A Systematic Review and Meta-analysis of the Effectiveness of Body Ownership Illusions in Virtual Reality

ASKE MOTTELSON, Department of Digital Design, IT University of Copenhagen, Denmark
ANDREEA MURESAN and KASPER HORNBÆK, Department of Computer Science, University of Copenhagen, Denmark
GUIDO MAKRANSKY, Department of Psychology, University of Copenhagen, Denmark

Body ownership illusions (BOIs) occur when participants experience that their actual body is replaced by a body shown in virtual reality (VR). Based on a systematic review of the cumulative evidence on BOIs from 111 research papers published in 2010 to 2021, this article summarizes the findings of empirical studies of BOIs. Following the PRISMA guidelines, the review points to diverse experimental practices for inducing and measuring body ownership. The two major components of embodiment measurement, body ownership and agency, are examined. The embodiment of virtual avatars generally leads to modest body ownership and slightly higher agency. We also find that BOI research lacks statistical power and standardization across tasks, measurement instruments, and analysis approaches. Furthermore, the reviewed studies showed a lack of clarity in fundamental terminology, constructs, and theoretical underpinnings. These issues restrict scientific advances on the major components of BOIs, and together impede scientific rigor and theory-building.

CCS Concepts: • **Human-centered computing** → **Virtual reality**; User studies; • **General and reference** → *Surveys and overviews.*

Additional Key Words and Phrases: Virtual reality, embodiment, body ownership illusions, systematic review, meta-analysis

SUMMARY

This systematic review provides a comprehensive assessment of the effects of virtual body manipulations on the experience of owning a virtual body. It presents data from 111 papers with 4,925 participants. The original empirical virtual reality (VR) studies had human participants wear head-mounted displays, in which a virtual avatar replaced their own body. Reported measures of embodiment were collected for analysis. The study presents (i) a first comparison of virtual body replacements on embodiment, (ii) a disentanglement of collection and analysis of subjective embodiment measures, (iii) a field-wide comparison of normalized embodiment constructs, (iv) exploratory analyses of the factors important for embodiment, and (v) a synthesis of practical experimental procedures. Results indicated that manipulation of visuo-motor synchrony renders the largest effect for body ownership ($g = 1.09$), but that a congruence of appearance, perspective, visuo-tactile stimuli, and abstraction of the avatar are also effective manipulations. We find that BOI studies mostly employ non-validated embodiment measures, and that specific embodiment constructs and questionnaire items origin from the Rubber Hand Illusion (RHI). We also observe that BOI studies typically have low power, with several conditions accompanied by a

Authors' addresses: Aske Mottelson, asmo@itu.dk, Department of Digital Design, IT University of Copenhagen, Rued Langgaards Vej 7, Copenhagen S, Denmark, DK-2300; Andreea Muresan, aam@di.ku.dk; Kasper Hornbæk, kash@di.ku.dk, Department of Computer Science, University of Copenhagen, Sigurdsgade 40, Copenhagen N, Denmark; Guido Makransky, gm@psy.ku.dk, Department of Psychology, University of Copenhagen, Øster Farimagsgade 2A, Copenhagen K, Denmark.

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modest number of participants. Of the two main components of embodiment, body ownership and agency, agency is generally reported to be higher than body ownership (i.e., participants report higher control of their virtual bodies compared to the belief that the virtual bodies are theirs). Furthermore, the heterogeneity in effects on agency due to experimental manipulation are substantially higher for agency than for body ownership ($I^2 = 79\%$ vs. $I^2 = 17\%$).

Our data suggest that tactile congruence compared to visual congruence between the physical body and the virtual avatar leads to lower body ownership ($\Delta BodyOwnership = -0.56$), yet greater agency ($\Delta Agency = 0.66$).

We observe a correlation between the time spent in VR and the agency scores reported, $r(32) = 0.31$, but less so for body ownership, $r(55) = 0.02$. We did not find a strong correlation between participants' gender and body ownership, comparing ratio of gender with effect sizes, $r(75) = 0.10$. Female participants, on a 7-point scale, on average report 0.16 higher body ownership and 0.58 lower agency, compared to male participants. We also find that the presence of virtual mirrors ($g = 0.67$) has a limited to negative effect on body ownership compared to studies without any mirror ($g = 0.78$). Finally, our review synthesizes the practicalities of conducting BOI studies, such as the time spent during the phase of embodiment ($M = 190$ s, $SD = 146$), the use of questionnaires, and the experimental designs (58% of studies use a within-participant design); based on these observations, we suggest ways to improve the science of BOIs.

1 INTRODUCTION

Scientific curiosity in multiple disciplines has long been fueled by the question of how the body shapes the mind. Influential theories of body–mind connections have been developed in philosophy [44, 117], biology [32], neuroscience [13], and psychology [98]. A central question that these theories have grappled with is what it takes for someone to experience something as their body, so-called *embodiment*. The challenge is that, on the one hand, it is phenomenologically clear that we experience our body in a particular manner and not just like any other object in the world [110]. Furthermore, the experience of our body is closely related to our experience of the self [25, 45]; it is, for example, generally not possible to misidentify a part of your body as belonging to someone else. On the other hand, spelling out *what* it takes for something to be experienced as embodied has proven difficult.

One approach to this question is to separate dimensions of embodiment. Gallagher [43] suggested that the sense of having a body covers at least two separate dimensions. One part is the feeling of controlling one's movements; this is largely based on motor control, and hence top-down. Another part is the feeling that one's body is the source of sensations; this is largely about integration of sensory input into a sense of ownership. Moreover, it has long been recognized that the experience of the location of the self is malleable. For instance, some patients with brain damage experience seeing a duplicate of their body away from their real body [17]. This suggests that the position of one's self in the world is also a component of embodiment. A general model of the dimensions of embodiment is due to de Vignemont [30], who separated ownership ("this is my body") from agency ("it is me who acts") and self-location ("it is me who is here"). Among these dimensions, body ownership has received the most attention, perhaps because it has received the most theoretical work [34] and because it was early and strikingly manipulated in experimental paradigms [113].

One such experimental paradigm is the rubber-hand illusion (RHI). Botvinick and Cohen [21] showed how synchronous stroking of the hidden hand of a participant and the rubber hand elicited reports of the rubber hand being experienced as real, while asynchronous strokes did not produce an equivalent response. The RHI is a commonly employed experimental paradigm. The experimental setup, however, has strict limits for further developing the understanding of body–mind links, due to constraints the physical rubber hand enforce. To counter the constraints of the RHI, researchers have used virtual reality (VR) technology to study body–mind links. This is achieved through an experimental procedure where participants experience their body replaced by a virtual body. The real body of the participant is tracked and its virtual replacement is rendered in real time via a head-mounted display (HMD). Usually, the experience of owning a virtual body creates an illusion that the virtual body is indeed your body. This has been called the body ownership illusion (BOI).

Researchers in psychology, neuroscience, and human-computer interaction have explored numerous variants of the BOI. Empirical studies of such variants commonly compare the experience of embodying a virtual body through consistent sensory information with the experience of inconsistent sensory information intended to break the embodiment illusion. Early studies manipulated the congruence of visual and/or tactile information so that the sensory information (visual, tactile) received was either synchronous or asynchronous with the virtual rendering (e.g., [166]). Later, this has been supplemented with creative studies of the cognitive effects of being in a body with amputations [76], in the body of a child [5], or being an out-group member [138].

BOIs have numerous applications beyond the study of the relationship between the body and the mind. Embodying a virtual avatar is an effective paradigm for designing engaging VR interventions that change people's attitudes and behavior [108, 138]. For instance, a reduction in implicit racial bias has been found after exposure to an immersive body illusion experience [6, 138]. Similarly, a reduction in age bias has been reported following the embodiment of an old avatar [7]. In recent health research, the embodiment of an old avatar was also shown to be effective in an intervention designed to increase intentions to vaccinate [122, 179]. Virtual embodiment is also an emerging technology to support motor learning and rehabilitation [54, 62, 177]. Moreover, a large randomized controlled trial showed that BOIs are effective in the treatment of fear of heights [40]. As consumer-oriented VR equipment is increasingly being adopted, a host of social applications have emerged (e.g., VRChat[1], Mozilla Hubs[2], Horizon Worlds[3], Spatial[4]). These applications offer a variety of social interactions based on embodiment [154]. Finally, the use of full-body tracked avatars is becoming prominent for commercial VR games (e.g., Guardians[5], Ready Player Me[6]). These applications and studies collectively show the breadth of use cases for BOIs in embodiment research, health interventions, training, treatment of mental health disorders, communication, and games.

Despite the work just mentioned, an overview of how these variations in virtual bodies *actually* influence body ownership is lacking. Thus, we do not know which conflicting sensory information reduces body ownership, nor by how much. The benefits of understanding such influences are several:

- It helps understand which effects are robust. For instance, it has been claimed that embodiment suffers when experiencing the body in a third-person (3PP) compared to a first-person (1PP) perspective; data have been presented that confirms [85] and rejects this assertion [37]. Our analyses supports that perspective has a strong effect on body ownership and agency.
- It helps HCI researchers design new virtual experiences and bodies. Work on body-based user interfaces is to a large extent informed by understanding the mechanisms involved in body ownership [170].
- It establishes best practices for measuring and collecting data on illusions of body ownership. This, in turn, can help researchers standardize measures and perform robust experiments.
- It identifies future research directions, including understanding the benefits of mirrors in establishing body ownership, the influence of gender on agency, and the impact of facial animations on feeling embodied in an avatar.

In BOI research, the analysis of dependent measures is conducted to uncover differences attributable to a successful body ownership illusion (i.e., by showing effects that are not present when the illusion is broken). In this

[1]vrchat.com
[2]hubs.mozilla.com
[3]oculus.com/horizon-worlds
[4]spatial.io
[5]virtualage.io
[6]readyplayer.me

work, we refer to the experimental condition of owning a virtual body through consistent sensory information as *embodiment*, and, conversely, to the experimental conditions of conflicting sensory information as *disembodiment*. Understanding the difference between these is the key to understanding the mechanisms involved in body ownership. This understanding of *disembodiment* should not be confused with research on the disownership of limbs [71] (i.e., "leaving one's own body").

The purpose of this paper is to review illusions of body ownership in VR. Our goal is to conduct a systematic review of how body ownership is affected by the manipulation of the virtual body. At the same time, we wish to quantify how well different manipulations affect body ownership. Consequently, we note the type of embodiment and disembodiment implemented, and we quantify the effects of cross studies of experiencing ownership of particular bodies by comparing *embodiment* and *disembodiment* conditions. Finally, based on the review and meta-analysis, we discuss what we still need to understand about body ownership in VR.

2 BACKGROUND AND RELATED WORK

Due to advances in consumer-oriented VR technology (such as HTC and Oculus devices) and body-tracking equipment (from Leap Motion, Oculus, and others), it has become easier to perform research in this field, resulting in a steady increase in publications on embodiment in VR across the last decade (2010-2012: 7 papers, 2013-2015: 24 papers, 2016-2018: 43 papers, and 2019-2021: 41 papers). The host of new studies is coupled with many complex decisions in experimental work, and as such, the increasing publication rate has diverged research practices. So far, these practices have not been the subject of a systematic review.

