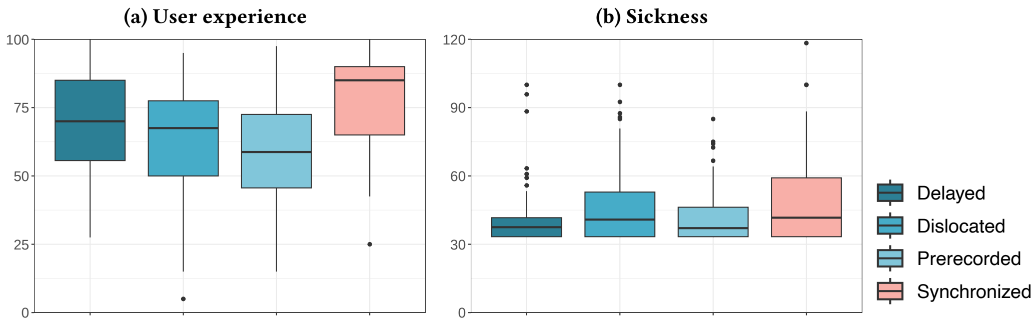

Figure 4: Distribution of responses to user experience [12] and virtual sickness [47] across conditions.

movement distortions of asynchronous conditions may have captured participants' attention to varying degrees, thereby diverting their focus away from the avatar and affecting their perception of its appearance. Finally, the implementations were rated differently in user experience following the same pattern as embodiment and its sub-scales. This repetition of pattern prompts speculation that user experience may partially shape the embodiment experience or vice versa (suggested by a relatively large correlation).

Overall, there are clear variations in embodiment and its subcomponents, as well as user experiences across asynchronous conditions. Asynchronous conditions are supposed to only distort embodiment, leaving everything else intact. Our data indicate that its influence on embodiment is not equivalent across implementations and that asynchrony also affects experiences beyond embodiment. However, numerical values do not explain what causes these numbers. Perhaps, the fundamentally different experiences of conceptually distinct implementations of asynchrony may introduce confounds we do not fully understand. To shed light on what the experience of asynchronous conditions is like, we conducted a second think-aloud study.

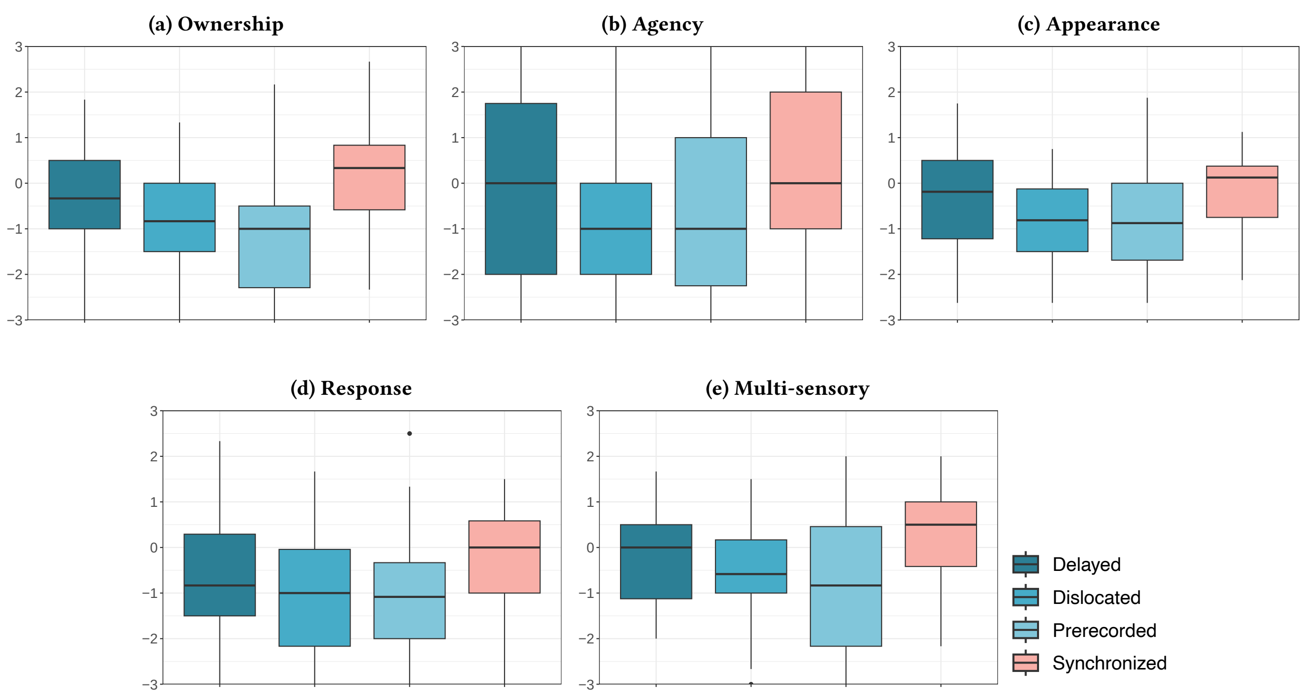

Figure 5: Distribution of responses to Avatar Embodiment Questionnaire [76] across conditions.

