Common Cues? Toward the Relationship of Spatial Presence and the Sense of Embodiment

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Abstract

The sense of presence and the sense of embodiment are two fundamental qualia, pivotal to many virtual reality experiences. Empirical research indicates a notable interdependence between these two qualia, where manipulations designed to affect one often exhibit a concurrent influence on the other. Existing theories on the development of qualia in virtual reality make no or only insufficient statements on this deep interdependence. In this work, we present a novel theoretical perspective on this connection. Based on existing theories, we argue that all the fundamental cues influencing one quale have the potential to impact the other one too. We present three studies (n = 42, n = 42, n = 32) that generally support this novel perspective. Among other things, they show that traditional spatial presence cues such as head-tracking and passive depth cues (stereoscopy, linear perspective, etc.) can potentially also serve as embodiment cues. Conversely, they show that typical embodiment cues such as the visuotactile and visuoproprioceptive synchrony of a virtual hand are also spatial presence cues. The cues only differ in terms of how strongly they influence the respective quale. This novel perspective not only enhances our understanding of fundamental mechanics of virtual reality but it can also guide the development of more effective measurement instruments.

Index Terms: Virtual reality, virtual embodiment, body ownership, spatial presence, mixed reality

1 Introduction

Virtual Reality (VR) can transport individuals to fantastical landscapes, replicating experiences once confined to imagination. In the realm of VR and Extended Reality (XR) a lot of research centers on identifying which characteristics of a VR experience convince users that they exist within this virtual space, rather than in the physical space. The degree to which one believes to exist within a mediated space, can be referred to as the sense of presence [17]. VR applications also offer a unique chance for their users to inhabit a body that differs from their actual physical appearance. The sensation that emerges when the properties of one's virtual representation, i.e. the avatar, are processed as if they were the properties of one's own biological body is referred to as the Sense of Embodiment (SoE) [21]. Empirical work continuously shows a connection between the two qualia. On the one hand, studies that manipulate traditional SoE cues find evidence that this manipulation not only affects the SoE but also the sense of presence. For example, VR users with avatars experience greater presence than those without [38, 23, 37, 49, 42]. Also the similarity between the virtual and biological body enhances both senses [19, 33, 44]. On the other hand, adjusting traditional presence cues, such as immersion levels [44, 29] or object congruency [12, Ch. 5], can also manipulate the SoE.

Several theoretical models explain how VR qualia arise and why this technology influences human experience to such a high degree e.g. [2, 30, 36, 21, 35, 22]. While these theories can adeptly explain many empirical findings, they often focus on either embodiment or presence, with very limited insight into their connection. The only exception to this is the Implied Body Framework (IBF) [11]. There seems to be a lack of understanding and in-depth explanation about the connection of two of the most fundamental qualia that VR has to offer. We want to drive this discussion on this topic forward and come up with an explanation that can give an idea of how this multi-level interdependence occurs. Moreover, we empirically test the validity of this explanation by conducting three studies.

We approach the interdependence at the cue level, arguing there are no (or hardly any) pure embodiment or spatial presence cues; a manipulation that is intended to increase or weaken one quale always has the potential to have a similar effect on the other quale. We present three studies that investigate this perspective: Study 1 manipulates head-tracking as a traditional spatial presence cue. Study 2 manipulates passive depth cues such as stereoscopy (also as traditional presence cues). Study 3 manipulates visuotactile and visuoproprioceptive synchrony of a virtual hand as traditional SoE cues.

Our results partially support our novel perspective. Study 3 shows how the visuoproprioceptive and viuotactile synchrony of a virtual hand can act as spatial presence cues. Study 1 shows how head-tracking can act as an embodiment cue. The results of Study 2 are mixed; there is an effect suggesting that passive depth cues may also be an embodiment cue. However, as this effect is not significant, we cannot draw any conclusions as to whether this effect appeared by chance or not. Overall, however, the trend of the results is as predicted by our novel perspective. A clear distinction between spatial presence and embodiment cues does not appear to be tenable.

2 Related Work

2.1 The Interrelation of Presence and Embodiment

Studies have shown that traditional embodiment cues tend to manipulate the sense of presence. In VR, the SoE usually refers to an avatar, which is why traditional SoE cues always assume the presence of an avatar. Traditional SoE cues involve synchrony between visual signals from the virtual body and signals from other modalities, such as visuoproprioceptive, visuomotor, and visuotactile synchrony [4, 41, 21, 24]. In addition, the first-person perspective, and the level of realism of the appearance (shape and texture) are important building blocks [26]. In a study on body-weight perception by Wolf et al. [49], participants who embodied a photorealistic avatar exhibited a significantly higher sense of presence, compared to those without an avatar. Having an avatar seems to be an important factor in convincing VR users that they actually are in the virtual environment [36, 37, 38]. A study by Unruh et al. [42] incorporated a more nuanced approach to embodiment, varying from low (just controllers) to medium (hands and controllers)

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to full avatar embodiment. Results indicated that the gradual increase in embodiment cues corresponded to a gradual increase in presence. The quality of the embodiment cues also seems to affect presence. Gall et al. [13] demonstrated that delaying the movement of a virtual hand negatively affected both SoE and the sense of presence. This effect even extends to top-down factors of avatar embodiment. Personalized avatars, whether full-body or just hands, led to higher presence and SoE scores when compared to generic representations [19, 44, 32, 18]. These studies suggest that various aspects of avatar embodiment, including quality, appearance similarity, and anatomical plausibility, contribute to the sense of presence [39, 13, 19, 44, 42, 23].