BOI research involves many practical and technical decisions. Researchers will have to decide on apparatus, sensory stimuli, experimental design, and visual instruments to employ, to name a few. So far, only anecdotal evidence describes the relative importance of these decisions, both impeding progress in experimental practices and building field-wide theory. It is additionally unclear to what extent experimental procedures, such as the presence of mirrors and the duration of the embodiment induction, influence experimental findings.

This paper presents a systematic review and meta-analysis whereby we summarize empirical findings across the field of BOI research, synthesize a reliable understanding of virtual embodiment's effect, and cultivate guidelines for future research in this domain.

Several earlier reviews have addressed the topic of illusory experiences in VR (e.g., [47]). Some reviews have specifically addressed BOIs [18, 77, 108, 165, 177], covering such aspects of BOIs as how to induce body ownership experimentally [165, 168], why BOIs are induced [77], the effects of BOIs on social cognition [108], and their applications in healthcare [115, 177] and therapy [18].

More than a decade ago, Slater et al. [165] reviewed evidence from three of their experiments that showcased the feasibility and impact of various techniques for illusory body ownership. The authors showed how the ownership of a virtual limb can be induced by means of visuo-tactile stimulation, visual-motor synchrony, and to some extent through a brain-computer interface. As an early report of successful body ownership induction using computer equipment (i.e., a data glove and a projection-based VR) the reported evidence is a cornerstone in the development of BOI practices. Since then, many studies have been conducted with inspiration taken from the reported studies.

Later, Kilteni et al. [77] examined known experimental illusory body ownership procedures, with or without the aid of computer equipment. Following a synthesis of effective apparatus and experimental methodology, they distilled the principles for triggering BOIs. As a comprehensive review of theories, practices, and evidence from experimental findings from illusions of body ownership, the work of Kilteni et al. [77] began an important discussion of how and why BOIs are induced, integrating contemporary embodiment frameworks.

Focusing specifically on the social cognitive effects of illusory body ownership, Maister et al. [108] reviewed recent evidence on the role of embodiment in implicit social bias. The authors posited that illusory ownership of an out-group individual (i.e., with respect to gender, age, or race) can reduce implicit biases against said group. The review highlighted recent findings related to embodying avatars with a skin color that differs from that of the participant and the subsequent impact on attitudes, thus documenting an important social psychological application of body ownership illusions.

The replacement of bodies in VR is both an effective and flexible manipulation. As an illustration of the flexibility of BOIs, Won et al. [188] wondered if and how participants would experience being a bat; for instance by controlling wings with one's arms. Through two studies, the authors found that virtual bodies can significantly differ from those of the participant, even if non-human, suggesting an adaptive body schema. Studies that explore this phenomenon have successfully investigated experiences of missing or altered limbs [78, 81].

The reviews above provide clear information on practical recommendations, theoretical accounts, and recent evidence in BOI research. However, large-scale comparisons, and importantly, meta-analytical estimations of evidence across many BOI studies remain unexplored, beyond specific applications of BOIs (e.g, healthcare [18, 115, 177]). Consequently, no clear evidence-based guidelines have been developed for BOI studies. The scientific literature also lacks comparisons of the effects of commonly used experimental manipulations for studies concerning embodiment in VR.

Table 1. Collected variables for the systematic review and meta analysis across the entire sample.

Paper	Year	Studies	Subjects Total	Gender *M/F*	HMD	Perspective	Mirror	Induction *sec.*	Incongruency	Body ownership estimation *M (SD)*	Agency estimation *M (SD)*	Estimates of effect body ownership *g [95% CI]*
Abtahi et al. [2]	2019	1	18	13/5	HTC Vive	1PP	No	60				
Alimardani et al. [3]	2016	1	38	17/21	Vuzix iWear VR920	1PP	No		Abstract	0.4 (1.6)	0.5 (1.4)	.2 [-0.4; 0.9]
Aymerich-Franch et al. [4]	2014	2	187	112/75	NVIS nVisor SX111	1PP	Yes					
Banakou and Slater [8]	2014	1	44	21/23	NVIS nVisor SX111	1PP	Yes	300	Visuo-motor	1.0 (1.6)	1.8 (1.6)	.7 [-0.2; 1.6]
Banakou and Slater [9]	2017	1	36	18/18	NVIS nVisor SX111	1PP	Yes	120	Visuo-tactile	1.0 (1.4)	1.8 (1.4)	-0.2 [-0.9; 0.5]
Banakou et al. [5]	2013	2	46	21/25	NVIS nVisor SX111	1PP	Yes		Visuo-motor	0.8 (1.8)		1.3 [0.6; 1.9]
Banakou et al. [6]	2016	2	90	0/90	NVIS nVisor SX111	1PP	Yes	300		1.8 (1.6)	1.3 (2.3)	
Banakou et al. [7]	2018	1	30	30/0	HTC Vive	1PP	Yes	300		1.0 (1.5)	1.8 (1.5)	
Barberia et al. [10]	2018	1	16	0/16	Oculus Rift DK2	1PP	Yes	360		0.8 (1.9)	1.0 (1.9)	
Barbot and Kaufman [11]	2020	1	65	34/30	HTC Vive	1PP	No					
Bekrater-Bodmann et al. [14]	2014	1	25	9/16	VisuaStimDigital	1PP	No		Visuo-tactile	-1.1 (2.0)		.4 [-0.2; 0.9]
Bergström et al. [16]	2016	1	31	10/21	NVIS nVisor SX111	1PP	Yes	300		-0.2 (2.4)		
Borland et al. [20]	2013	1	12	4/8	NVIS nVisor SX111	1PP	Yes			0.1 (2.1)		
Bourdin et al. [22]	2017	1	32	0/32	Oculus Rift	1PP	Yes	660		1.2 (1.5)		
Bourdin et al. [23]	2019	1	24	7/17	NVIS nVisor SX111	1PP	No		Displace	1.4 (1.0)	1.2 (1.8)	.2 [-0.4; 0.7]
Bovet et al. [24]	2018	1	19	15/4	Oculus Rift	1PP	No		Displace	1.6 (1.2)		2.9 [2.0; 3.8]
Brugada-Ramentol et al. [26]	2019	1	44	15/29	Oculus Rift DK2	1PP	No		Visuo-motor	0.4 (1.8)		.4 [-0.1; 0.8]
Burin et al. [27]	2019	1	31	15/16	NVIS nVisor SX111	1PP/3PP	No	240	Perspective	-0.3 (1.7)	-0.3 (1.7)	.4 [-0.1; 1.0]
Christofi et al. [28]	2020	1	40	21/19	Oculus Rift	1PP	Yes					
Galvan Debarba et al. [46]	2017	1	48	40/8	Oculus Rift DK2	1PP/3PP	Yes		Visuo-tactile	1.5 (1.8)	2.6 (1.8)	.0 [-0.5; 0.6]
Dobricki and de la Rosa [31]	2013	2	79	45/34	Nvis nVisor SX60	3PP	No	180				
Falconer et al. [37]	2014	1	43	0/43	Oculus Rift	1PP/3PP	Yes	180	Perspective	0.8 (1.8)	1.2 (1.4)	.3 [-0.3; 0.9]
Feuchtner and Müller [39]	2018	1	16	12/4	HTC Vive	1PP	No		Displace	1.8 (1.5)	1.8 (1.5)	1.9 [1.1; 2.7]
Friedman et al. [41]	2014	1	32	16/16	NVIS nVisor SX111	1PP	Yes			0.6 (2.2)	1.8 (1.3)	
Fusaro et al. [42]	2018	1	36	12/24	Oculus Rift DK2	1PP/3PP	No	6		0.8 (1.0)		
Gonzalez-Liencres et al. [49]	2020	1	32	32/0	NVIS nVisor SX111	1PP/3PP	Yes	150	Perspective	-0.8 (3.0)		.2 [-0.5; 1.0]
González-Franco et al. [50]	2010	1	20	10/10	Fakespace Labs Wide5	1PP	Yes	30	Visuo-tactile	1.0 (1.2)	1.2 (0.7)	3.5 [2.1; 4.9]
Grechuta et al. [51]	2017	1	36	20/16	Oculus Rift	1PP	No		Visuo-tactile	0.8 (2.1)		1.1 [0.2; 1.9]
Grechuta et al. [52]	2019	1	16	8/8	HTC Vive	1PP	No		Visuo-motor	1.1 (0.7)	1.5 (1.3)	2.4 [1.1; 3.7]
Hamilton-Giachritsis et al. [56]	2018	1	20	0/20	NVIS nVisor SX111	1PP	Yes	300		1.2 (1.4)	2.0 (1.4)	
Hara et al. [57]	2015	3	40	21/19	Sony HMZ-T1	1PP	No			1.3 (2.1)	2.2 (2.1)	
Hasler et al. [58]	2017	1	32	0/32	Oculus Rift DK2	1PP	Yes	180		1.1 (2.4)	1.5 (1.7)	
Heydrich et al. [61]	2013	2	36	20/16	Virtual Viewer 3D	3PP	No	120				
Jun et al. [65]	2018	2	61	35/26	Oculus Rift DK2	1PP	Yes	300	Visuo-motor	1.5 (1.2)	2.2 (1.0)	1.2 [0.7; 1.8]
Jung et al. [68]	2017	1	40	30/10	HTC Vive	1PP	Yes		Abstract	0.5 (2.3)	1.2 (1.4)	.3 [-0.3; 0.9]
Jung et al. [69]	2018	1	20	6/14	HTC Vive	1PP	No	20		1.0 (2.1)		
Jung et al. [67]	2018	1	24	7/17	HTC Vive	1PP	No		Appearance	1.3 (1.9)		1.2 [0.5; 1.8]