4 Study 2: How do people experience asynchrony

The quantitative data sourced in Study 1 do not provide a depth of understanding of why implementations of asynchrony vary in their effects on embodiment, nor do we know how asynchronous bodies are experienced apart from the user experience metric. This raises doubt about whether the questionnaires we use suit the purpose of answering the research questions we pose. To shed light on these questions and capture the experiences, we conducted a laboratory-based think-aloud study. We reused the implementations of conditions from Study 1 and explored them qualitatively with a relaxed think-aloud protocol [35] and a post-hoc semi-structured interview. The data were analyzed using inductive coding of the transcripts of audio recordings of participants' verbal reports.

Comparison	t-value	p-value	p-adjusted	Cohen's d
Embodiment				
Delayed	1.80	0.075	0.226	0.36
Dislocated	4.30	< 0.001	< 0.001	0.80
Prerecorded	4.38	< 0.001	< 0.001	0.87
Asynchrony	4.29	< 0.001	< 0.001	0.65
Ownership				
Delayed	2.29	0.024	0.072	0.46
Dislocated	4.71	< 0.001	< 0.001	0.94
Prerecorded	5.45	< 0.001	< 0.001	1.09
Asynchrony	5.11	< 0.001	< 0.001	0.80
Agency				
Delayed	2.53	0.013	0.038	0.50
Dislocated	5.73	< 0.001	< 0.001	1.14
Prerecorded	5.23	< 0.001	< 0.001	1.04
Asynchrony	5.59	< 0.001	< 0.001	0.86
Appearance				
Delayed	0.65	0.518	1.000	0.13
Dislocated	3.59	0.001	0.002	0.71
Prerecorded	3.07	0.003	0.008	0.61
Asynchrony	3.07	0.003	0.008	0.46
Response				
Delayed	1.15	0.253	0.759	0.23
Dislocated	2.85	0.005	0.016	0.57
Prerecorded	3.30	0.001	0.004	0.66
Asynchrony	3.02	0.003	0.013	0.47
Multi-sensory				
Delayed	2.41	0.018	0.054	0.48
Dislocated	3.58	0.001	0.002	0.71
Prerecorded	4.12	< 0.001	< 0.001	0.82
Asynchrony	4.29	< 0.001	< 0.001	0.65
User Experience				
Delayed	2.23	0.028	0.084	0.44
Dislocated	3.89	< 0.001	0.001	0.78
Prerecorded	5.07	< 0.001	< 0.001	1.01
Asynchrony	4.69	< 0.001	< 0.001	0.72
Sickness				
Delayed	1.79	0.076	0.230	0.36
Dislocated	0.49	0.623	1.000	0.10
Prerecorded	1.93	0.057	0.170	0.38
Asynchrony	1.59	0.118	0.470	0.29

Table 5: Results of the t-test analysis of the synchronized condition against delayed, dislocated, and prerecorded asynchronous conditions in Study 1. P-adjusted indicates the results of the Bonferroni correction.

4.1 Method

The study used a within-participants design. In the first phase, participants, in counterbalanced order, experienced four implementations of movements: delayed, dislocated, prerecorded, and synchronized, with gender-matched avatars. To capture the participants' verbalizations of their experiences with each condition, we employed a relaxed think-aloud (RTA) protocol [35, 67]. This approach allowed participants to freely comment on any aspect of their experience, ranging from usability issues to their personal feelings and emotions. RTA was chosen because it enables researchers to interact with participants, provide instructions, and encourage them to reflect on their experiences. Audio recordings were made of both the participant and the experimenter. The experimenter was positioned to simultaneously observe the participant, communicate with the participant, and take notes.

In the second phase, a semi-structured interview was conducted to gather general feedback on the experience of using virtual bodies in asynchrony. The interview covered several key topics. First, we asked participants if they experienced a body ownership illusion and felt a sense of control over the virtual body. Next, we explored their overall user experience and any virtual sickness they might have encountered. Finally, we invited participants to reflect on how the asynchrony affected their movements and whether they found any meaning in this experience.

The transcripts of the think-aloud and interview reports are available at OSF[5].

4.2 Participants

We invited 16 participants with little or no prior experience of VR. Participants were required to have an English proficiency level of B2 or higher, as specified in the recruitment form. We selected participants without VR experience to avoid potential biases, as those familiar with a synchronized virtual body might compare the asynchronous conditions to a previous experience of a synchronous avatar. Participants were recruited locally through an internal mailing list, and word-of-mouth. The participants were seven males and nine females, with a mean age of 33.8 years ($SD = 5.2$). Participants were reimbursed with a gift worth USD $15.

4.3 Apparatus

Participants were fitted with a Meta Quest 3 head-mounted display (HMD). The experiment was conducted in a VR laboratory, with a tracking space of approximately 1×1 m. We used an iPhone 14 Pro to record the studies and interviews. The software Delve[6] was used for inductive coding of the think-aloud and interview transcripts. The virtual environment was reused from Study 1.

4.4 Procedure

At the beginning of the study, the experimenter explained the procedure and that we were interested in understanding the experience

[5] https://osf.io/b94gs/
[6] https://delvetool.com

of owning a virtual body. After obtaining informed consent, participants were introduced to simple stretching exercises to help them explore the possibilities of the virtual body. Participants also conducted warm-up exercises to get into the flow of thinking aloud: verbally solving a math task and brainstorming improvements for a vacuum cleaner [35]. Participants were only informed that they would experience a virtual body, with no additional details provided about the content of the experience. When participants felt confident that they understood the procedure, protocol, and VR system, they were fitted with the headset.