Conversely, traditional presence cues also tend to influence the SoE. Those traditional presence cues are the typcial immersive properties of VR, such as the extend of tracking, a wider field of view, or sound and image quality [5, 36]. Waltemate et al. [44] found that participants using a full-immersive Head-Mounted Display (HMD) experienced higher levels of both SoE and presence compared to those using a CAVE-like setup. Roth and Latoschik [29] reported similar results when comparing high immersive HMDs to a stereoscopic projector setup. Wolf et al. [48] found that the level of immersion influenced SoE in VR versus augmented reality headsets. Gall [12] manipulated presence by changing the location of a table in a room, making its position congruent or incongruent with the virtual representation seen through an HMD. A representation of the participant's right hand was displayed in the virtual environment, matching the position of the real hand. The results showed that by manipulating the congruency of the virtual table, the SoE was manipulated as well. In the high presence condition, participants also experienced higher SoE for the virtual hand, although nothing has been manipulated on the virtual (or the real) hand. These findings indicate that traditional presence manipulations can also alter the SoE, even when the avatar embodiment process remains constant. However, there are fewer findings here than on the influence of traditional embodiment cues on presence. The impact of the immersive properties on the SoE is largely unknown. A qualitative study by Tham et al. [40] provides evidence that this connection could exist. There, participants reported that a richer stimulation and higher fidelity made them feel more embodied in VR.

2.2 Theoretical Models on XR-related Qualia

A notable working definition for the SoE is provided by Kilteni et al. [21], who conceptualize it as 'the ensemble of sensations that arise in conjunction with being inside, having, and controlling a body.'. This concept of embodiment has its root in cognitive sciences where the more general SoE centers around the subjective experience of having and controlling a body [3]. In VR, these sensations can be related to an avatar. The idea is that the properties of this avatar are processed as if it was part of one's biological body. This includes self-location (being inside the avatar), agency (controlling the avatar), and body ownership (owning the avatar). A way of understanding this phenomenon is that the brain uses Bayesian interference to determine whether two different stimuli have the same source or not [34]. This Bayesian inference takes various things into account, e.g. temporal and spatial discrepancy or visual events close to the virtual body [25]. If the stimuli are synchronized, the brain no longer makes a distinction between the virtual and biological body. Although the working definition of Kilteni et al. [21] does not directly link presence and embodiment, they recognize that 'a more extended approach to embodiment could potentially include the presence subcomponent' [21, p. 376]. Skarbez et al. [35] and Slater [36] discuss presence through two orthogonal factors, namely the Place Illusion and the Plausibility Illusion. The Place Illusion refers to the sense of actually being there in the virtual environment, sometimes also referred to as spatial presence [47, 46, 27, 35]. According to Slater [36], having an avatar is relevant for the Place Illusion because it gives a strong indication of actually being in the virtual world. Looking at the empirical results, however, this explanation falls short. It is not just avatar versus no-avatar manipulations that show an impact on presence, but also those that manipulate the quality and extent of embodiment [23, 13, 42] or the appearance of the virtual body [19, 44]. The extension of Skarbez et al. [35] adds two additional qualia to the model (Social Presence Illusion and Copresence Illusion) but does not factor in the SoE.

It is important to understand that the biological body still plays a role in both theories through sensorimotor contingencies. These contingencies allow users to perceive and explore the virtual environment using their bodies in ways that mimic physical reality. For instance, head-tracking enables natural exploration, and higher pixel density allows closer examination of objects. This concept is embedded in many presence theories. Schubert et al. [30] describe 'embodied presence' as arising from the representation of body movements in the virtual world, while Biocca [2] calls it 'progressive embodiment'. The IBF of Forster er al. [11] also incorporates these ideas. It suggests that each multisensory integration infers the presence of implied bodies. An implied body is inferred for example, by visuomotor correlations during head-tracking. The IBF 'understands presence as depending on embodiment processes' [11]. This aligns with the enactive view on cognition, which emphasizes the role of interaction between the mind, body, and environment [6]. These ideas will also be relevant for our own theoretical perspective (see Sec. 3).

Recently, Latoschik and Wienrich [22] introduced a generic model that explains how changes in XR applications' manipulation space affect the qualia space. Although the model does not make any explicit statements about the connection between the sense of presence and the SoE it conveys two ideas that can help us broaden our understanding. Firstly, the model does not make a 1 to 1 link between cues and qualia. Instead, it assumes that cues affect the overall plausibility of the VR experience and thus also contribute to several qualia. Secondly, the XR-related qualia are not arranged hierarchically, e.g. one quale does not cause or is the prerequisite for another quale. These two ideas will be relevant for the novel perspective we formulate in the next section.

In summary, current XR theories do not make decisive statements about the interdependence between the sense of presence and the SoE, with the IBF being an exception [11]. The first aim of this paper is to further push this theoretical discussion and establish a novel theoretical perspective on the connection between both qualia. The second aim is to empirically test this perspective, thus establishing more evidence that either speaks for or against it.

3 Approach

3.1 Common Cues - A Novel Perspective

Our new perspective distinctly positions the connection between both qualia on the level of spatial presence (and not the more general presence concept). When we talk about 'general SoE' we mean the general feeling of having and controlling a body [3, 21]. If we now look at the ideas anchored in the various discussed theories about XR-related qualia [2, 30, 36, 21, 22], we can notice an overlap in the definitions of spatial presence and the general SoE: Spatial presence is about the coupling of the biological body and its motor and perceptual abilities to the user interface (in our case the HMD). The general SoE is about the sensation of having and controlling a body. One could argue that the more capabilities of the body are supported by the computer interface, the more information one gets about the spatial composition of the environment (spatial presence increases) and the more one becomes aware of owning and controlling a body (embodiment increases). The traditional immersive properties of VR (headtracking, depth perception, image quality, update rate, ...) are examples of how spatial understanding and the supported interaction possibilities are increased by the user interface. This, in turn, increases spatial presence. At the same time, increasing support for immersive properties always means increasing support for bodily abilities. The conscious and unconscious use of the body and its motor and perceptive abilities are the basis for immersive properties to become effective in the first place. It is the activation and support of these motor and perceptive abilities by the user interface that reinforces the sense of owning and controlling a body. Since every form of perceiving and interacting in an environment presupposes an underlying bodily ability, **every traditional spatial presence cue could potentially also be an embodiment cue**. It is important to understand that the general SoE occurs and is manipulated in all VR environments. Even without an avatar, a VR experience changes the body image by making the own body invisible. However, this does not negate the general feeling of being embodied. In the end, there are not just visual stimuli that make people aware of their bodies, but many more, e.g. proprioceptive, vestibular, or kinesthetic stimuli. An avatar merely manipulates the visual subcomponent of being embodied. Thus, traditional spatial presence cues have the potential not only to influence the general SoE, but also to affect the SoE towards an avatar.