Paper	Year	Studies	Subjects Total	Gender *M/F*	HMD	Perspective	Mirror	Induction *sec.*	Incongruency	Body ownership estimation *M* (*SD*)	Agency estimation *M* (*SD*)	Estimates of effect body ownership *g* [95% *CI*]
Jung et al. [66]	2020	1	42	20/22	Oculus Rift CV1	1PP	Yes	300	Visuo-motor	1.4 (1.1)	2.2 (0.8)	1.7 [1.0; 2.4]
Karnath et al. [72]	2019	1	22	10/12	Oculus Rift DK2	1PP	No					
Keenaghan et al. [73]	2020	1	34	9/25	Oculus Rift	1PP	Yes		Visuo-motor	0.6 (1.9)	2.4 (0.8)	.4 [-0.1; 0.9]
Keizer et al. [74]	2016	1	59	0/59	Oculus Rift DK2	1PP	No		Visuo-motor	-0.3 (1.6)	-0.2 (1.9)	.5 [-0.1; 1.0]
Kilteni et al. [79]	2012	1	50	36/14	NVIS nVisor SX111	1PP	No		Visuo-tactile	-0.5 (2.3)		-0.2 [-1.1; 0.6]
Kilteni et al. [75]	2013	1	36	17/19	NVIS nVisor SX111	1PP	Yes					
Kilteni et al. [76]	2016	1	40	20/20	Sensics zSight 60	1PP	Yes	60	Invisible	0.0 (1.9)		.0 [-0.6; 0.6]
Kim et al. [80]	2020	1	40	16/24	Oculus Rift DK2	1PP	Yes		Visuo-motor	1.2 (1.5)		1.4 [0.9; 1.9]
Kocur et al. [84]	2020	1	32	32/0	HTC Vive	1PP	Yes	30				
Kocur et al. [83]	2020	1	30	15/15	HTC Vive	1PP	Yes	60	Appearance	1.1 (2.0)	2.3 (2.0)	1.4 [0.6; 2.2]
Kocur et al. [82]	2021	1	24	12/12	HTC Vive	1PP	Yes					
Kokkinara et al. [86]	2015	2	32	13/19	NVIS nVisor SX111	1PP	Yes		Visuo-motor	0.8 (1.9)	1.6 (2.2)	.1 [-0.6; 0.8]
Kokkinara et al. [85]	2016	1	28	8/20	NVIS nVisor SX111	1PP/3PP	Yes		Perspective	1.2 (1.5)	0.8 (2.0)	1.0 [0.2; 1.8]
Kondo et al. [87]	2018	3	50	50/0	Oculus Rift DK2	3PP	No	300	Visuo-motor	1.0 (1.9)	2.2 (1.1)	2.4 [1.6; 3.2]
Kondo et al. [88]	2020	3	54	51/3	HTC Vive Pro	1PP/3PP	No		Visuo-motor	1.9 (1.0)	2.3 (1.0)	3.6 [2.4; 4.7]
Kong et al. [89]	2017	1	43	20/23	Oculus Rift DK2	1PP	No		Invisible	-0.3 (1.4)	-0.7 (1.6)	.1 [-0.6; 0.7]
Latoschik et al. [91]	2017	1	20	9/11	Oculus Rift	1PP	Yes	120	Abstract	0.5 (1.9)		.5 [-0.1; 1.1]
Lee et al. [93]	2020	2	26	23/3	HTC Vive Pro	1PP	No	120	Visuo-motor	0.7 (2.0)		.8 [-0.0; 1.6]
Leyrer et al. [96]	2011	1	54	27/27	Nvis nVisor SX60	eye-height $\pm\phi$	No	300				
Lin and Jörg [100]	2016	1	15	14/1	Oculus Rift	1PP	No		Appearance	1.4 (1.4)		1.2 [0.4; 2.0]
Lin et al. [101]	2019	1	20	12/8	Oculus Rift	1PP	No			0.5 (1.7)		
Lopez et al. [103]	2019	1	24	24/0	HTC Vive	1PP	Yes	300		1.1 (2.5)	2.1 (1.4)	
Lugrin et al. [104]	2018	1	75	26/49	HTC Vive	1PP	Yes		Invisible	-0.2 (2.7)	1.1 (1.9)	.0 [-0.6; 0.6]
Martini et al. [112]	2013	1	30	0/30	NVIS nVisor SX111	1PP	No			1.7 (1.1)		
Martini et al. [111]	2015	1	24	0/24	NVIS nVisor SX111	1PP	No	60		0.8 (1.8)		
Maselli and Slater [113]	2013	3	72	39/33	NVIS nVisor SX111	1PP/3PP	No	30	Visuo-motor	1.2 (1.6)		.1 [-0.8; 1.1]
Maselli and Slater [114]	2014	3	34	12/22	NVIS nVisor SX111	1PP/3PP	No	10	Perspective	1.0 (1.9)		1.1 [0.5; 1.8]
Medeiros et al. [116]	2018	1	24	24/0	Oculus Rift DK2	1PP/3PP	No			0.0 (1.8)	0.0 (1.8)	
Mine et al. [118]	2020	2	59	44/15	Oculus Rift	1PP	No			1.0 (1.5)		
Mottelson and Hornbæk [120]	2017	3	88	47/41	HTC Vive	1PP	Yes	120	Visuo-motor	0.4 (2.7)		.4 [-0.3; 1.1]
Mottelson et al. [123]	2021	1	282	255/20	Oculus Quest	1PP	Yes	60	Appearance	0.3 (2.1)	1.7 (1.7)	.1 [-0.1; 0.3]
Nataraj et al. [124]	2020	1	16	12/4	Oculus Rift	1PP	No					
Nesti et al. [125]	2018	1	15	6/9	Oculus Rift	3PP	No	300	Visuo-motor	-0.6 (2.8)		.2 [-0.5; 1.0]
Neyret et al. [126]	2020	1	60	60/0	HTC Vive	1PP	Yes	150		0.8 (1.9)		
Normand et al. [127]	2011	1	22	22/0	Fakespace Labs Wide5	1PP	No	240	Visuo-motor	0.5 (1.8)		.8 [0.1; 1.4]
Ogawa et al. [129]	2019	1	22	11/11	Oculus Rift	1PP	No		Abstract	1.4 (1.6)	1.3 (1.4)	1.0 [0.4; 1.7]
Ogawa et al. [130]	2020	1	91	63/28	HTC Vive Pro	1PP	Yes	30	Abstract	1.2 (1.6)		.3 [-0.3; 0.9]

Paper	Year	Studies	Subjects Total	Gender *M/F*	HMD	Perspective	Mirror	Induction *sec.*	Incongruency	Body ownership estimation *M (SD)*	Agency estimation *M (SD)*	Estimates of effect body ownership *g* [95% *CI*]
Osimo et al. [131]	2015	2	22	22/0	Oculus Rift DK2	1PP	Yes	300	Visuo-motor	1.0 (1.6)	2.0 (1.6)	1.2 [0.3; 2.1]
Patané et al. [133]	2020	1	40	13/27	Oculus Rift CV1	1PP	Yes	180				
Peck et al. [138]	2013	1	60	0/60	NVIS nVisor SX111	1PP	Yes	300		1.5 (1.7)		
Peck et al. [135]	2018	1	64	0/64	HTC Vive	1PP	Yes	180	Appearance	-0.5 (2.0)	0.2 (2.0)	.4 [-0.4; 1.1]
Peck et al. [137]	2020	1	125	63/62	HTC Vive	1PP	Yes	180				
Perepelkina et al. [140]	2018	1	33	16/17	Oculus Rift CV1	1PP	No	240				
Pfeiffer et al. [142]	2013	3	81	47/34	Virtual Viewer 3D	3PP	No		Visuo-tactile	-0.7 (1.7)		.8 [0.3; 1.3]
Piryankova et al. [143]	2014	1	32	0/32	NVIS nVisor SX111	1PP	No	480	Visuo-motor	-0.1 (2.0)	0.1 (2.0)	.3 [-0.4; 1.0]
Pittera et al. [144]	2019	1	20	11/9	Oculus Rift DK2	1PP	No					
Podkosova and Kaufmann [145]	2018	1	51	33/18	HTC Vive Pro	1PP	No			0.0 (1.7)	1.2 (1.2)	
Pomes and Slater [146]	2013	1	30	30/0	NVIS nVisor SX111	3PP	No	180	Visuo-motor	0.4 (1.7)		.3 [-0.4; 1.0]
Porssut et al. [147]	2019	1	18	14/4	Oculus Rift	1PP	No					
Pritchard et al. [148]	2016	1	50	20/30	Oculus Rift DK2	1PP	No		Abstract	1.5 (2.1)	1.0 (2.5)	1.5 [1.1; 2.0]
Pyasik and Pia [149]	2021	1	17	5/12	Oculus Rift S	1PP/3PP	No	270	Perspective	0.8 (2.9)	0.0 (2.9)	.9 [0.2; 1.6]
Pyasik et al. [150]	2020	1	45	13/32	Oculus Rift	1PP	No	60	Visuo-motor	1.4 (1.6)	-0.6 (1.6)	1.1 [0.6; 1.5]
Roth and Latoschik [155]	2020	3	168	63/105	Oculus Rift CV1 FOVE 0 HMD	1PP	Yes	900				
Rubo and Gamer [156]	2019	1	40	20/20	HTC Vive	1PP	Yes	40				
Salomon et al. [157]	2013	1	22	14/8	Real Viewer 3D	3PP	No		Visuo-tactile	-0.6 (2.4)		.5 [-0.1; 1.1]
Schwind et al. [158]	2020	3	68	39/29	HTC Vive	1PP	No	30	Visuo-motor	0.2 (1.8)	0.6 (1.8)	-0.0 [-0.6; 0.5]
Seinfeld and Müller [161]	2020	1	31	9/22	HTC Vive	1PP	No			1.0 (1.3)	2.0 (1.3)	
Shin et al. [162]	2020	1	74	30/44	HTC VIVE Pro	1PP	No	120	Abstract	1.0 (1.6)		.4 [0.1; 0.8]
Škola and Liarokapis [182]	2019	1	10	6/4	Oculus Rift	1PP	No			0.7 (2.3)	1.5 (2.3)	
Škola et al. [191]	2019	1	19	12/7	Oculus Rift	1PP	No			0.6 (1.6)	1.1 (1.4)	
Slater et al. [166]	2010	1	24	24/0	Fakespace Labs Wide5	1PP/3PP	Yes		Visuo-motor	0.7 (2.7)		.3 [-0.9; 1.4]
Slater et al. [163]	2019	1	58	28/30	HTC Vive	1PP	Yes	30		0.7 (1.7)	1.0 (1.7)	
Spanlang et al. [167]	2019	1	27	0/27	Oculus Rift DK2	3PP	No		Visuo-motor	0.8 (1.7)		1.2 [0.6; 1.8]
Tajadura-Jiménez et al. [171]	2017	1	34	0/34	Oculus Rift DK2	1PP	Yes			1.0 (2.3)	1.5 (1.2)	
Tambone et al. [172]	2021	1	30	0/30	Oculus Rift CV1	1PP	No	120				
Toothman and Neff [173]	2019	4	96	48/48	Oculus Rift	1PP	No		Visuo-motor	1.8 (1.6)		.5 [-0.1; 1.1]
Tran et al. [174]	2017	1	24	24/0	HTC Vive	1PP	No	600				
van der Veer et al. [178]	2019	1	25	12/13	HTC Vive	eye-height chest-height	Yes	300	Perspective	-0.1 (1.0)	1.8 (1.3)	.9 [0.3; 1.5]
Waltemate et al. [183]	2018	1	29	14/15	HTC Vive	1PP	Yes			-0.3 (1.7)		
Weeth et al. [185]	2017	1	32	5/27	Oculus Rift DK2	1PP	No	20		1.2 (3.3)		
Weijs et al. [186]	2021	1	33	8/25	HTC Vive Pro	1PP	Yes	40	Visuo-motor	0.5 (1.7)	1.1 (1.6)	.4 [-0.1; 0.9]
Wolf et al. [187]	2021	1	56	0/56	HTC Vive Pro	1PP/3PP	Yes	456	Perspective	-0.1 (1.5)	1.8 (1.0)	1.4 [1.0; 1.8]
Wu et al. [189]	2019	1	25	13/12	HTC Vive Pro	1PP/3PP	No			1.1 (0.7)	1.6 (0.6)	
Zhang et al. [190]	2020	1	42	21/21	HTC Vive	1PP	No		Appearance	1.2 (1.9)	1.7 (1.6)	.1 [-0.4; 0.5]

Note that not all studies measure body ownership or agency. Not all studies manipulate embodiment as an independent variable.
The body ownership and agency estimates are scaled to [-3; 3], and represent the visuo-motor synchrony condition.