The scene portrayed a virtual room decorated with everyday furniture, with a virtual screen on the wall reminding participants of the instructions. Participants were instructed to press the 'Start' button to initiate the first condition and extend their arms in front of them to calibrate the avatar. During the experience, we asked them to tilt their heads down as if they were looking at their bodies. During the first minute of the experiment, the experimenter reminded the participant to perform the stretching exercises, used to explore the possibilities of the virtual body and underpin the embodiment illusion [e.g., 4]. After completing the stretching exercises, participants were free to move and explore the body as they wished. Sometimes the experimenter would remind them to "keep talking". When the time limit of 180 s was reached, the virtual body disappeared, and participants were informed that the next condition would begin in ten seconds. We picked a 180 s exposure time as a result of a pilot study ($N = 3$) that showed that this is the approximate time after which participants ran out of thoughts. The procedure was the same across conditions.

Participants remained in VR through the four conditions. After the last condition finished, the experimenter instructed participants to remove the headset and proceeded with the semi-structured interview. Overall, the study took approximately 30 minutes.

4.5 Analysis

The first author analyzed the data using bottom-up coding. Although our study is based on the premises of current theoretical models and questionnaires on the sense of embodiment [45, 76], we worked inductively when developing the codes.

After transcribing, the first author got familiar with the data by reading the whole corpus and taking notes. Each transcript was split into separate parts identifying which condition the person had experienced. The codes were generated separately for each condition. If the same code appeared in multiple conditions, we named the code identically but indicated to which condition it referred. With this approach, we were able to conceptualize the experience in each condition separately but also left room for comparing experiences. Initial codes referred to discrete aspects of participant's experience (e.g., expression of an emotion or association). If two or more codes referred to the same emotion, or experience, the codes were merged. Open coding was followed by clustering similar codes into broader themes, with comparisons made across conditions to highlight unique and shared experiential aspects.

The qualitative findings are predominantly based on reports from the think-aloud procedure, with a minor addition of quotes from interviews where participants were reflecting on their experiences of perceiving asynchronous bodies (∼ 5% of the analysis).

4.6 Results

At the beginning of each condition, participants were trying to make sense of what was happening, which was generally associated with emotional utterances. Each condition was also accompanied by distinct patterns of movements that participants were doing when exploring the bodies. Finally, the bodies evoked associations, outlining how participants relate to the body (see overview in Table 6). In the following, we describe the experiences of participants for each condition.

Delayed. For most of the participants the delayed body was connected with negative emotions. Participants expressed that having a delayed body is *"creepy"*, *"freaky"*, *"offputting"*, *"worrying"*, *"jarring"*, and *"annoying"*. Multiple participants compared the experience of having a delayed body to being drunk (P4, P9, P15), under the influence of drugs (P0), or having brain damage (P15).

The delay of the avatar's movements also influenced how the participants were moving during the condition. They tended to slow down so that it was not the avatar that followed their movements; instead, they were trying to synchronize with the avatar. P14 said: *"It's making me slow down. I feel like I'm doing Tai Chi, by trying to get them to move the same route as me."* Five participants (P2, P12, P14–16) were making a movement and then waited until the avatar caught up with it: *"I move my hand and then I would typically wait for it to get there"* (P2). P11 stopped moving at all to get the connection with the body: *"This is a trick, probably – just being still."* Participants also reported that they could adjust to the delay, and if they thought about the body as an instrument to achieve some task, the delay condition had utility. For example, P14 was trying to play the chopsticks finger game and explained: *"The longer the delay between my movement and the display of my movements is, then the longer preparation I can make."*

In terms of the relationship to the avatar, participant reports were inconsistent. In the delay condition, they mostly called the avatar "their" body, as in: *"I feel as if my body is thinking about, like deliberately thinking through the kind of motions that I'm telling it to make"* (P12), or: *"I recognize that it's my kind of movements, but now it's somewhere from the past"* (P11). The majority of participants said that the delay feels like slow internet, and that the avatar was theirs, just lagged, similar to being in a Zoom call with a bad connection (P9). In contrast, three participants (P3, P11–12) reported that the delay was too big to feel that the body was their body. For example, P12 said: *"Right now I'm not feeling that it's my body, because I already forgot what I did."*

Dislocated. The dislocation of movements garnered a strong emotional response from participants. Participants judged the condition as extremely uncomfortable, saying that it made them *"anxious"*, *"frustrated"*, *"disoriented"*, and *"annoyed"*. Because the movements were hard to predict and *"arms were [explicit] around"*, some participants reported feeling unsafe (P12, P15, P16). For example, after making an amplitude movement, P16 exclaimed: *"Don't hit me!"*. A share of participants reported that this condition elevated their motion sickness (P4, P8, P12, P15), and P8 even asked to exit the experience in this condition.