Turned around, all the stimuli that convince (or remind) users that they own and control a body in the virtual environment (general SoE increases) can also contribute to the conviction that one is in the environment in which one acts with and sees this body (spatial presence increases). This therefor also applies to the traditional embodiment cues that always refer to a visual representation of the user (the avatar) and its behavior relative to the virtual environment. For example, visuotactile synchrony describes congruent tactile information *relative* to a virtual object and visuomotor or visuoproprioceptive synchrony describe a congruent body motion through the environment, i.e. *relative* to all the entities it contains. In this sense, the virtual body is the interface between the self and the environment. If one receives more congruent information about the own embodiment, in this case via your avatar, one also receives more congruent information about the virtual environment, specifically about the *relative* position of the own body in the virtual environment. On the one hand, this increases the spatial understanding, on the other hand, this also increases the perceived possibilities to act in the virtual environment. This ultimately feeds the conviction that one is currently located in this (virtual) environment. That means, **potentially every traditional embodiment cue could also be a spatial presence cue**.

The more congruence there is between the processed and expected information, the stronger the influence of the cues on both qualia. So we take the basic definitions of spatial presence and SoE expressed in established theories [36, 35, 2, 30, 46, 21] and connect it with the assumptions of Latoschik and Wienrich [22], as elucidated in Sec. 2.2. From our novel perspective, SoE and spatial presence do not exist in a hierarchical relationship with one another. They would exist at the same level (qualia space), being steered by common cues. The congruence of these cues with what the user expects would then lead to an increase in both qualia. This does not mean that we see both qualia as one and the same. We assume that they share building blocks that contribute to the respective quale with different strengths, i.e. that there are cues that are more important for presence or embodiment. The significance of a cue for one of the qualia can therefore also be negligible. Ultimately, we cannot say whether all cues that contribute to spatial presence also contribute to the SoE. However, we believe that all cues have the potential.

3.2 Implications of the Novel Perspective

Several implications can be deduced from our common cue perspective. We aim to assess three distinct implications through three separate studies. All of the three studies are based on the assumption that traditional spatial presence and traditional SoE cues always have an concurrent influence on the respective other quale.

If every form of spatial presence cue also generates SoE, it would follow that embodiment takes place even without a visible avatar. To understand this, one has to take the more general view of embodiment. Moreover, we argue that all cues that help people to understand the spatial composition of their environment, also require the support for a bodily ability that makes this information accessible to consciousness (traditional spatial presence cues also impact the SoE). On the one hand, this has an active component: The active use of motor skills to understand the spatial properties of the virtual environment also increases the general SoE. Head-tracking is one of the most central spatial presence cues [5]. A user interface that supports head-tracking supports a central human motor skill. Following our novel perspective this would mean that even without an avatar, head-tracking alone could serve as an embodiment cue.

RQ1: Can the manipulation of head-tracking decrease the SoE in a VR application without an avatar?

This reasoning is also consistent with the IBF, in which the multisensory integration that goes along with headtracking is considered important for both, the sense of presence and embodiment [11]. However, our argument extends further than this. On the other hand, the impact of traditional spatial presence cues on the general SoE also has a passive component: Properties of the biological body that help a person to understand the spatial properties of the virtual environment can also increase the SoE, even when they are not actively or consciously used. Immersive properties such as stereoscopy or pixel density create spatial presence because they increase the possibilities to act (more precisely) in the virtual environment. Unlike with head-tracking, this happens even though the user does not actively or consciously decides to use these capabilities. Technically, head-tracking is also a depth cue, as it can be used to generate motion parallax. But there are also a large number of passive depth cues that do not require the active or conscious use of motor skills, e.g. stereoscopy, linear perspective, or texture gradient. In order for this depth information to become effective, sensory and perceptive abilities of the biological body are still required. VR applications support various of these cues and they are traditionally associated with spatial presence [5, 1, 16, 7]. Following our novel perspective, even these passive depth cues should also be embodiment cues. A user interface that supports them presupposes the sensory and perceptual abilities of its users to process these cues. Reducing the depth information in a virtual environment should also lead to a reduction in the sense of being embodied.

RQ2: Can the manipulation of passive depth cues decrease the SoE in a VR application without an avatar?

The IBF makes no statement on this, as it is only based on multisensory integration [11]. *RQ1* and *RQ2* aim to find out whether traditional spatial presence cues also influence embodiment. For the reverse case, i.e. the influence of traditional embodiment cues on spatial presence, there is already some evidence [49, 42, 38, 13, 37, 23]. However, these were often found incidentally as side-products of the experiments. To deepen our understanding, we aim to conduct a dedicated study that isolates the influence of traditional embodiment cues on spatial presence, focusing specifically on this research question. This also allows us to compare the magnitudes of the effects on spatial presence and the SoE. We have established the proposition that any form of traditional SoE cue also influences spatial presence. This should happen even if there are no other spatial stimuli and no active control of the virtual body is established. Two traditional SoE cues with which we can test this would be the visuoproprioceptive and visuotactile synchrony of a virtual hand.

RQ3: Can the manipulation of visuoproprioceptive and visuotactile synchrony of a virtual hand in an otherwise minimalist environ-

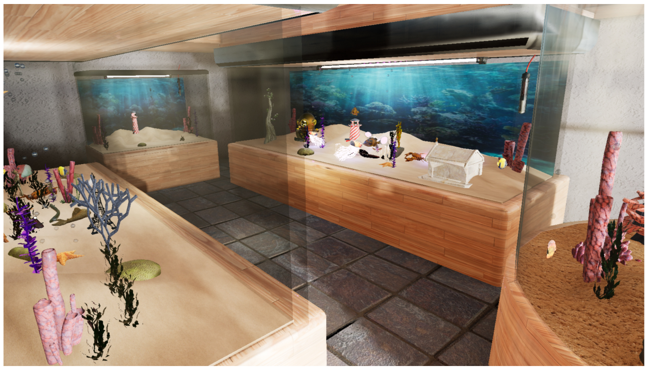

Figure 1: The virtual environment of Study 1 from an elevated position. The subjects were located in the centre between the aquariums.

ment decrease the sense of spatial presence?