3 OBJECTIVES

The concept of *body ownership* is the most prominent dimension of embodiment and central for conducting empirical investigations of how the body shapes the mind [77]. A thorough understanding of the theoretical and practical limitations of body ownership is fundamental to improve virtual reality (VR) interfaces [63], with applications for, among other things, entertainment, education, and clinical purposes [12, 97, 109].

To our knowledge, no prior meta-analytical review of VR and body ownership illusions exists, despite the need for it, as outlined above. Therefore, we set out to conduct a systematic review and meta-analysis, with the following five objectives:

O1 to identify the most effective experimental manipulations for inducing body ownership;
O2 to investigate the practices employed for measuring subjective embodiment, by examining the origins, constructs, items, and statistical treatment of the questionnaires used;
O3 to describe the fundamental embodiment constructs and estimate their mean scores;
O4 to identify other factors affecting the strength of the BOI (including gender of participants, duration of induction, presence of mirrors); and
O5 to present commonly employed induction procedures, and study designs related to BOIs, with the resulting synthesis serving as a resource to guide future research.

4 METHODS

4.1 Eligibility criteria and data sources

We searched the academic databases ACM Digital Library (727 results), PubMed (19 results), ScienceDirect (633 results), and IEEE Xplore (367 results). We furthermore searched the Frontiers databases (63 results). These were chosen based on breadth of research areas (computer science, engineering, health sciences, and general science), and based on recommendations by Gusenbauer and Haddaway [53] (i.e., principal sources).

We limited the scope of the search to only include research on BOI in virtual reality (VR), and hence not illusions for mixed reality (MR) technology such as augmented reality (AR). AR renders virtual computer generated graphics on top of the real world, and hence participants can see their physical bodies. Although this technology also supports body illusions (e.g., arm extensions [38]), it is a fundamentally different experience in VR. Illusions in AR have their own set of challenges and opportunities, which is why findings are not directly comparable with findings from VR.

4.2 Paper identification and selection

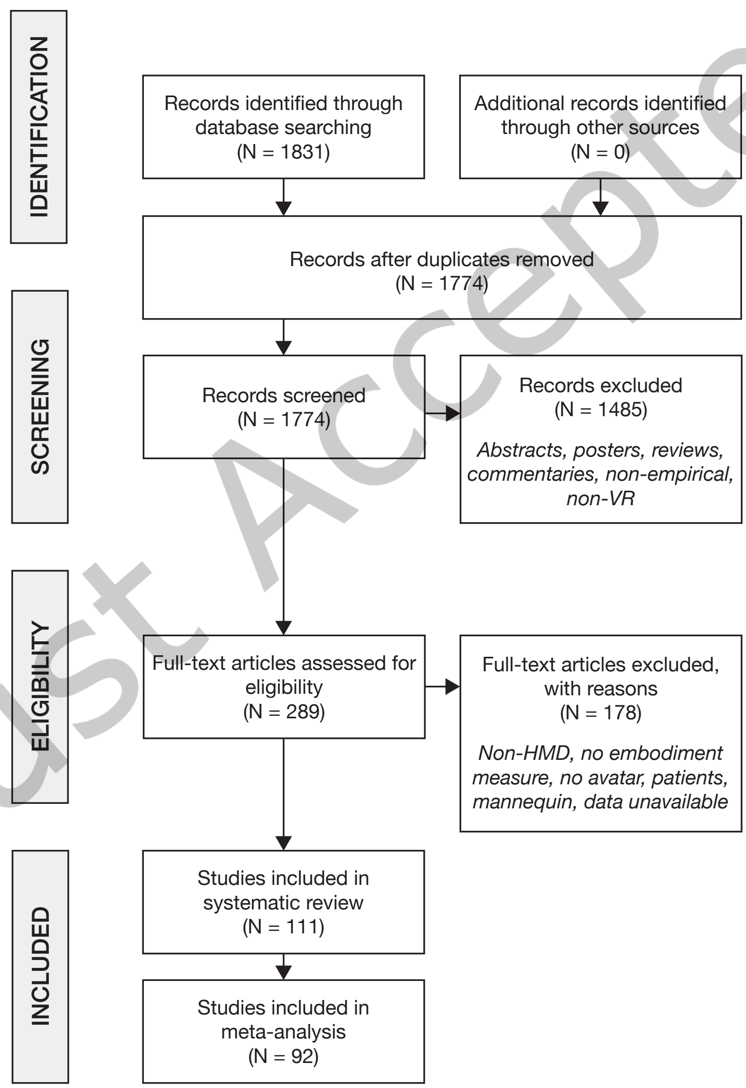
Figure 1 shows a PRISMA-style flowchart for the paper selection process [119, 132]. BOI research is cross-disciplinary. The disparate publication traditions within the contributing fields—principally, social scientists' preference for journal publications and technical fields' preference for conference proceedings—led us to consider both journals, in such areas as psychology and behavioral science, and proceedings from conferences in computer science and engineering.

We searched the relevant research databases (query: `("VIRTUAL REALITY") AND ("BODY OWNERSHIP" OR "EMBODIMENT" OR "SELF PRESENCE")`) across the title, abstract, and full text of papers written in English published in 2010 through 2022 and identified 1774 unique papers. We designed the query to inclusively target all VR research that dealt with embodiment, taking into consideration that the concepts of body ownership, embodiment, and self presence are sometimes used interchangeably. Then, we scanned the articles and included those that met the following criteria:

- representing original research (this criterion excludes systematic reviews, posters, and commentaries),

- used a head-mounted display (this excludes projection-based VR, smartphone VR, CAVEs, and other less immersive media),
- describing an empirical study with healthy human participants,
- presenting work in which participants had a human avatar (this excludes work using non-humanoid avatars, mannequins and 360-degree video), and
- measuring some form of embodiment (e.g., body ownership or agency).

Fig. 1. A PRISMA-style flowchart of the selection of studies for the systematic review and meta-analysis.



In all, 289 papers appeared to meet these criteria. After reading their full text, we excluded 178 for ultimately not adhering to them. Consequently, the review presented here covers 111 papers, spanning 11 years of BOI research (see Table 1)).

Our meta-analysis, in turn, included the 92 papers in the corpus that (i) include reporting on virtual embodiment with a standard avatar (a control condition) and that (ii) report descriptive statistics for embodiment (e.g., mean, standard deviation, median, or interquartile range) or contain box plots or bar charts from which these can be extracted. Of these, 61 papers experimentally manipulate embodiment as an independent variable (e.g., through manipulating appearance, abstraction, or perspective of the avatar), enabling comparisons of effect sizes across experimental manipulations.

4.3 The source data and materials

Each paper that met the eligibility criteria underwent manual extraction of relevant variables. Due to the triviality of the task, three individuals collectively sourced data without overlap. We collected the following information:

Study design, procedures, and methods. Number of studies, number of participants (by study and by gender), type of VR headset, completeness of body ownership (full body, arm(s), or hand(s)), perspective, presence/absence of a mirror, manipulation of embodiment (visual synchrony, tactile synchrony, an abstract body, etc.), induction duration, study design, and objective measurements of embodiment.

The subjective measurements. Reference to the questionnaire(s) employed, number of questions, number of constructs, scale (min., max., and delta), statistical analysis, and reliability.

Meta-analysis. Type of disembodiment, number of participants for each condition, and condition-specific descriptive statistics for each subjective embodiment variable.

4.4 Measurements

In addition to reviewing the data obtained in the aforementioned manner, we conducted meta-analyses involving four constructs recurrently applied for measurements in BOI studies: agency, body ownership, mirror body, and two bodies. The specific wording of questions is often adapted to the experiment's context and hence differs across samples. Likewise, the scales employed vary, although measurements are commonly collected with a 7-point Likert scale ([-3; 3] or [1; 7] is typical, though some studies use [1; 5] or [1; 100]).

4.5 Effect sizes

Effect sizes facilitate comparison between studies, help estimate the required sample size for future studies, and aid in assessing the importance of experimental findings [1].

We report Hedges' g, since it is less biased with small sample sizes than Cohen's d [59]. We computed effect sizes from means, standard deviations, and sample sizes using the `R` function `esc::esc_mean_sd` [107], with per-condition sample sizes considered (we assumed an even distribution of participants when the authors did not report group-specific sample sizes).

Most BOI studies feature a baseline control condition, in which the participant experiences an adult humanoid avatar matched to gender in first-person perspective (1PP) with visuo-motor synchrony. This enables comparison with a condition wherein participants experience a body with some form of *disembodiment* (e.g., appearance, feature, or perspective changes or incongruence of visual/tactile cues). Therefore, the effect sizes reported from the meta-analysis represent the magnitude of the difference in the dependent variables between the given study's embodiment and disembodiment conditions. The employed statistical practice is furthermore described in Appendix A.

5 RESULTS

The cumulative evidence from our review supports the hypothesis that manipulations to virtual avatars influence subjective ratings of embodiment, the central aspect of body ownership illusions (see the summary in Table 1). A detailed analysis of publication bias can be found in the Appendix B; weight-function modeling and funnel plot analyses did not uncover evidence for systematic publication bias.

5.1 Effects of avatar manipulation

The most fundamental aspect of virtual embodiment, body ownership, are collected from both baseline and body-manipulation conditions in 61 papers in the sample; similarly, 35 studies manipulating avatars have reported subjective agency scores. We use these scores to compare the effectiveness of experimental manipulations.

5.1.1 On body ownership. Body ownership measurements are reported in 61 of the articles. These reports enable field-wide comparisons of embodiment and disembodiment effect sizes, respectively. The effects for body ownership are grouped by type of disembodiment (see Figure 2). Due to the modest sample size, we did not compute the mean weighted effect sizes for studies manipulating avatar placement. Across all disembodiment manipulations, the largest effect on subjective body ownership emerged for visuo-motor asynchrony; $g = 1.1$, 95% CI $[0.83; 1.35]$. Perspective (i.e., first- or third-person perspective; $g = 0.88$), abstraction (i.e., use of a non-humanoid avatar; $g = 0.72$), and visuo-tactile asynchrony (i.e., incongruence between visual and tactile stimulation; $g = 0.68$) similarly manifested consistent effects on body ownership. Interestingly, "embodying" an invisible avatar showed consistent null effects on body ownership, $g = 0.07$, 95% CI $[-0.02; 0.16]$, providing evidence that incongruence in sensory stimuli diminishes the sense of body ownership while absence of stimuli does not. These meta-analytical findings are important for weighing the relative importance of the various components of multi-sensory integration, and they may have implications for future experiment design in BOI research.

5.1.2 On agency. Figure 3 shows the effect sizes of avatar manipulation on agency, for individual studies and in the aggregate. Visuo-motor asynchrony proved to be the most influential manipulation, with a mean effect size of $g = 1.54$, 95% CI $[0.93; 2.2]$. No other types of avatar manipulation showed large effects on agency. It follows that congruence of vision appears as the most prominent stimulus in body ownership illusions.