In contrast, the rest of the participants found the randomness around their arms to be fun. They said that the spatial offset made

	Emotions	Movements	Relation to body
Delayed	Awkward, confusing, creepy, worrying, weird, offputting	Measured the delay, slowed down the movements, waited while the avatar caught up with their movements, tried to align the movements with the delay	Similar to a slow internet, being drunk, being under drugs, having brain damage, doing meditation exercises; the body is like own body, the feeling of losing real hands
Dislocated	Frustrating, annoying, wild, disorienting, distracting, strange, fun	Tried not to notice the hands, calm the hands down, repeat hand movements, catch the control, compensate for the movements with own movements	Similar to Parkinson disease, other diseases, being drunk, being under drugs, dancing, doing DJ set, feeling like the body is in panic, the mind already moved the body, the body is trying to tell something, like hands have consciousness
Prerecorded	Uncanny, unnerving, weird, unsafe, cringe, strange	Tried to repeat the movements, stopped to move and observed what the avatar was doing, tested movements to get the link between own movements and movements of the avatar	Similar to paralysis, Sims character; feeling like the body moves in its own way, like mind is put in someone else's body, like the body knows the moves, body is like a house, feeling of being trapped into the body
Synchronized	Nice, natural, funny, cringe, weird	Scrutinized the details of appearance to compare similarities with oneself, checked the accuracy of VR tracking, checked the nuanced movements	Did not like the avatar, perceived a need to appropriate the personality of the avatar, feeling that the body is too different in terms of appearance to be the own body, feeling like the body is owned because of the synchronization of movements

Table 6: Summary of the codes from the think-aloud reports across conditions. The 'Emotions' column refers to the emotions that participants verbalized during the condition. The 'Movements' column refers to the actions or movements participants performed while experiencing the condition. The 'Relation to body' column describes associations and descriptions related to the avatar that participants talked about.

them feel like they were dancing or doing a DJ set (P1–2, P4, P6, P9, P14–15): *"It doesn't completely follow my movements, but it's as if I'm in a discotheque dancing to hip-hop music"* (P9), and *"Kind of as if I'm doing a DJ set or a very bad lap"* (P6).

The dislocation affected how participants moved. Some were trying to remove the hands out of their sight to not see them and calm them down (*"I just put them down. Don't look at them"*, P3), and some started to explore the scene (*"I'm getting used to this, but I would prefer to look in the window and distract"*, P12). Several participants were trying to repeat the movements of the avatar because *"it feels like more in order"* (P3), or because it gave them a feeling of control (P3–4, P6, P11, P13, P16). They explained: *"Okay, if I move very fast, I don't see the difference"* (P4), *"Oh, I can control these weird movements by moving"* (P16).

Participants reflected that dislocation attracts a lot of attention, and can even be used as a distraction technique (P2, P3, P12). P2 noticed: *"They're definitely the focus of my attention right now"*, and *"If I were designing a UI, and, in this case, I needed to attract users' attention to something, this could be a way to do it"*. Notably, reports about the appearance of the avatar in this condition were rare.

In terms of the relation to the virtual body, the reports were inconsistent. The randomness added to the movements made participants describe the movements as *"unpredictable"* and out of their control (P10–13, P15). At the same time, some participants reported the feeling of immediate response of the avatar to their actions (P2–3, P5–6, P9, P15). P5 said that she felt that her arms didn't know what to do, or something was driving their movements, but the body is her: *"I would say that whatever it is driving the movements, it understands what I'm doing, but the precision could be a little bit better"*. P4 reported that he felt like *"my body is trying to tell me something"* or *"the mind already moved my body"*. Others said that the condition felt like having Parkinson's disease (P9, P12, P15), suggesting that they might felt the body as their body but that this body is sick. This did not hold for all participants, though, and some of them declared that it was not their body, but they felt the connection with it: *"It feels like it's not my body"* (P13), and *"But I feel some connection with this substance, so"* (P11).

***Prerecorded*.** Some participants in the prerecorded condition immediately guessed that the body moved independently. Others, for some time, thought that it was delayed or that it was an experimenter who generated the movements based on what participants talked about (*"Because it seems to me that I describe something and then it starts moving"*, P5). The unpredictability of the movements made them report feeling uncomfortable and unsafe: *"When the body is not moving much, you feel kind of safe, but when now the body* *starts moving, you feel very unsafe, because you feel a loss of control"* (P10). Participants also claimed feeling *"trapped"*, *"uncanny"*, or experienced a *"twinge of cringe"*, or *"like someone is invading my personal space"* (P15).

After participants figured out that the body had nothing to do with their own movements, half of the participants tried to imitate what the body was doing (P1–6, P12–13). For example, P12 told: *"I understand what I want to do. I want to try to repeat what the body is doing in order to, to feel that it's right. I mean, that it's my body"*, *"otherwise, it feels weird that my body is moving and I'm not corresponding, and I'm staying in the wrong direction"*. P4 said that the hands *'are trying to show me something"*, and *"what if I try to repeat after my body?"* Towards the end of the exposure, participants generally just stopped moving: *"I don't even use my arms. I can put them behind me"*, and *"Now I'm just observing my own movements"* (P16).