4 METHODS

4.1 Study 1

4.1.1 Design

Study 1 aimed to investigate the impact of head-tracking on the SoE and spatial presence. It is based on a one-factor between-subjects design. The factor we were manipulating was the availability of head-tracking. We distinguish two groups:

ACTIVE: The head-tracking of subjects in this group was *activated*, i.e. they were able to use their heads to explore the virtual environment.

FIX: The head-tracking of subjects in this group was deactivated, i.e. their head was *fixed*.

4.1.2 Material and Stimuli

The virtual environment used in our study was based on an asset obtained from the Unreal Marketplace [14]. We created an environment in which the participant sat in a room, surrounded by aquariums. Overall, the environment was designed to encourage visitors to look around and explore. In addition, a simple soundscape was created by the aquariums producing a low hum plus the sound of rising air bubbles. The virtual environment is depicted in Fig. 1. Head-tracking was prevented for people in the *FIX* group, both in terms of software and mechanically. On the software side, we have deactivated translational and rotational updates of the VR headset, resulting in a fixed image. To minimize the risk of cybersickness, we also fixed the headset mechanically by attaching it to a clamp, which in turn was attached to a tripod. This allowed us to adjust the height of the clamp and the headset to the respective participants. An Intel i7 3.60 GHz, 32 GB RAM computer with an NVIDIA GeForce RTX 2080 Ti graphics card rendered images at 90 Hz. We used the Valve Index VR-headset [43]. We implemented the VR application in the Epic Games Unreal Engine 4.27.

4.1.3 Procedure

At the beginning, the participants read an information sheet and signed a declaration of consent. They then completed a demographic questionnaire and the Fast Motion Sickness Scale (FMS). The participants then sat down on a chair in the middle of the room, where they remained for the entire duration of the experiment. There they also received the HMD, through which they were immersed in the aquarium environment for 4 minutes. In the *FIX* group, the headset was attached with the clamp beforehand. The participants were instructed to simply let the virtual environment take effect on them. This can be referred to as a habituation phase. This was deliberately chosen because it was a task that could be completed by both groups. After four minutes passed the participants completed the Igroup Presence Questionnaire (IPQ), the Virtual Embodiment Questionnaire (VEQ), and the FMS (for more details see Sec. 4.4).

4.1.4 Participants

The final sample consisted of 42 participants (*ACTIVE*: $n = 21$, *FIX*: $n = 21$). All participants were students and 36 out of 42 were female. The average age was 20.78 (SD = 1.62). The amount of experience that participants had with VR was fairly low, as 81% had a view time of less than 5 hours.

4.2 Study 2

4.2.1 Design

With the second study, we wanted to find out if passive depth cues of a virtual environment could also serve as embodiment cues. In the context of this study, we leveraged a one-factor between-subjects design. The factor we manipulated was the wealth of depth information available. We distinguish two groups:

RICH: Subjects in this group had a *rich* set of depth cues at their disposal, i.e. the depth cues remained unmodified.

REDUCED: Subjects in this group had a *reduced* set of depth cues at their disposal, i.e. monoscopic instead of stereoscopic vision, no linear perspective, no shadows, and no (or only little) texture gradient.

4.2.2 Material and Stimuli

In the *RICH* group, participants were on a plain with a tile-based texture that generated a linear perspective. In front of the participant were 10 cubes of equal size. Each cube was a different distance away from the participant. In the sky, a sun served as a source of light. The cubes cast shadows downwards (onto the ground and other cubes). The cubes were surrounded by two walls with a brick texture which provided increased linear perspective and texture gradient. In the *REDUCED* group the plane had a one-colored texture removing the linear gradient, the cubes did not cast shadows, and the two brick walls were removed. Moreover, the virtual environment was rendered monoscopic. The technical implementation of monoscopic VR was inspired by Fink et al. [10]. A more detailed description of this implementation can be found in the Appendix. Fig. 2 illustrates how the *RICH* and *REDUCED* environments differed. The hard- and software used were the same as in Study 1.

4.2.3 Procedure

The participants first read an information sheet, signed consent forms, and filled out the FMS. They then sat down on a chair in the middle of the room where they remained throughout the study. The study consisted of two phases. First, there was a four-minute habituation phase in which the subjects simply had to let the virtual environment take effect on them. They then completed the IPQ, VEQ, and FMS (for more details see Sec. 4.4). In the second phase, the participants then had to perform a depth estimation task. Letters appeared on the cubes. The participants had to put the 10 cubes in an order, starting with the cube closest to them and ending with the one furthest away. The participants had to say the resulting sequence of letters out loud. There were 10 different tasks in total. The answers were recorded via a microphone on the HMD.

4.2.4 Participants

For Study 2 we analyzed the data of 42 participants ($M_{age} = 20.76$, $SD_{age} = 1.61$). 20 participants were in the *RICH* group and 22 in the *REDUCED* group. The sample consisted of 36 female subjects and 6 male subjects. 95% of the subjects had a previous VR experience of 5 hours or less.

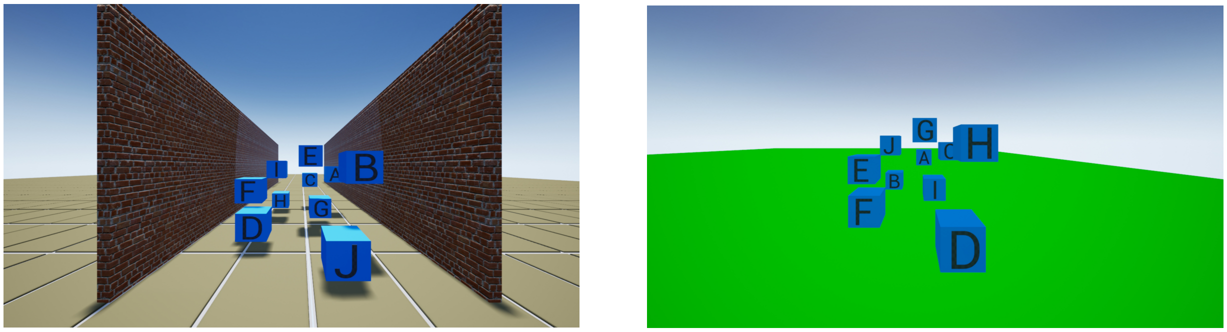

Figure 2: The depth task from Study 2. Participants had to put the cubes in an order depending on how far away they were. The left image shows the environment with many depth cues (RICH group). The right image shows the environment with reduced depth cues (REDUCED group).