However, embodying an abstract avatar consistently showed some effect on agency ($g = 0.49$), demonstrating that, across the board, embodying non-humanoid avatars (such as robots, primitive shapes, wooden bodies, or mannequins) reduced both body ownership and agency from the levels seen in control conditions.

Furthermore, perspective showed as an effective manipulation on agency $g = .89$. Tactile asynchrony also had effect ($g = 0.66$) on agency. Thus, congruence of tactile stimulation affects body ownership and agency to similar degrees. The effect of avatar appearance (e.g., facial features, clothing, and skin color) on agency, relative to body ownership, is limited $g = 0.19$, 95% CI $[0.05; 0.32]$.

In line with the effects of avatar manipulation on body ownership, the data for invisible avatars suggest null effects on agency.

Fig. 2. Body ownership effect sizes, grouped by embodiment manipulation, where error bars denote the 95% CI and red diamonds depict the weighted means of means with a 95% CI of means (omitted for ‘Displace‘ because of sparsity and high variance.)

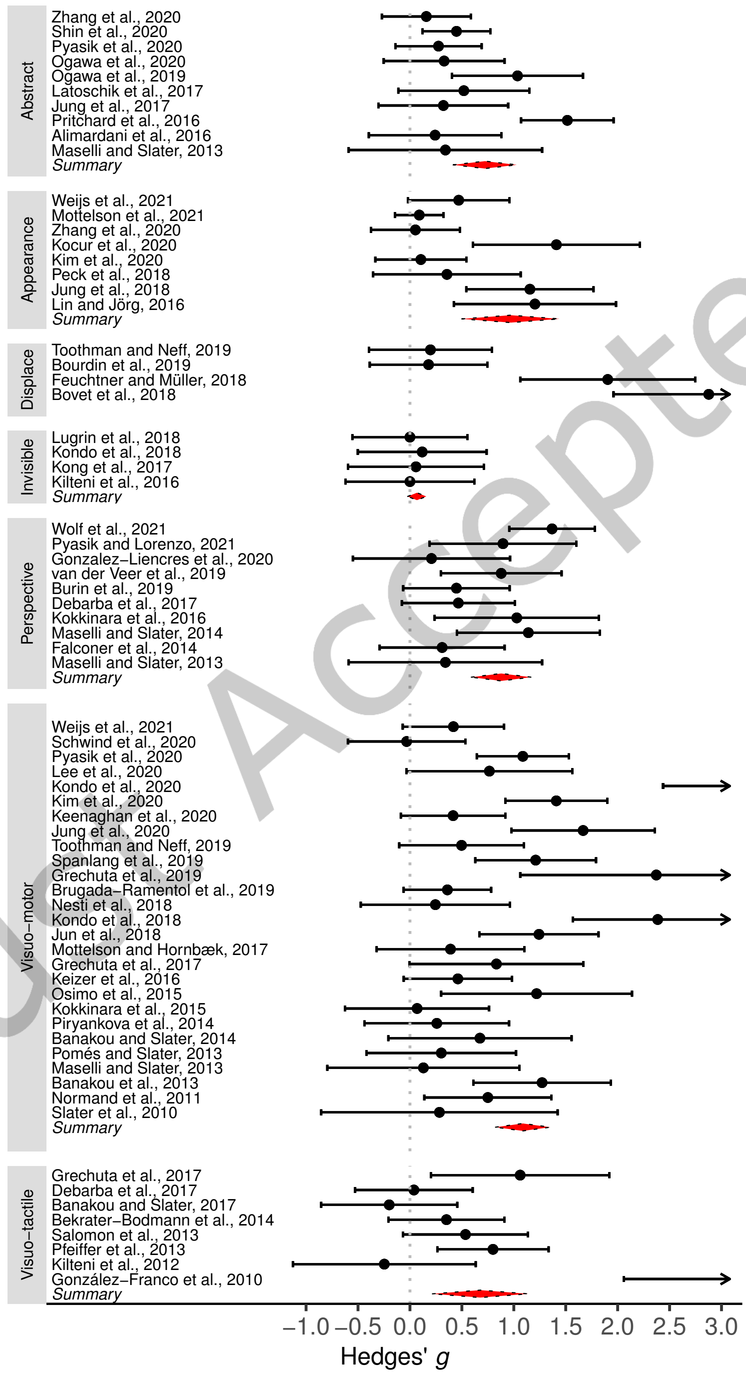
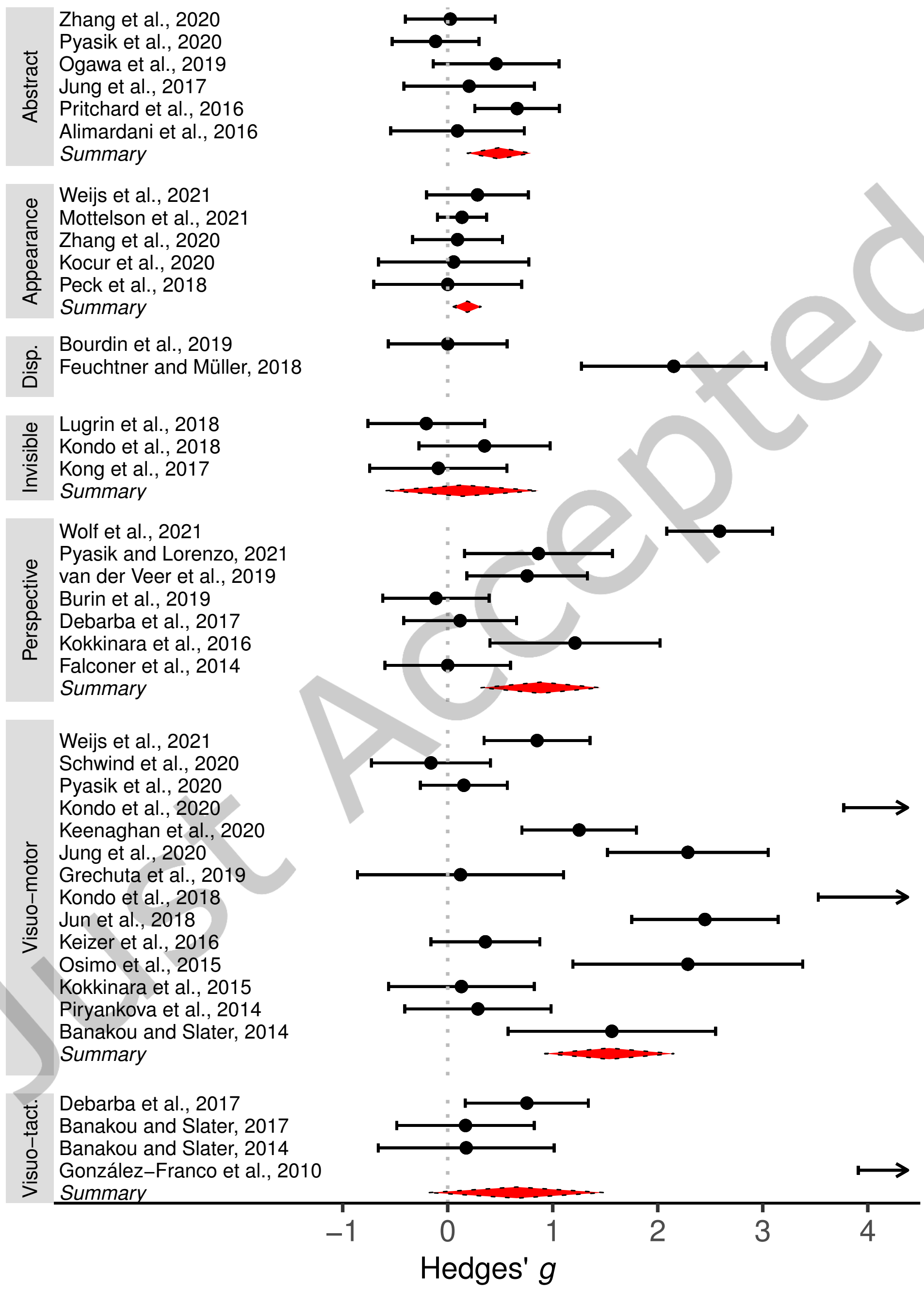


Fig. 3. Agency effect sizes, by embodiment manipulation, where error bars denote the 95% CI and red diamonds depict the weighted means of means with a 95% CI of means (omitted for 'Displace' because of sparsity and high variance.).



5.2 Subjective measurement of embodiment in VR

BOI studies often employ questionnaires to measure the subjective embodiment of virtual bodies. These vary in the number of constructs and items, the scale's number of steps and its minimum and maximum values, and analysis approach. To investigate the field's subjective measurement practices, we collected data related to embodiment questionnaires across BOI studies. For each paper, we collected

- any references to the embodiment questionnaire(s) employed;
- the number of constructs and number of items used; and
- the scale's minimum, maximum, and number of steps.

Ad hoc questionnaires are commonly used, sometimes as a sub-set or super-set of pre-existing questionnaires' items. Of the 111 papers included in the review, 26 employ unique embodiment measurements. In comparison, 90 papers directly employ previous embodiment measures.

In some cases, the references cited for the embodiment measurements point to other studies, with the resulting "chains" of references to embodiment questionnaires ultimately pointing to original research rather than to psychometric instruments.

Due to mixed practices with respect to subjective embodiment instruments, we noted when questionnaires were adapted, overlapped, and/or were identifiable from their references or wordings, so that we collected the most complete set of data possible. Finally, only 12 of the papers address the reliability of subjective measurements (e.g., by Cronbach α). This limitation makes conclusive estimations difficult; however, isolated papers report low or even negative reliability [130, 137], while other report high α values for embodiment constructs above 0.9 [67, 93].

The data suggest six commonly employed questionnaires for subjective embodiment, summarized in Table 2. In Table 2 we also report Cronbach's α for some of the commonly employed embodiment questionnaires using the data reported in their original studies, and find acceptable, yet not unambiguous levels (i.e., α-values in the range of 0.78-0.85). It is evident that the practices of measuring subjective embodiment vary greatly. Most importantly, few of these practices have been formally validated, and the questionnaires utilized have, for the most part, been developed for purposes other than VR research (often for the rubber-hand illusion). The six most commonly employed measurements are summarized in Appendix C.

Table 2. Summary description of the most common BOI questionnaires (top six), and other BOI questionnaires (bottom three).