Participants appropriated the body differently. Some stated that they did not feel a connection to the body: *"The first thing is that, as if it is me, like my mind is with me, my head is with me, but the body is not with me"* (P10). However, others reported a connection to the body because the co-location with it created a partial multisensory integration with the torso: *"Just simply because the line of sight on my chest and my legs is very similar"* (P11). Six participants (P1–2, P9–10, P14, P16) described a feeling that they became a part of someone else, as in: *"You actually start to feel like part of someone else"* (P10), and *"I am dead already, and then, they have sent me back to the earth to guide someone"* (P1). P6 even said that she was appropriating the personality of the avatar: *"I'm saying that I am somebody who also gestures a lot when I talk."* P13 said that she felt a shared agency with the avatar: *"It's kind of the avatar has its own agency, and part of it shares my agency, but the other part is out of my control."* Similarly, P14 described a *"a kind of latent sense of body ownership"*. *"I don't know how much I feel like if I was looking at somebody else doing it or it's actually myself doing it."*

Synchronized. In the study, we included a synchronous virtual body as a control. The difference in participant's attention was pronounced compared to the asynchronous conditions. Remarkably, participants paid a lot of attention to the appearance of the avatar and how it was different from their own looks. *"By the way, I think that's also something peculiar because I'm wearing full black most of the time. And looking at the blue outfit is very weird, because I almost never wear blue. That's also probably wrong"* (P11), and *"I know I don't have the nails. And when I see hands with nails, it's something very alien to me"* (P10). Some thought that the avatar was a replication of their body, especially when the watches or bracelets on the avatar models coincided with what participants wore: *"I was thinking if computer just replicated [me] because the skin color was plus minus the same"*, (P1).

In terms of the movements, the synchronous avatar forced exploration of the body, and in contrast to the asynchronous conditions, participants did not stop to move. Rather, they started to check very fine or nuanced movements to explore the quality of synchronization. P6 noticed: *"It very accurately tracks every one of my fingers"*. P9 did a yoga pose and commented: *"Okay, sorry, I'm gonna do a stupid thing. I don't know if it's gonna work or not. No, it's not gonna work, but that's because it doesn't feel where the legs are."*

All the participants reflected on the tactile congruence with what they saw in the VR, and how slight misalignment of the virtual body and haptic feedback influenced their sense of body ownership. For example, P8 reflected: *"It's like my fingers are touching, but then the avatar fingers are not touching properly, because they are, I guess, skinnier than my fingers"*, and P6 noted that: *"I have this touch feeling without seeing the visual feedback, kind of exasperating"*.

Notably, after noticing the difference in visual appearance and small imprecision in synchronization, some participants reported that they do not feel that the virtual body is their body, even though it's synchronous and they can control it. For example: *"I'm not taller than usual, but something is wrong with the shape of my body. I don't feel that it's my body"* (P12). After noticing the difference in clothes, P11 also said: *"Still something disconnects me"*.

Summary. The way participants moved and what they paid attention to was markedly distinct across the conditions. While in the asynchronous conditions, participants were trying to get the pattern of how the virtual body reacted to their own movements, in the synchronous condition, they merely focused on the avatar's appearance. It is also notable that a share of participants (N = 9) expressed feeling body ownership over all the avatars or over none of them, regardless of the condition. For example, after saying that he did not feel that the virtual body is his body in any of the conditions, P14 elaborated: *"So it's just, it's VR, it's like I know what it is. It's just obviously not my body."* Curiously, P6 reported the opposite: *"I mean, in all of them, I wanted to see the body as my body. It felt more like mine. It was my body, but just not listening to me at the moment."* Additionally, two participants (P2, P9) reported that they felt that the virtual body was theirs in all conditions except the prerecorded one.

Overall, asynchrony differs from synchrony not only in how the body is perceived but also in a host of other things, including affect, attention, comfort, and movements.

5 Discussion

The conclusions and implications of the research on body ownership illusions in VR extend well beyond controlled experimental contexts. Research leveraging body ownership illusions has demonstrated their potential to manipulate attitudes [5], encourage certain behaviours [69], and serve as medical interventions [26, 63]. The asynchronous conditions are routinely used to validate findings from studies on embodiment, with the premise that participants will not experience body ownership illusions if their virtual body does not move synchronously with them. Yet, the use of the asynchronous conditions has not been justified nor standardized. This paper has compared various asynchronous implementations in VR, focusing on their different effects on self-reported embodiment and on how participants experience asynchrony. We found that asynchronous conditions do not work as intended.

Our findings indicate that the implementations of asynchrony used in research vary substantially. We found that the asynchronous conditions do not consistently fulfill the intended function of validating conclusions drawn from studies on embodiment. Instead, we found that asynchrony introduces unanticipated effects that may compromise the experimental outcomes. In the following sections, we integrate these findings: first, outlining the intended purpose of including asynchrony in experiments; second, examining how the asynchronous condition fails to fulfill this intention; third, identifying unintended consequences introduced by asynchrony; and finally, discussing potential strategies for researchers to address the problems related to the asynchronous conditions.

5.1 What is asynchrony supposed to do, but does not?

Experiments that employ an asynchronous condition usually study how characteristics of the virtual body influence some dependent variable [e.g., 4, 5, 69]. The intention of including an asynchronous condition is to confirm that the effects in the dependent variable are due to the characteristics of the virtual body, and just them. Following the premise that the body influences the mind, the sense of embodiment toward the virtual body is crucial [e.g., 28, 66]. Asynchrony is supposed to knock out the illusion of body ownership without affecting anything else. If the changes in the dependent variable are observed in the synchronous condition and not in asynchronous, then it is concluded that the effect in the dependent variable is caused by embodying the virtual body [e.g., 4].

Study 1 showed that not all the implementations of asynchrony are effective in their distortion of the body ownership illusion. Specifically, we found that delaying the body does not result in a significant difference in embodiment scores with a synchronous condition, even though the delay we implemented was twice as long as the highest delay we found in the literature [34, 98]. Thus, delay is an ineffective condition to distort embodiment. Out of the variations of asynchrony, the prerecorded body resulted in the lowest embodiment scores, suggesting it to be the most effective manipulation to distort the body ownership illusion. However, the variance of responses (see Figure 3 and Figure 5a) suggests that the effectiveness of the manipulation likely depends on the individual participant. Some participants reported high scores, indicating the presence of the body ownership illusion. Thus, prerecorded movements cannot guarantee the distortion of embodiment.