4.3 Study 3

4.3.1 Design

Study 3 worked with a design based on the traditional Rubber Hand Illusion [4], as it gave us a simple and controlled way to manipulate traditional embodiment cues, i.e. breaking visuotactile and viusoproprioceptive synchrony by inducing a latency. Here, we refer to it as the Virtual Hand Illusion (VHI). The implementation of the VHI is based on Gall et al. [13]. For this study, we used a 2x2 mixed design. The within-groups factor was the presence or absence of visuoproprioceptive and visuotactile synchrony. Visuoproprioceptive synchrony refers to the synchrony between the movement of the virtual hand and the biological hand. Visuotactile refers to the synchrony of a virtual and a real ball that touches the hand. We distinguish two conditions:

SYNC: Subjects in this condition experienced a synchronous virtual-hand illusion, i.e. the motion of the virtual hand and the virtual ball were *synchronous* with the motion of the biological hand and the physical ball.

ASYNC: Subjects in this condition experienced an *asynchronous* virtual-hand illusion, i.e. the motion of the virtual hand and the virtual ball had a delay of five seconds compared to the motion of the biological hand and the physical ball.

We had a an additional between-groups factor that was the presence or absence of stereoscopic cues. However, this factor plays no further role in our discussions. For the sake of completeness, we will nevertheless report the corresponding results later.

4.3.2 Material and Stimuli

For this study, we leveraged a 3D-printed hand rest that defined a fixed position for the right hand of the participants. The hand rest was fixed on a wooden board, which could be rotated by 20 degrees. Thus, we were able to rotate a hand lying in the rest around its wrist, without directly touching it. The rotation of the board, and thus of the hand, was tracked with a HTC Vive controller. In addition, there was a styrofoam ball that was used to provide tactile stimulation to the participants' hand. The styrofoam ball was attached to a second HTC Vive controller. Consequently, also the styrofoam ball was tracked. The styrofoam ball was the basis for establishing a visuotactile synchrony and the tracked hand rotation was the basis for establishing visuoproprioceptive synchrony. The described elements of the hand rest are shown in Fig. 3. The virtual environment consisted only of the hand, a table, the ball and a scarf that covered the arm stump. Otherwise it was completely black. We worked with generic 3D models of a male and a female hand from the Unreal Marketplace [8], which were used depending on the gender of the subjects. The virtual environment of study 3 can be seen in Fig. 3. An Intel i7 4.00 GHz, 16 GB RAM computer with an NVIDIA GeForce GTX 1080 Ti graphics card rendered images at 90 Hz. The HMD we used was the HTC Vive PRO [15]. We implemented the VR application in the Epic Games Unreal Engine 4.27.

4.3.3 Procedure

After the participants have been welcomed, they read and signed information and consent documents. Then they filled out questionnaires concerning demographics and the FMS in a notebook. Afterwards, the participants sat down at a second table which had the wooden board fixed on it. They put their right hand on the hand rest. The experimenter then helped the participants to put on the HMD. In the virtual environment they saw the gender-matched hand in the same position as their biological hand. The participants' only task consisted of a habituation. Thus, participants were instructed to just sit there and let the situation and stimuli take effect on them. The participants had a short time to get used to the virtual environment. After that, the VHI was induced with the help of visuotactile and visuoproprioceptive stimulation. The experimenter stroked the hand of the participants with the styrofoam ball in circular movements. The experimenter also realized the visuoproprioceptive stimulation, by rotating the board with the hand rest on it by 20 degrees inward and back again. The two kinds of simulation were alternated. Each simulation lasted 30 seconds and was applied 4 times, resulting in an overall stimulation time of 4 minutes. Afterward, the IPQ, VEQ, and FMS were answered in a notebook (for more details see Sec. 4.4). Each participant experienced this procedure twice in a randomized order. In the *SYNC* condition, the motion of the virtual hand and the virtual ball were synchronous, while in the *ASYNC* condition, there was a delay of five seconds in the motion.

4.3.4 Participants

The final sample for the analysis consisted of 32 participants (29 female, 3 male, M_{age} = 20.94, SD_{age} = 1.98, all students). Participants were equally distributed to the conditions. Two participants had a VR experience of 5 hours or more.

4.4 Measurements

In each of the three studies, we collected three different dependent variables. A measure of cybersickness, a measure of the sense of presence, and a measure of the SoE. For presence, we chose the IPQ [31]. The questionnaire has the advantage that it contains a subscale for spatial presence, which is the part of presence that we are particularly interested in, as our novel perspective only makes statements about this (and not about general presence). This definition of spatial presence is also based on the idea of the connection between body and space by Schubert et al. [30], so it is very close to the definition from which we derive our perspective and hypotheses. The IPQ was answered on a 7-point Likert scale. In Study 1, our analyses for the IPQ revealed a very low Cronbach's α value for

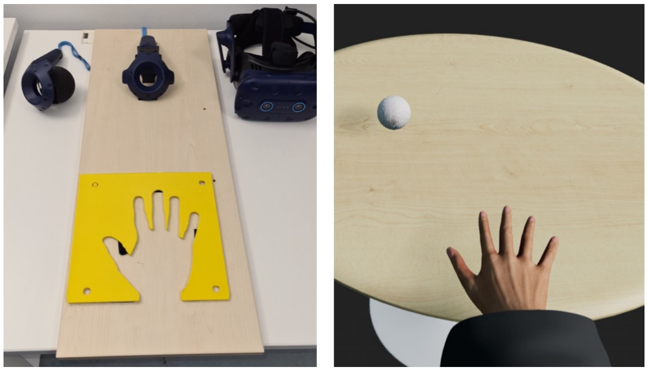

Figure 3: Study setup of Study 3. The left images shows the physical setup. The fixed hand position is in the yellow frame and tracked by the controller which is clamped to a mount on the board. To the left of the board is the second controller with the ball attached. The right images shows the corresponding virtual environment from the view of the participant. The image shows the female version of the hand.