Authors/year	Concept	N	Constructs	Items	Min./max./delta	Validation	Order	Psuedo R	Citations	α
Botvinick and Cohen, 1998	RHI	10	9	9	-3/3/7	No	random	`t.test(Q ~ condition)`	4748	-
Lenggenhager et al., 2007	VR video	14, 14	7	7	-3/3/7	No	sequential	`aov(score ~ sync * question)` `t.test(Q ~ sync)`	1416	-
Longo et al., 2008	RHI	131	3	10	-3/3/7	Yes	random	`aov(score ~ component * sync + Error(P/sync))`	929	-
Banakou et al., 2013	BOI child	30	4	4	-3/3/7	No	sequential	`friedman.test(Q, condition, sync)`	648	0.85^{A}
Banakou and Slater, 2014	BOI speaking	44	5	5	-3/3/7	No	sequential	`polr(factor(Q, ordered=T) ~ sync * condition)`	174	-
Gonzalez-Franco and Peck, 2018	VR avatar	N/A	6	25	-3/3/7	No[B]	random	`wilcox.test(PCA_factor ~ condition)`	264	0.80^{C}
Martini et al., 2013	VR arm	30	1	1	1/7/7	No	-	`friedman.test(Q, condition, trial)`	111	-

Slater et al., 2010	VR avatar	24	8	8	0/10/11	No	sequential	`polr(factor(`
								`(Q+2) %/% 3, ordered=T`
								`) ~ perspective * movement * touch)`
									990	-

Roth and Latoschik, 2020	VR avatar	50, 48, 70, 22	3	12	1/7/7	Yes	random	`aov(var ~ latency + Error(P/latency))`	91	0.78^{D}

N = number of participants.
Citation counts are from Google Scholar as of December 31, 2022.
α = internal validity as Cronbach's α.
[A] Computed from data found in the paper's supplementary material. Two items were used (`vrbody` and `mirror`). Including `features` and `twobodies` yields $\alpha = 0.75$
[B] Validation study later presented by Peck and Gonzalez-Franco [136]
[C] Computed from data found on first author's GitHub. Items for body ownership were used (Q1-Q5).
[D] For ownership (four items), reported in the paper. Almost identical values reported for other embodiment constructs.

5.3 Terminological confusion

Eighteen papers report body ownership as the only subjective measurement of embodiment. Sometimes, the assessment of body ownership involves only a single item (e.g., [111, 112, 138]). Othertimes, it involves the application of an elaborate questionnaire with many questions, including constructs often considered to represent agency or self-location. Hence, VR research sometimes uses the notions of body ownership and embodiment interchangeably. In the embodiment literature, a specific question may refer to various named constructs; a case in point is the use of the question "[...] did you feel as if the virtual right arm was your own right arm?" referred to measuring both the 'level of ownership' [23, 111] and the 'embodiment level' [112]. Also prevalent are combined constructs, such as "embodiment" [173] or "body ownership and agency" [28]. Furthermore, researchers often collect multiple body ownership measurements—for instance, by asking about the body seen upon looking down (often called "me down"), on looking in a mirror (or "mirror body"), and more generally ("my body"). Additionally, material for constructs similar to embodiment gets collected in BOI studies, such as "self presence." For this, researchers (e.g., [4]) use a 15-item presence instrument with such questions as "To what extent did you feel that the avatar's body was your own body?" Arguably, this touches on the same aspects of bodily self-consciousness as body ownership. Similarly, Dobricki and de la Rosa [31] suggested the three sub-scales 'self-identification', 'spatial presence', and 'agency' for measuring 'Conscious Full-body Self-perception'. Finally, the wealth of detailed neuropsychological accounts of embodiment related to limb ownership, agency, and body ownership [35, 55, 70, 102, 175, 176] does not provide an easily accessible vocabulary for VR researchers. This shortcoming makes scientific output difficult to compare and often raises validity concerns, thus creating what Ekkekakis and Russell [36] characterized as a "terminological Gordian knot" when documenting disparate measurements of affect in health-behavior research.

5.4 Consistency checks

In addition to direct embodiment constructs, the control questions often used in embodiment questionnaires as consistency checks are of interest. For instance, six of nine questions in the original RHI study were control items; only three questions being expected to show differences across conditions. A review by Gonzalez-Franco and Peck [48] reports that 60% of the studies examined use such control questions (not to be confused with control of avatar actions or *agency*). The number and type of control questions in BOI studies vary, as does the approach to any analysis conducted. In 23 studies, the "two bodies" construct (e.g., "I felt as if I had two bodies") is measured and reported.

Practices of employing control questions as a consistency check in embodiment questionnaires lack uniformity. Control items originally developed for this purpose are commonly included without any analysis of consistency; they function merely as "filler items." Researchers seldom actively hypothesize about or test for consistency across conditions. Furthermore, some studies even use control questions as part of the embodiment metric; for instance, Peck et al. [138] suggested computing body ownership as $(MyBody + 6 - NotMe)/2$.

Practices related to control questions are inconsistent in general, as exemplified by influential works, with Petkova and Ehrsson [141] and Banakou and Slater [8] suggesting the use of "Features" as a consistency check (i.e., "I felt that my virtual body resembled my own (real) body in terms of shape, skin tone, or other visual features"). More recent research has most often employed this construct directly as a sub-dimension of embodiment [48] despite its original intention.

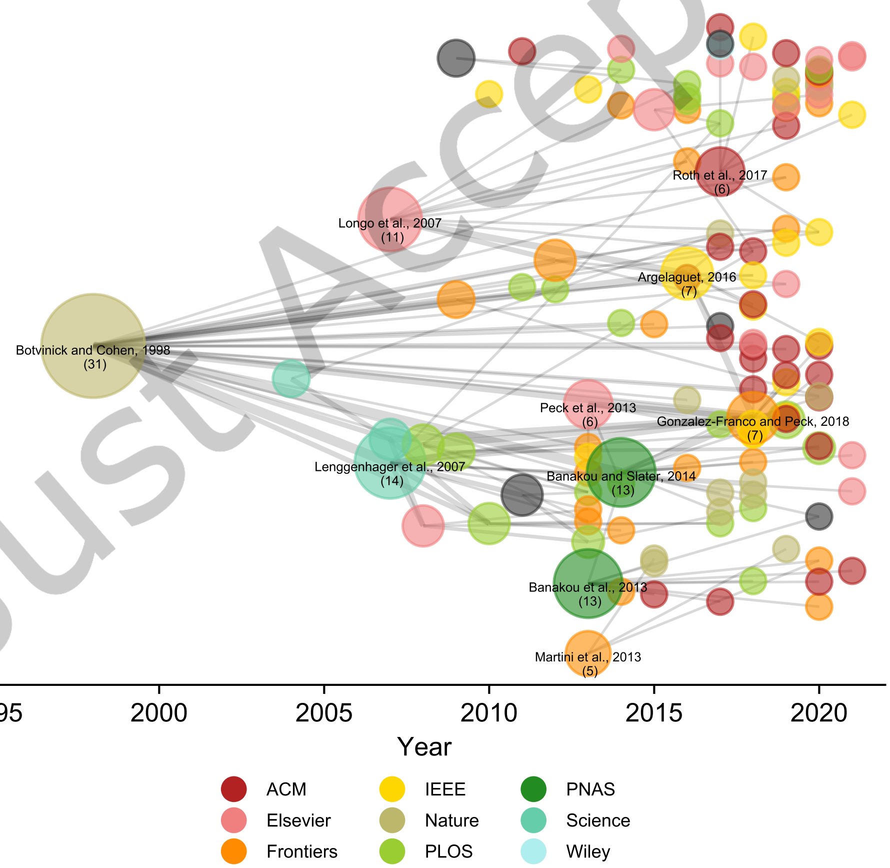
Taking into account the use of control items in RHIs, Riemer et al. [153] emphasized that "empirical support justifying this practice is lacking". More recently, Lush et al. [106] suggested that the use of control questions in embodiment research exacerbates the risks of demand characteristics. Indeed, our review shows that, while control questions are commonplace in BOI settings, there is great disparity in their use, a lack of clear hypotheses, and inconsistency of approach (they may be treated as dependent variables or filler items). Finally, this general state of affairs may introduce threats to the statistical validity.

Notwithstanding the questionable approach to control questions, the most commonly employed embodiment-connected control question, on "two bodies," does not seem affected by experimental manipulations of disembodiment (g = -0.06, 95% CI [-0.24; 0.12]). The mean response across means for all control conditions is M = -1.02, SD = 0.68 (range: -3 to 3), showing that participants, as expected, in fact do not experience two bodies when embodied in one.

5.5 All roads lead to rubber hands

Following the path of references for embodiment questionnaires leads to the embodiment questions associated with the RHI (see Figure 4). For instance, Patané et al. [134] stated that their items addressing the level of subjective ownership over one's virtual body are adaptations of Banakou et al. [6] and Banakou et al. [7]'s work; both

Fig. 4. A diagram connecting each study in the survey to other papers referencing the subjective embodiment scale employed, such that the lines' and circles' size denote the number of references (number of references in parentheses). The colors differentiate between publisher.



publications address the questions considered by Banakou and Slater [8], who, in turn, referenced Botvinick and Cohen [21] as inspiration. Although this observation itself is harmless, two concerns arise. First, the fundamental principle behind all subjective embodiment measurements in VR research is, by transitive relationship, based on the RHI, an experiment paradigm popularized well before modern advances in VR BOIs. While the RHI and the BOI phenomena are inherently related, the questions, constructs, and analyses developed specifically for the latter's analogue setup have never been validated for the fundamentally different medium of the digital domain, which features greater immersion, presence, and visuo-motor synchrony. Second, the practices seem to illustrate collective confusion surrounding both the origin of the measurements and the corresponding analyses. The chains of references make convergence to similar practices difficult, and junior researchers may find it especially hard to unearth the relevant resources for conducting solid empirical research.

5.6 Subjective embodiment scores

The corpus of reports on BOI studies measures many dependent variables related to embodiment. In our presentation of results, constructs with high similarity are matched to allow for field-wide comparison. Among the most commonly employed notions and terms are (i) body ownership, (ii) agency, (iii) mirror body, and (iv) two bodies. Numerous other constructs were measured in the studies surveyed, among them "other person," yet these show limited application (with 10 or fewer occurrences in the corpus). See Table 3 for an overview. The constructs reported vary slightly in the name used (e.g., "VRBody" and "MyBody") and in the specific wording of the measurement items.

Research into BOIs typically employs a control condition and a body-manipulation condition, for a two-by-two design, with independent variables such as embodiment (e.g., skin color) and disembodiment (e.g., related to the synchronicity of movements or tactile feedback). This type of work advances our understanding of bodily self-awareness through estimating the differences in embodiment responses across conditions. In designing such studies, researchers will often ask themselves what range of embodiment scores they could expect the participants to report.

Table 3. Commonly employed subjective metrics for embodiment in BOIs.

Construct	**Similar variables**	**Example questions**
Body ownership	VR Body, My Body, Own Body, Sense of Ownership, Virtual Body Ownership, Self presence, Me Down, Avatar Acceptance, Self Identification, Embodiment, Embodied Avatar, Embodied presence	How much did you feel that the virtual body you saw when you looked down at yourself was your own body? I felt as if the virtual body were my body How much do you feel like your avatar is an extension of your body
Agency	Control, Sense of Agency, Own Agency, My Movements, Control Move	I felt that the movements of the virtual body were caused by my own movements I felt that if I moved my real body (arms, hands, legs), the virtual one would also move accordingly
Mirror body	Me Mirror	I felt that the virtual body I saw when looking at myself in the mirror was my own body How much did you feel that the virtual body you were looking at in the mirror was your own (real) body?