The think-aloud study offered a deeper understanding of the experience of embodiment, complementing the more common approaches primarily based on quantitative questionnaire data. Introducing incongruency between visual and motor senses is complex. Participants exert agency over their bodies in the synchronous condition and report retained agency when movements of the body are delayed, dislocated, or even prerecorded. In the prerecorded condition, the camera view is typically synchronized with the participants' head movements, and since the virtual body is typically viewed from a first-person perspective [e.g., 17, 69, 90], participants might experience a partial body ownership with the head of the avatar. This experience is reflected in how participants in the think-aloud reports contemplated their perceptions about their control over the head. (e.g., P8 in the prerecorded condition noted: *"It's as if my head was taken and put on top of other body"*). We found that the first-person perspective and agency over the head view of the virtual avatar might make participants relate to the asynchronous virtual body as their body, only intoxicated or sick and, for that reason, not perfectly responding to their actions. On top of that, some participants started to imitate the movements of the prerecorded body, which might have resulted in a diminished distortion of the illusion. The correspondence of movements might have induced agency over the virtual body, which is a major component of embodiment [45, 68].

5.2 What is asynchrony doing that it is not supposed to

While asynchrony does not necessarily break the illusion of body ownership, it brings a handful of side effects that we were unaware of and have not seen reported elsewhere.

First, we observed that asynchronous conditions often influence how participants *move*. Participants routinely tried to mimic the movements of the asynchronous bodies and synchronize with them by slowing down the body in the delay condition, producing more movements in the dislocated condition, and imitating the prerecorded body. Some participants stopped moving at all in the asynchronous conditions. Developments in cognitive load theory suggest that movements and their amplitude influence cognitive load [89]. As body ownership experiments sometimes investigate effects on cognitive abilities [e.g., 4, 6, 73], the heightened cognitive load might confound the experimental outcomes.

Second, we found that *attention* is influenced by the asynchronous condition. The think-aloud study showed that in the asynchronous conditions, participants were trying to make sense of the asynchronous movements and focused on understanding the correlation between their and the avatar's movements rather than on the features of a virtual avatar. In addition, the crowdsourced study showed significantly different ratings on the appearance of the avatar, even though the avatar model was the same for all participants. VR experiments routinely study how visual features of the avatar influence behaviour and attitudes [4, 73, 77], and a shift of attention from and to these visual features might confound the results of the experiments.

Third, we found that the *experience* of the asynchronous body is worse compared to the synchronous conditions. This means that participants assigned to asynchronous conditions might be occupied with their discomfort, and resulting negative emotions, which can distract them from the main task in the experiment. Additionally, we found that the scores on user experience correlated with the scores on embodiment in Study 1. This suggests that user experience can contribute to or explain the experience of embodiment.

Finally, asynchronous conditions might be a source of *demand characteristics* – experimental confound that occurs when characteristics of the experimental design may hint the 'correct' answer that the experimenter is looking for and influence participant's responses [72]. As Lush [61] cautioned, contrasting synchronous and asynchronous conditions in embodiment studies gives a good hint to participants about what the study is aiming to test. Participants can guess that the asynchronized body should result in lower embodiment scores than the synchronized body [61]. Even in between-participants studies, the combination of the asynchronous condition with a questionnaire on body ownership might make participants understand that the intention of the manipulation is to induce low body ownership scores. Lush et al. [62] showed that in synchronous and asynchronous conditions, participants implicitly know how to respond in each case to match the expectation of the researcher, and concluded that asynchronous condition does not serve as an adequate control in embodiment studies.

5.3 What asynchrony tells us about the validity of body ownership studies?

The issues related to asynchronous conditions outlined above are critical to the validity of studies investigating ownership of synchronous bodies.

Our results showed that asynchronous conditions do not guarantee disruption of embodiment. Therefore, we cannot be certain that the effects observed in embodiment studies are due to the body ownership illusion. This is particularly relevant for studies that implement asynchrony as a delay of movements. Notably, in Study 1, the delay did not result in a significant difference in embodiment with the synchronized condition, even though the delay of the avatar movements was twice as long as the highest delay we found in the literature [34, 98]. The non-replication of the disruption of embodiment in the delayed condition might stem from within-subjects designs in the reviewed studies, suggesting the potential presence of demand characteristics effects [38, 61]. In contrast, our study was between-subject. Moreover, none of the reviewed studies used validated questionnaires.

Our results also hint that the measures used in the studies on body ownership might be problematic. In both studies, we included a synchronous condition as a control. The mean embodiment score (measured from -3 to 3) in the synchronous condition in Study 1 was not significantly different from zero ($t = -0.004,\ p = 0.996$). Even though the score was significantly different from the prerecorded and dislocated conditions, taking it in isolation, it is relatively low, and the conclusion that the effects in embodiment studies are caused by the body ownership illusion might be an overstatement. While our synchronization implementation (limited to the upper body) may partly explain these responses, similar findings have been observed in studies examining full-body embodiment [68]. Additionally, the experiences of the synchronous body as expressed in the laboratory study are very different from what is asked in the commonly used questionnaire on embodiment [68, 76]. The avatar embodiment questionnaire [76] has questions that concern the process of the real body turning into the avatar body, taking the VR embodiment as a process developing over time. We did not observe any such experiences in the think-aloud study. Instead, participants reflected on the accuracies of movements, the potential utility of the body, and the perspective-view on the body, which appear to be important for the sense of embodiment but not captured in any of the embodiment questionnaires commonly used [e.g., 18, 23, 76, 85]. We suggest an in-depth examination of the questionnaires currently used to assess embodiment in VR.