Table 1: Adapted items of the VEQ for the subscales of body ownership and agency. These items were used in Studies 1 and 2.

Question	Subscale
In the virtual world, it felt as if I had a body	Ownership
It felt like I was owning a body	Ownership
I had the feeling of possessing a human body	Ownership
In the virtual world, I had a body that belonged to me	Ownership
In the virtual world, I had the feeling that I had a body that followed my movements	Agency
It felt like I was controlling the movements of a body	Agency
It felt like I was causing the movements of a body	Agency
I had the feeling that I had a body whose movements were synchronized with my movements	Agency

the spatial presence subscale (α = .450). Therefore we conducted a Principle Component Analysis and item 2 displayed a notably low loading of -0.050. The very low loading of Item 2 suggested more or less no association with the underlying factor. That's why we eliminated item 2 from further analysis in Study 1. Cronbach's α was thus increased to 0.551.

For embodiment, we chose the VEQ of Roth and Latoschik [29] as it has specific subscales for agency and body ownership. These two subscales are close to the general definition of embodiment that we used to derive our novel perspective, i.e. embodiment is about the subjective experience of having (body ownership) and controlling (agency) a body. Nevertheless, the questionnaire targets embodiment *toward* an avatar, so for experiments one and two, we adapted the questionnaire. We did this so that the subscale for body ownership focused more on the general feeling of owning a body in the virtual world and the subscale for agency focused more on the general feeling of controlling a body in the virtual world. The adapted items that we used in the first and second studies can be found in the Tab. 1. In the third experiment, we took the original items, but we replaced the term 'virtual body' with 'virtual hand'. Participants had to answer the VEQ questions on a 1-7 scale (strongly disagree - strongly agree).

For cybersickness, we used the FMS [20]. As the VR exposure in all three experiments was not too long, we wanted to reduce the number of questions. The scale was answered from 0 ('No nausea at all') to 20 ('Severe nausea/immediate vomiting').

4.5 Hypothesis

H1.0: In each of the three studies we expect our measure for spatial presence and embodiment to move in concurrently. Thus, manipulations that intensify or attenuate the sense of spatial presence have the same effect on the SoE and vice versa. We, therefore, expect the following for the individual studies:

H1.1: Subjects that have activated head-tracking (*ACTIVE* group) show a higher sense of spatial presence and a higher SoE compared to subjects that have their heads fixed (*FIX* group) during the VR experience.

H1.2: Subjects that have a rich set of passive depth cues at their disposal (*RICH* group) show a higher sense of spatial presence and a higher SoE compared to subjects that have a reduced set of depth cues (*REDUCED* group) at their disposal during the VR experience.

H1.3: Subjects that experience the VHI with no latency (*SYNC* condition) show a higher SoE and a higher sense of spatial presence compared to subjects that experience the VHI with a latency of five seconds (*ASYNC* condition).

5 Results

We restrict the questionnaire results we report here to the spatial presence subscale of the IPQ and the two subscales of body ownership and agency of the VEQ. Those three measures relate precisely to our novel perspective and our hypotheses. The results of the other subscales of the two questionnaires can be found in the Appendix.

For Studies 1 and 2 we used a t-test for independent samples or the Mann-Whitney-U-Test as the non-parametric alternative to analyze the data. For Study 3 we employed a mixed ANOVA. To ensure comparability, we indicated all effects sizes with Cohen's d. Conversions of other effect size indicators (*r* and *eta-squared*) are based on Rosenthal et al. [28, p. 239]. We tested for the equality of variances with Levene's Test and the assumption of normality with the Shapiro-Wilk-Test. We set the α level to 0.05 to indicate significance and to 0.1 to indicate a trend. We compared the pre- and post-scores of the FMS and eliminated participants that had an increase of five or more. This resulted in the elimination of one participant in the *ACTIVE* group of Study 1. Due to technical issues during the experiment, we eliminated two subjects from Study 1 and two subjects from Study 2. We used JASP version 0.17.3 for the statistical analysis. All the descriptive results described here can also be viewed in tabular form in the Appendix.

5.1 Study 1: The Manipulation of Head-Tracking

The mean value of spatial presence was higher for subjects in the *ACTIVE* group (M = 4.845, SD = 0.838) compared to subjects in the *FIX* group (M = 4.476, SD = 1.104). The t-test for independent samples showed no significant difference between the FIX and ACTIVE group, t (40) = 1.220, p = .115, d = 0.377.

The embodiment scores also showed higher values for the group with active head-tracking (body ownership: M = 4.357, SD = 2.068; agency: M = 4.571, SD = 1.729) compared to the subjects that had a fixed head (body ownership: M = 3.560, SD = 1.737; agency: M = 2.167, SD = 1.324). The Shapiro-Wilk-Test showed a deviation from normality for the agency scores of the ACTIVE group (W = .905, p = .044) and the FIX group (W = .824, p = .002). The test also showed a trend for the body ownership scores of the ACTIVE group, W = .913, p = .062. For the comparison of mean values, we therefore use the Mann-Whitney-U-Test. The U-test reveals the trend that people in the *ACTIVE* group exhibit higher body ownership compared to participants in the *FIX* group ($N1$ = 21, $N2$ = 21), U = 274.500, p = .088. The effect size (d = 0.505), suggests a moderate positive relationship between group membership and body ownership values. A power analysis showed that this effect would have become significant with a total sample size of 104 subjects (α = .05, power = .80). The agency scores are significantly