Fig. 5. A summary of four commonly measured constructs across all BOI studies for baseline conditions, involving (parts of) an adult human avatar in visuo-motor synchrony, where mean values are represented by horizontal lines in which each dot denotes the estimated mean from one study scaled to [-3; 3].

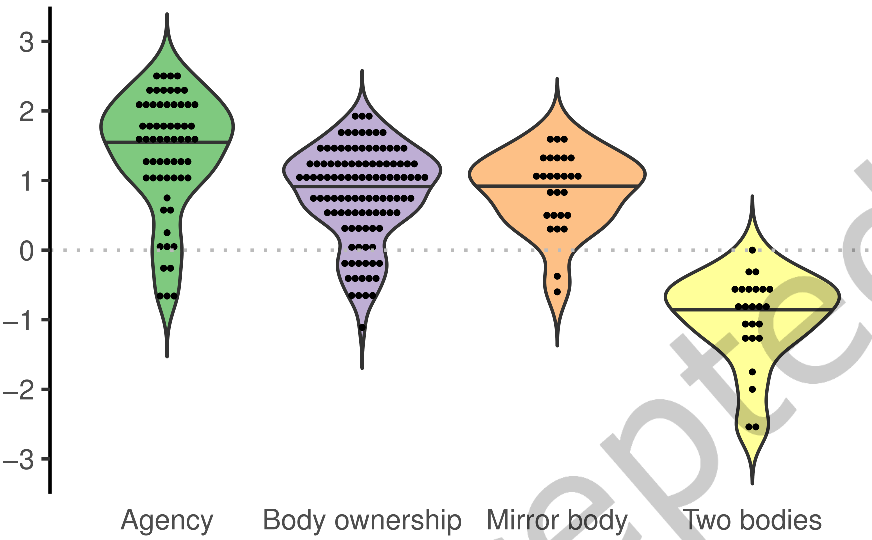


Figure 5 shows the distribution of the study-specific embodiment-response means. It raises several interesting points. First, the ratings for agency is higher (M = 1.39, SD = 0.83) than those for body ownership (M = 0.80, SD = 0.67), on average. This finding is unsurprising when one considers that agency involves one's control of actions and does not require humanoid bodily properties. Second, average body ownership is fairly modest across "embodiment" conditions—that is, conditions in which participants experience a body with visual congruence from 1PP. Therefore, researchers should expect absolute mean body ownership ranges between 0.1 and 1.4 (on a scale from -3 to 3) for avatars with sensor congruency in BOI studies. This finding implies great potential for technical contributions that improve BOI-research (e.g., related to visual and tracking fidelity, kinematics algorithms, and 3D modeling) in addition to research avenues whereby experiments pinpoint techniques that improve the sense of embodiment with virtual avatars.

5.7 Criticism of subjective embodiment measures

More than a decade ago, Slater and colleagues identified methodological challenges with subjective embodiment measurements [164], later noting that "questionnaires in this area are problematic unless supported by behavioral or physiological evidence" [166]. Our review shows that only about half of BOI studies include such physiological evidence, most commonly galvanic skin response to a threat (e.g., the appearance of a saw), heart-rate variability, and proprioceptive drift of limbs (for a full list of the objective measurements, see Table 4). While such measures might complicate study procedures, and, especially for physiological measures, are seldom available with off-the-shelf VR equipment, the collection can significantly increase validity of findings. To this end Table 4 can serve as an inspiration for VR embodiment studies considering an expansion of dependent measures beyond subjective.

In light of a significant difference in non-illusion questions between synchrony conditions, Slater et al. [164] stressed the importance of the issues accompanying questionnaires, underlining that "over-reliance on questionnaires is methodologically dubious." Because of their applicability to most experimental setups, subjective measures continue to dominate measurement of embodiment. To this end, being terminologically accurate and applying standardized tools and analysis techniques is of high importance to the validity of measurements; which unfortunately is often not the case in BOI research.

5.8 Correlations with subjective embodiment

The subjective embodiment scores demonstrate correlation to numerous measurements. We identified correlations of dependent variables related to embodiment scores' for subjective, cognitive, motor-function, and physiological measurements (see Table 4).

Many of the physiological outcomes in particular—such as skin response to a threat and various heart-rate responses—are often treated as evidence for embodiment, whereas subjective, cognitive, and motor-function outcomes (apart from drift) are commonly regarded as the exploratory part of a study. Still, examples of objective cognitive measures taken as direct evidence for dimensions of embodiment do exist (e.g., Libet's clock [99] for measuring sense of agency in VR [15], or the mental ball task to measure implicit self-location [94]).

Analysis of embodiment correlations together show the host of attitudes and behaviors connected with subjective embodiment of virtual bodies. Empirical support for embodiment correlates has been shown repeatedly with regard to (age-, race-, and gender-) biases, size estimations (for objects and bodies), and empathy. Since most of these correlations have been reported only once, we refrain from estimating mean effect sizes across categories. Note that many of the reports do not demonstrate causal relations to embodiment, but rather demonstrate relations to embodiment specific virtual bodies (e.g., affect of embodying a smile or frowning avatar [65]). Because of the limited studies for each measurement, the data is too scarce to conduct meta-analytical estimations of the correlations.

5.9 Mirrors

Mirrors give the participant an opportunity to see their bodies in first-person perspective; hence, they are relevant primarily for full-body illusions. About half of the studies surveyed used mirrors in the induction procedure. Of these, half ($N = 27$) examined body ownership with reference to the body seen in the mirror—"mirror body." The latter representation shows a strong correlation with more general body ownership (i.e., "my body"), with Pearson's $r(14) = 0.96,\ p < 0.0001$. Furthermore, as Figure 5 attests, these constructs' distributions are highly similar, reflecting that the two constructs probably measure the same thing.

Our data suggest that the presence of a mirror might impinge on the size of the resulting effect for body ownership. Studies without a mirror yielded a weighted mean effect size of $g = 0.78$, while the effect was smaller in those with a mirror present, at $g = 0.67$. It should, however, be noted that studies with mirrors present might reflect task designs that incorporate activity to body parts that without the presence of a virtual mirror would be out of sight.

Table 4. Correlation of subjective embodiment to subjective, cognitive, motoric, and physiological measurements.

Subjective measurement	Studies
Age bias	Banakou et al. [7]
Racial bias	Aymerich-Franch et al. [4], Hasler et al. [58], Patané et al. [134], Peck et al. [138]
Health decisions	Mottelson et al. [123], Tambone et al. [172]
Gender bias	Lopez et al. [103], Peck et al. [137]
Math confidence	Peck et al. [137]
Self-criticism	Falconer et al. [37]
Bodily awareness	Bergström et al. [16]
Empathy	Barbot and Kaufman [11], Christofi et al. [28], Hamilton-Giachritsis et al. [56], Patané et al. [134]
Perception of risk	Shin et al. [162]
Social-interaction quality	Latoschik et al. [91]
Guilt, Regret	Friedman et al. [41]
Social anxiety	Aymerich-Franch et al. [4]
Attitudes to life change	Barberia et al. [10]
Fear of death	Bourdin et al. [22]
Affect	Jun et al. [65], Osimo et al. [131]
Feelings of vulnerability	Gonzalez-Liencres et al. [49]
Presence	Kim et al. [80], Schwind et al. [158]
Pain	Weeth et al. [185]
Human-likeness	Latoschik et al. [91]
User experience	Wu et al. [189]
Cognitive measurement	**Studies**
Navigation	Medeiros et al. [116]
Cognitive performance	Banakou et al. [7], Bergström et al. [16], Latoschik et al. [91]
Cognitive load	Kocur et al. [84]
Size estimation	Banakou et al. [5], Jung et al. [67], Keizer et al. [74], Kokkinara et al. [86], Leyrer et al. [96], Normand et al. [127], Ogawa et al. [129], Piryankova et al. [143], Tajadura-Jiménez et al. [171]
Localization	van der Veer et al. [178]
Weight perception	Wolf et al. [187]
Reaction time	Banakou et al. [5]
Learning of motor imagery	Alimardani et al. [3]
Delegation of electric shocks	Neyret et al. [126]
Body-change recognition	Peck et al. [137]
Motoric measurement	**Studies**
Reach	Bourdin et al. [23], Nataraj et al. [124]
Movements	Burin et al. [27], Rubo and Gamer [156]
Mimicry	Hasler et al. [58]
Vection	Nesti et al. [125]
Collision avoidance	González-Franco et al. [50], Ogawa et al. [130]
Drumming	Kilteni et al. [75]
Drift	Hara et al. [57], Kondo et al. [87], Perepelkina et al. [140], Pomes and Slater [146], Pyasik et al. [150]
Kinematics	Perepelkina et al. [140]
Motor performance	Grechuta et al. [51], Kocur et al. [82, 83], Seinfeld and Müller [161]
Throughput	Peck et al. [135], Tran et al. [174]
Grip strength	Kocur et al. [83]
Speaking	Banakou and Slater [8], Tajadura-Jiménez et al. [171]
Physiological measurement	**Studies**
ERD	Škola et al. [191]
HR	Bergström et al. [16], Slater et al. [163]
HRV	Bergström et al. [16], Slater et al. [163]
HRD	Maselli and Slater [113], Slater et al. [166]
MEPs	Kilteni et al. [76]
ERPs	Spanlang et al. [167]
GSR	Galvan Debarba et al. [46], Gonzalez-Liencres et al. [49], Grechuta et al. [51]
SCR	Fusaro et al. [42], Pyasik and Pia [149], Tambone et al. [172], Weeth et al. [185], Weijs et al. [186]
EMG	Bourdin et al. [23]
Skin temperature	Salomon et al. [157]

ERD = event-related desynchronization, HR = heart rate, HRV = heart-rate variability, HRD = heart-rate deceleration, MEPs = motor evoked potentials, ERPs = event-related brain potentials, GSR = galvanic skin response, SCR = skin conductance reactivity, and EMG = electromyography.