Finally, we found that all participants in the think-aloud study were testing the visuo-tactile correspondence by touching themselves and reflecting on the correspondence of self-touch with the movements of the avatar. Even though visuo-motor integration is considered to be the most effective manipulation to induce body ownership [68], the question of whether visuo-motor integration exists in isolation arises. Perhaps multisensory integration with visuo-motor congruence, is never isolated from the tactile modality.

5.4 How to control the validity of embodiment studies?

The question of how to control the validity of body ownership studies is complicated. To highlight its complexity, we want to once more reflect back on the rubber hand illusion study [10]. The issue with the direct adoption of asynchronous conditions from the rubber hand illusion is the difference in the causal mechanism theorized and tested in RHI and VR studies. In RHI, the asynchronous condition was used to show that the embodiment illusion occurs because of multisensory integration. When the visual and tactile stimuli were not integrated, the illusion did not occur. In studies on body ownership in VR, the experimental design is generally more complicated. The multisensory integration is used to claim that a certain body has an effect on some third dependent variable, and this effect works *through* the body ownership illusion. Thus, body ownership is not a dependent variable but rather a mediator for the main effect. By disrupting multisensory integration in body ownership VR experiments, the authors usually do not claim the successful or unsuccessful body ownership illusion (like in the RHI). Instead, they claim that the body ownership illusion has an influence on behaviour, attitudes, or other dependent variables measured. However, as we showed, the disruption of multisensory integration in the visuo-motor scenario does not necessarily lead to the absence of body ownership, making the validity of much contemporary empirical and theoretical work on embodiment questionable.

Out of the implementations of the asynchronous condition we explored, the results clearly indicate that the prerecorded condition is the most effective intervention to disrupt embodiment. However, we are cautious to establish it as a golden standard. First, we observed the tendency of participants to imitate the movements of the asynchronous body in this condition. Second, the prerecorded condition renders the lowest user experience. Third, the synchronization of the head and first-person perspective view does not allow for a full disconnection from the avatar for some participants.

As the camera must be synchronized with the participant's head movements, achieving complete asynchrony of the avatar from a first-person perspective is not possible. A complete disruption of BOI appears unattainable with a synchronous camera view. This is because self-location is inherently tied to the perceived origin of an egocentric visuo-spatial perspective [21, 37]. Although it is possible to introduce asynchrony between head movements and the camera view, this mismatch between visual and vestibular cues may lead to virtual sickness [36]. Full avatar asynchronisation is possible when observing the avatar from third-person perspective. However, fist-person-perspective enhances the sense of virtual embodiment and makes the experience of owning a virtual body more realistic [33, 65, 80, 91]. Consequently, shifting the avatar to a third-person perspective can weaken the embodiment illusion. Moreover, an asynchronous avatar viewed from third-person perspective may not be interpreted as a disruption of embodiment but rather as the presence of another person in the scene.

The main premise of VR embodiment experiments is to test the effects of a particular body on some third variable. The control, therefore, does not have to be an absence of body ownership illusion. Instead, it could be a body that is as much as possible similar to the real body of the participants (which is, following the recent developments of VR, should be possible [e.g., 60]). Another way to control the effects of having a body is to introduce a condition in which participants have no body or have some body that visually has nothing to do with the hypothesis tested. An example of such control is a study that explored the effect of a black-skinned avatar on racial bias [77]. In this study, an avatar with purple skin was included as a control.

If an asynchronous avatar is still the best choice, the way it is used should be considered. In both the think-aloud and crowdsourced studies, we aimed to replicate a typical experiment on body ownership in VR. Participants were not given any specific tasks while experiencing the virtual body, except for suggested stretching exercises designed to help them explore the possibilities of the virtual body [e.g., 4–7]. The possibilities of interacting with the environment were also restricted. However, the normal experience of having a real body suggests the use of the body for interacting with the world around. This was reflected in reports from the think-aloud study, where participants tried to evaluate the asynchronous bodies in terms of functionality, reflecting on whether the delayed body would be effective for, for example, grabbing a cup or interacting with a UI. Including a task or creating an interactive environment might create a more natural experience of having a body. Additionally, it can remove the confound that participants try to mimic the prerecorded body, which may lead to the maintenance of the body ownership illusion. With a task, participants likely will not have a willingness to repeat the prerecorded avatar.

Finally, synchronous and asynchronous conditions are usually contrasted as conditions in which participants experience and do not experience embodiment correspondingly. This approach treats embodiment as a binary concept: you either have a body, or you do not have it. Meanwhile, the embodiment is measured with a continuous scale (i.e., from -3 to 3 in the Avatar Embodiment Questionnaire [76]). Thus, rather than contrasting synchronous and asynchronous conditions, the embodiment score could be included in the analysis as a covariate.