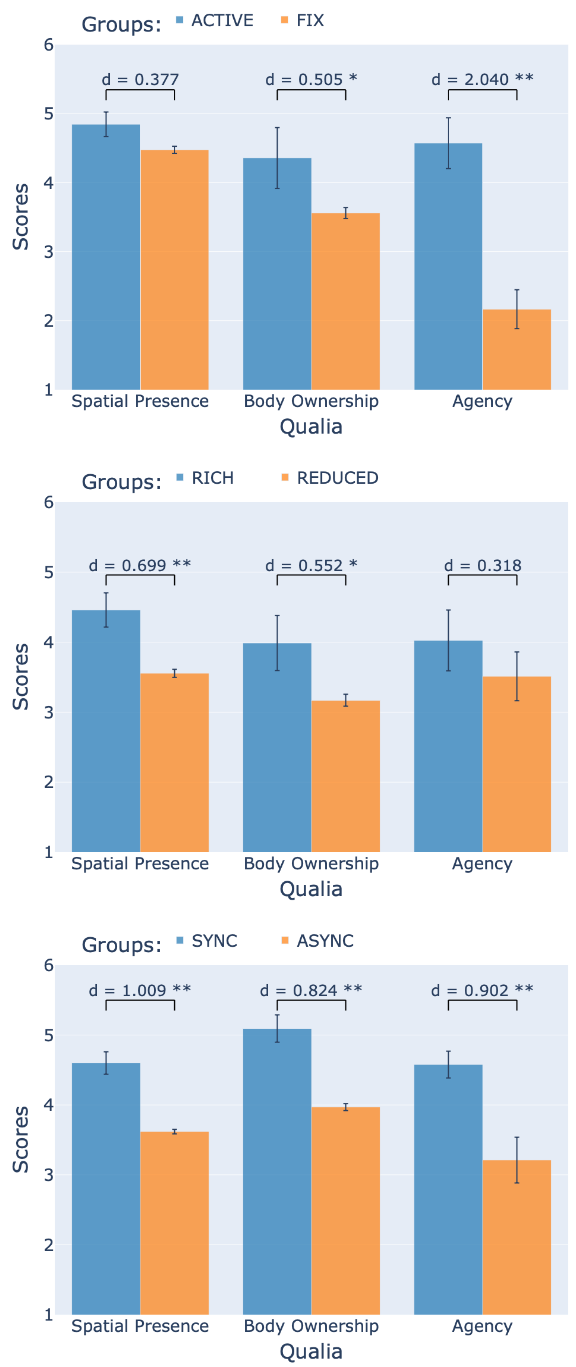

Figure 4: Results for spatial presence, body ownership, and agency, respectively for Study 1 (top), Study 2 (middle), and Study 3 (bottom). Effect sizes are indicated with Cohen's d values. Values marked with ** indicate a significant difference between the respective conditions ($p < .05$). A marking with * indicates a trend ($p < .1$)

higher for the *ACTIVE* group (*N1* = 21, *N2* = 21), U = 378.500, $p < .001$, d = 2.040. Overall, the manipulation of head-tracking had a similar effect on spatial presence and body-ownership. Compared to this, the effect on the sense of agency was strikingly high.

5.2 Study 2: The Manipulation of passive Depth Cues

Subjects in the *RICH* group showed a higher sense of spatial presence (M= 4.460, SD = 1.126) than subjects in the *REDUCED* group (M = 3.555, SD = 1.296). A t-test reveals a significant difference (t (40) = 2.406, p = .010) with a medium to high effect size (d = 0.699).

On average, subjects in the *RICH* group showed a higher sense of body ownership (M = 3.987, SD = 1.802) than subjects in the *REDUCED* group (M = 3.170, SD = 1.929). The same pattern is true for the agency values (*RICH*: M = 4.025, SD = 1.993; *REDUCED*: M = 3.511, SD = 1.673). The Shapiro-Wilk-Test shows a deviation from normality in the *REDUCED* group for both, the body ownership (W = .875, p = .010) and the agency scores (W = .885, p = .015). We, therefore, used the Mann-Whitney-U-Test to compare the samples of both groups. The test shows the trend that body ownership scores are higher for people in the *RICH* group than in the *REDUCED* group (*N1* = 20, *N2* = 22), U = 278.500, p = .072). There is a moderate positive effect between the available depth cues and the sense of body ownership (d = 0.552). A sensitivity analysis with a group size of n = 21, α-level of .05, and a power of .80 revealed that significance can be expected for effects of $d > 0.8$. This gives rise to the assumption that our sample size was just too small to show a significant effect, which could have been expected for a sample size of 88. For agency scores, the difference between groups is comparatively smaller in magnitude and no trend is shown (*N1* = 20, *N2* = 22), U = 254.500, p = .195, d = 0.318.

5.3 Study 3: The Manipulation of Synchrony in the VHI

The mixed ANOVA revealed that participants in the *SYNC* condition experienced significantly higher spatial presence than those in the *ASYNC* condition, F (1, 30) = 38.486, $p < .001$, d = 1.009. It shows that our manipulation of the fundamental embodiment cues had a large effect on the sense of spatial presence (*H1.3*). For the between-subjects factor (monoscopic vision vs. stereoscopic vision) the ANOVA did not show an effect, F (1, 30) = .047, p = .830, $\eta^2 < .001$. This suggests that our manipulation of monoscopic vs. stereoscopic did not work sufficiently, as an appropriate manipulation of stereoscopy should result in a change in spatial presence. Our results also do not show an interaction effect between the availability of stereoscopic cues and the synchrony of embodiment cues F (1, 30) = .014, p = .906, $\eta^2 < .001$. For the influence of the *SYNC* vs. *ASYNC* manipulation on spatial presence, it did not seem to matter, whether the scene was viewed stereoscopically or monoscopically.

The results for the VEQ follow the same pattern as the results for spatial presence. A significant main effect for manipulating the synchrony of embodiment stimuli emerges for body ownership (F (1, 30) = 22.454, $p < .001$, d = 0.824) and agency (F (1, 30) = 19.472, $p < .001$, d = 0.902). As expected, participants had a significantly higher SoE for the virtual arm when visuotactile and visuoproprioceptive synchrony were maintained, as opposed to the participants where both synchronicities were broken. In contrast, the manipulation of stereoscopic vision showed no effect on body ownership (F (1, 30) = .669, p = .420) and agency (F (1, 30) = .449, p = .508). Thus, the concurrent trend in effects is also found in the manipulation of stereoscopic vision, since it did not influence either embodiment or spatial presence. Consequently, no interaction effect for the embodiment measures was shown by the ANOVA.

6 Discussion

The overall picture provided by our results tends to confirm *H1.0* and thus supports the theoretical perspective that we formulated. This becomes particularly clear when looking at Fig. 4. It shows how the results of all three experiments exhibit the same pattern. Study 1 shows how head-tracking can also be an embodiment (specifically an agency) cue. Study 2 shows the influence of passive depth cues on spatial presence. However, the influence on the SoE remains unclear. Our sample does show an effect on body ownership, but it does not become significant (p = .072), which is why the inference to the population is not given (the same is true for the effect of depth cues on body ownership (p = .088). However, just because the effects have missed the alpha cut-off, they should not be considered non-existent [45, 9]. Studies 1 and 2 show how immersive properties such as head-tracking and passive depth cues can potentially also be embodiment cues. Further evidence is needed to clarify this. Study 3 shows fairly strong evidence that visuoproprioceptive and visuotactile synchrony of a virtual body should also be regarded as spatial presence cues. The results are in line with the various studies we discussed in the related work, that showed how fundamental VR cues have a concurrent influence on the SoE and spatial presence. The picture that emerges is that a distinction between spatial presence cues and embodiment cues is not tenable. The cues should rather be differentiated according to the extent of their influence on the respective qualia.

Interestingly, Study 1 suggests that head-tracking may be a stronger agency cue than a spatial presence cue. While the effect of head-tracking on spatial presence was rather small (d = 0.377), the effect on body ownership was somewhat larger (d = 0.505) and even very large for agency (d = 2.040). Although the difference between the effect sizes is very large, a comparison can only be made with great caution, as we are talking about the effects of different measurement instruments here. Still, this difference is very surprising, considering that head-tracking is a traditional spatial presence cue. The sense of having a body and especially the sense of controlling a body in the virtual world was massively restricted by the fixation of the head. It seems that head-tracking alone, a cue that comes with every VR experience, already creates body ownership and agency. The effect on agency is very strong because the removal of head-tracking causes a fundamental restriction on the active use of physical or motor skills. Of course, this restriction of a basic motor skill is anything but subtle and the control over the own body inevitably decreases. The results for body ownership and spatial presence both show a medium effect that was not significant. This could be due to the fact that the feeling of being located in a body and the feeling of being located in the virtual environment is a similar experience. Eventually, these results also show that the feeling of being embodied in a virtual environment also occurs without an avatar and can therefore also be manipulated without an avatar. However, we would have expected the impact of the restriction on head-tracking on spatial presence to be greater. The meta-review of Cummings and Bailenson [5] showed that the manipulation of the tracking level usually has a relatively large impact on spatial presence (r = .408 or d = 0.894). We can rule out the possibility that the head-tracking was inadequately manipulated (it was manipulated mechanically and on the software side). It is noticeable here that the Cronbach's α for the subscale was still very low, even though we have already eliminated item 2 (α = .551). Our interpretation is that the IPQ is not a suitable tool for measuring the effects of disabling head-tracking on spatial presence.

Study 2 shows, that depth stimuli are a relatively strong spatial presence cue (d = 0.699). The limitation of depth perception means a limited perception of the spatial structure and thus also a limitation of options to act (precisely) in the virtual world. At the same time, we also observed medium effect on body ownership (d = 0.552), which was not significant though (p = .072). That means we can not provide an inferential statement about the effect on VR users in general. The effect is consistent with the observations from the related work (that presence cues also have an influence on embodiment). So we do not think it appeared by chance. However, this work cannot yet confirm whether this effect really exists. If it exists in the population, it appears to be rather small, which is to be expected. This is also confirmed by our power analysis, which shows that our sample was probably too small to show a significant effect. In contrast to head-tracking, depth perception is not actively or consciously used. Fixing the head means restricting a motor skill, which every affected person is immediately aware of. The significance of depth perception for the feeling of being embodied is of course much more subtle. The fact that we, nevertheless, found a medium effect (d = 0.552) is remarkable. Whether this effect really exists in the population and how large it is must be clarified in further studies.

Study 3 shows strong effects of visuoproprioceptive and visuotactile synchrony of a virtual hand on the sense of spatial presence (d = 1.009), body ownership (d = 0.824), and agency (d = 0.902). It has thus shown in a minimalist design without distractors or other stimuli that the traditional embodiment stimuli also affect spatial presence. This experiment gives us deeper insights into how strongly these embodiment cues contribute to spatial presence and embodiment in comparison. It is noteworthy that that we found such a strong effect for spatial presence. Contrary to usual expectations the synchronous stimulation of the virtual hand served as a very strong spatial presence cue. The congruent stimuli emanating from the virtual hand located the subjects in the virtual environment. They provided crucial information about the spatial composition of the environment and where exactly the subject's hand was located relative to other entities in the environment. A hand that does not behave as one would expect makes one doubt the entire virtual environment and thus also that it is the current location, i.e. the latency created an amplification of disbelief. In Study 3, we found no effect of the between manipulation (monoscopic vs. stereoscopic) on spatial presence ($\eta^2 < .001$). Usually, one would expect a medium to strong effect of a stereoscopy manipulation on spatial presence [5]. We assume that the scene as a whole consisted of too few stimuli for the manipulation to make a real difference. We therefore refrain from further interpretations of the between manipulation or interaction effects of Study 3.

7 Limitations and Conclusion

The experiments we have shown here all work with very simple experimental setups. The subjects' tasks consisted mostly of habituation. On the one hand, this had the advantage that we were able to minimize possible unwanted influences and were able to show that the very basic effects we hypothesized exist. On the other hand, of course, it remains unclear how transferable the results are to practically relevant applications. Other things also remain unanswered. For example, there are several other traditional immersive features of VR whose influence on the SoE could be investigated, e.g. pixel density, field of view, or update rate. According to our new perspective, these should also turn out to be embodiment cues. Future studies could examine measurement instruments for embodiment and presence more closely to see where the common factors of the respective measurement instruments lie. In this way, we would explore the connection not at the theoretical level, but at the level of the measurement instruments. Our research therefore also could have a major influence on existing and future measurement instruments in the realm of presence and embodiment. In addition, our research contributes to an elimination of the dichotomization of two fundamental VR qualia. We show that both share essential building blocks and create a theoretical foundation that explains this overlap. It is precisely these building blocks, i.e. the cues, that define the design space of many XR applications. They are the typical controls that researchers and designers of XR applications manipulate to shape their applications in a way that elicits the desired experience. This insight holds particular significance for all people who work in the design space of presence or embodiment, emphasizing that the localization in (virtual) space and the perception of it cannot be separated from the perception of one's own body.

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