5.5 Limitations

Each concept in our conceptual scheme can be realized through multiple implementations. For example, for temporal asynchrony, the length of delay can be altered, and movements can be predicted instead of delayed [42]. Prerecorded implementation may include variantions of movements, as well as multiple strategies for dislocating movements of participants exist. We tested one implementation for each concept, aiming to capture their conceptual variability. However, our interpretation of the results is inherently limited to the specific implementations used in this study.

We did not use a mirror in our study, as the presence of virtual mirrors, despite their common use, was reported to have a limited to negative effect on body ownership [68]. Mirrors make the visual discrepancy between the person and the avatar more noticeable, and make the avatar's static face apparent [68]. Whether the use of mirrors in body ownership experiments is useful, is an ongoing scholarly discussion [68]. The use of mirrors also raises specific questions in the context of asynchronous avatars. Our study outlined that seeing the body from a first-person perspective may be an important factor in building a connection with the avatar. Even in the prerecorded condition, participants reported that their mind was enclosed in a virtual body. Some thought that the body generated actions based on their speech, and felt a connection with the body. Having a mirror with an asynchronously moving body might influence this connection. Anecdotally, our findings suggest a shift of attention from features of the body to the action happening in the mirror. Additionally, it may lead to the feeling of the presence of a third person in the scene, which is evidenced in how participants relate to asynchronous bodies in the mirrors in existing research [4, 6]. The illusion of having a third person in the scene might serve as a confounding contextual variable, as social theories attest that being observed by other people influences behavior, attitudes, and presence [3, 8, 29]. Therefore, mirrors may serve as a possible confound in body ownership experiments. However, given that about half of virtual embodiment studies use mirrors in the induction phase [68], future work may deepen the understanding of asynchronous body perception by adding its display in the mirror.

In our study, we relied solely on upper-body tracking, instructing participants to maintain a static pose and refrain from moving their legs. This approach was chosen due to hardware limitations that prevented leg tracking. The simplistic setup allowed us to crowdsource the study with higher internal control. By limiting movement, we reduced the risk of confounding variables introduced by user motion. However, participants could not explore the body to the same extend as they would in real life. To fully understand the experience of synchronous and asynchronous avatars, it would be worthwhile to study full-body synchronization in future work.

For measuring participants' experience of the embodiment illusion, we relied on questionnaires [76] and think-aloud reports. Both methods are subjective self-reports about the experience, and conclusions from them should be drawn with caution [62]. Participants' reports might be influenced by the abovementioned demand characteristics [38, 61, 62]. In the rubber hand illusion, the fact that participants experienced the embodiment illusion is objectively validated with proprioceptive drift (a measure of how far away participant feels their own hand has moved from the fake hand) [10]. In visuo-motor VR research, even though objective measures for embodiment have been suggested (e.g., response to a threat [27] or skin conductance [93]), they are rarely used, and their validity is questionable [62]. Therefore, we did not validate the presence of the body ownership illusion in participants. Future work could benefit from developing validated ways of measuring embodiment objectively or using recently develped psychometric investigations of virtual embodiment [16].

For Study 2 we recruited novices, whereas Study 1 was crowdsourced using existing VR users' own headsets. Employing experienced VR users through crowdsourcing allowed us to achieve statistical power. Also, we considered that recruiting participants with substantial VR experience was appropriate for Study 1, as our focus was on the effectiveness of asynchrony in disrupting the illusion of virtual body ownership—a phenomenon that should occur regardless of prior VR experience. In Study 2, our goal was to capture participants' unfiltered experiences of asynchrony while minimizing comparisons to prior VR use.

There was a gender imbalance among participants in Study 1. We fitted a set of linear regressions to test if gender had an interaction effect on the main effects in the study. None of the interaction terms between gender and condition yielded significant for any of the dependent variables. We therefore have no evidence to suggest that the effects of the condition are unique for males and females. The results of the regression analysis are presented in OSF.

We did not collect data on participants' body mass index or skin color, which could influence the degree of appearance discrepancy between their real body and the virtual body, potentially varying across participants. We used the same avatar for all participants. Research indicates that it is possible to induce embodiment of a body that differs significantly from one's own [e.g., 4, 77], and that an avatar's similarity to the user does not significantly impact the sense of virtual embodiment [85].

6 Conclusion

In this paper, we conducted two studies to understand whether asynchronous conditions, routinely used in body ownership studies, work as intended. In a crowdsourced quantitative study with 202 participants, we found that various implementations of asynchrony lead to systematically different scores on the embodiment and user experience, rendering different implementations of asynchrony not commensurable. Prerecorded movements were the most effective in distorting embodiment but also resulted in the lowest user experience. Sixteen participants in a think-aloud study revealed that the experience of asynchronous conditions is complex and brings unexpected side effects that might confound experimental outcomes. We found that asynchronous conditions produce peculiar and emotionally vivid experiences that capture participants' attention, influence their movements, and might increase cognitive load. Moreover, asynchrony can sometimes reinforce, rather than distort, the sense of embodiment, as participants may inadvertently imitate the movements of asynchronous bodies to maintain a connection with the avatar. We conclude that the current use of asynchrony does not serve as an adequate control in embodiment experiments in VR. In light of this, our findings cast doubt over the validity and interpretation of VR body ownership studies. We discuss the questions that our findings raised about studies on body ownership and avenues of how the validity of experiments on body ownership can be increased.

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