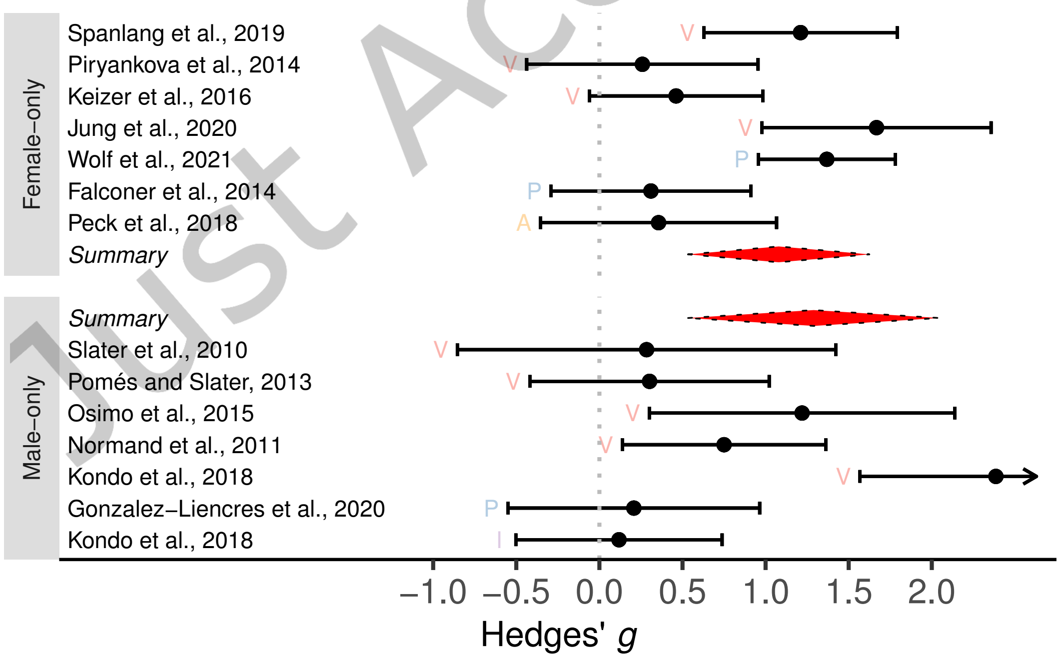
5.10 Effects of gender

VR studies with only one gender of participants present several practical advantages. Only one 3D model needs to be developed and rigged, and greater bodily consistency might afford more uniform experimental practices—for instance, connected with stroking the virtual and physical body simultaneously. Furthermore, some studies suggest that there are gender differences in somatosensory perception [33, 90], with the potential to confound embodiment scores. Also, some research questions or settings have an inherently gender-bound component, as in conditions of maternity [56] or being Sigmund Freud [131]. In addition, there may be a gendered confound to research questions on factors such as sexual harassment [126] or anorexia nervosa [74]. These grounds have together been used to argue for recruiting people of only one gender for a BOI study.

Consequently, 26 of the papers we reviewed used a single-gender sample (10 recruited only males; 16 used only females). Of these, 14 included both an embodiment and a disembodiment condition (seven of the male-only studies and seven of the female-only ones), allowing comparison of effect sizes between genders.

We did not find conclusive evidence for a gender effect on body ownership (see Figure 6). The BOI studies with female-only participants present a mean effect size of $g = 1.08$, 95% CI [0.53; 1.63]; the corresponding figure for male-only studies is $g = 1.29$, 95% CI [0.53; 2.05]. Neither did we identify a gender effect for agency—female-only: $g = 1.45$; male-only: $g = 1.79$. Furthermore, the ratio of female/male participants across all studies did not correlate with body ownership effect size: Pearson's $r(69) = 0.10,\ p = 0.40$; the effect of gender ratio on agency effect size was, however, more pronounced: $r(39) = 0.28,\ p = 0.08$.

Fig. 6. Body ownership effect sizes found in studies with participants of only one gender, grouped by gender (error bars denote 95% CIs, and red diamonds show the weighted means of means with a 95% CI of means), with the disembodiment manipulation highlighted for each study: Appearance, Visio-motor synchrony, Perspective, and Invisible.



5.11 Participants and designs

The 111 papers report on a total of 142 empirical studies (the median number of studies is 1, with $SD = 0.65$), involving 4,925 participants. The studies employed between 10 and 282 participants, with a median participant count of 30 ($SD = 31.3$). A similar number of male and females participated, with an average of 17.5 males and 17.2 females per study. Twenty-six studies recruited only one gender (10 enrolling only males and 16 only females). Across all 142 empirical BOI studies, eight participants were reported as non-binary (across two studies [11, 122]).

The experiment design cannot be readily characterized: BOI studies employ various designs. There are commonly both within-subjects factors (e.g., synchronicity of stimulation) and between-subjects ones (e.g., avatar manipulation), though many studies feature either exclusively within- or between-subjects factors.

Summarizing only the research with experimental manipulations of embodiment (presented in 71 studies), we found a mean power for body ownership of 0.53, which is relatively modest in that it implies an approximately 50% chance of null findings even when an effect exists (note that this figure pertains only to the fundamental differences in body ownership, not the behavioral effects that followed). We computed the power using the `R`-function `stats::power.t.test` [151], which takes the mean difference, pooled standard deviation, and the number of participants as inputs. Accordingly, research into embodiment could benefit from, among other improvements, larger sample sizes and greater precision of the measurements.

5.12 Apparatus and environments

Most often, studies employ the HMD Oculus Rift (42 papers), HTC Vive units (33 papers), and the NVIS nVisor (25 papers), with various versions of the devices being employed (Rift CV1/DK2, Vive / Vive Pro, nVisor SX111/SX60, etc.).

Most papers presented the body ownership illusion from first-person perspective, while considerably fewer adopted a third-person one (1PP: 74 papers; 3PP: 8 papers). Thirteen utilized both perspectives.

Most papers (76 of them) describe a full-body ownership illusion; i.e., the participant is represented by a complete humanoid avatar. Seventeen papers used only the hand(s), 17 used only the arm(s), and the rest involved some combination of virtual limbs.

5.13 Induction procedures

About half of the papers reviewed ($N = 58$) present details of the induction of virtual embodiment, collectively referred to as the *embodiment phase*. A mean duration of induction of slightly more than three minutes ($M = 190$ s, $SD = 146$) was found. The procedures and their length vary between studies, oftentimes as a function of the manipulation employed (e.g., synchronicity of tactile feedback has a more immediate impact on induction procedures).

For this phase, it is common practice to ask participants to look down at their body or tilt their head downward [141]. This is a powerful induction, as emphasized by Slater et al. [165].

> *The very act of looking down, changing head orientation in order to gaze in a certain direction, with the visual images changing as they would in reality is already a powerful clue that you are located in the virtual place that you perceive.*
> Slater et al. [165, p. 219]

This induction is most effectively conducted using visuo-motor synchrony (i.e., physical body movements are virtually reflected in real time), since participant movements would otherwise break the illusion. The induction can also be further underpinned, using visuo-tactile synchrony: here, tactile cues on the participant's body (e.g., vibration, poking, or stroking) are performed in synchrony vith visual stimuli (e.g., a virtual ball, stick, or brush).

The practice of directing participants to look down at their body is linked to the two-construct operationalization of body ownership (oftentimes abbreviated *DownBody* and *MyBody*) wherein a distinction is proposed between, on one hand, subjective body ownership as experienced during looking down ("I had the sensation that the virtual body I saw when I looked down at myself was mine") and, on the other, a more generic sense ("I had the sensation that the virtual body I saw was my body"). Querying ownership from the perspective of looking down (7 papers) shows 35% reduction in ownership ($M = 0.52,\ SD = 2.00$) compared to the generic operationalization ($M = 0.81,\ SD = 1.73$). No significant correlation emerged between induction duration and body ownership scores (Pearson's $r(55) = 0.02,\ p = 0.86$); similarly, we did not find induction duration to be strongly correlated to the size of the embodiment manipulation's effect on body ownership: $r(37) = 0.19,\ p = 0.25$. Agency displays a slightly stronger correlation to the duration of induction: $r(32) = 0.31,\ p = 0.07$.

5.14 How embodiment is treated statistically

Subjective embodiment measurement shows heterogeneity across BOI studies; the statistical analyses conducted show comparable variation. The introduction of a measurement instrument or scale is often accompanied by directions for the statistical handling of the outcome variables. Table 2 presents the scale-linked differences in proposed statistical procedures. The range includes Student's *t*-test for single items, ANOVA for means of constructs, non-parametric testing, logistic regression, and Bayesian analysis, with each practice having specific implications for statistical validity and power, in addition to particular purposes in the explanation of results.

Generally, statistical analyses should follow the protocols prescribed by the original source of the instrument. This is especially true of validated scales and pressing for small samples. Many analyses in the BOI domain could benefit from more conservative statistical analyses, such as non-parametric tests, since embodiment scores seldom consist of ratio data and certain assumptions of general linear models are typically violated (e.g., those of normality and homogeneity of variance). We provide example pseudo-*R* code in Table 2 for an overview of statistical procedures corresponding to the various subjective metrics and their scales.

There are, however, valid reasons for deviating from such analysis practices. Hence, we consider it most important to characterize the intended methods explicitly at the outset (i.e., through pre-registration, per Nosek et al. [128]).

In some cases, specific statistical tests are preceded by various pre-processing of the embodiment variables. Among these steps are binning [166] and PCA decomposition [48]. Perhaps even more importantly from a data-processing standpoint, some researchers also remove outliers. Because ownership over the virtual avatar is a fundamental requirement for subsequent scientific inquiry in BOI studies, it may be reasonable to formulate standard quantitative embodiment-score criteria for respondents' inclusion in the analyses. Several methods have been proposed to detect outlying embodiment scores, among them a cutoff value for residual error [8, 79], visual identification [5], use of box plots for outliers [114, 169], and definition in terms of standard deviations—such as $2SD + M$ [160] or $3SD$ [129]. While simpler manipulation checks such as a mean embodiment score (e.g., across ownership and agency) of ≥ 0 might suffice, these have not achieved widespread adoption in BOI studies.

6 DISCUSSION

The findings of this review and meta-analysis serve two purposes: They aid in the important task of distinguishing sensory prominence—the relative importance of each embodiment-related factor—to advance multi-sensory integration theory. Furthermore, the outputs and critical assessments can contribute to guiding future BOI research and, thereby, serve as a resource for conducting good science that addresses body ownership illusions in virtual reality. We can thus enrich our understanding of how the body shapes the mind.

6.1 Implications

Investigating which factors are associated with embodiment of virtual bodies has both theoretical, practical, and empirical implications.

Our meta-analysis identified the most effective experimental manipulations for BOIs. Visuo-motor synchrony emerged as the most important means to this end, for the outcomes of body ownership and agency (see Figure 2). The results shed light on the sensory prominence for inducing ownership illusions, and our findings suggest that visuo-motor synchrony is of greater importance than congruence of other visual congruence (e.g., realism, tactile stimuli, or perspective). This finding supports that avatar realism is not a critical top-down factor, as previously suggested [64, 77, 105]. In comparing realistic and personalized hand models, Heinrich et al. [60] found mostly differences related to subjective realism, and not embodiment. Some evidence, however, suggests that avatar realism positively influence acceptance of the virtual body [92]. About half of the studies in this meta-review found the appearance of the avatar to affect body ownership; the other half did not (see Figure 2). It should be noted that appearance covers a wide array of avatar changes (e.g., facial features, skin color, age), hence a future categorical investigation of avatar appearance is needed. For agency, however, the appearance of the avatar seems to have little importance (see Figure 3). For agency, visuo-motor synchrony showed to be the only reliable manipulation for induction of illusions of body ownership (see Figure 3).

When calculating the means of the embodiment scores across the four key constructs, *agency*, *body ownership*, *mirror body*, and *two bodies*, we identified body ownership and the mirror-body construct to be nearly identical statistically (i.e., querying ownership from looking down or in the mirror yields identical responses). We therefore suggest omitting the latter, or only include it for sanity testing rather than formulating specific hypotheses in relation to it.

Studies with the presence of mirrors generally report smaller effects on body ownership, compared to studies without mirrors. This observation is purely correlational, and the causal mechanism for this effect could be unrelated to the presence of the mirror itself. Speculatively, mirrors might reduce the sense of body ownership by making the facial region clearly appear non-interactive and that misalignment of visual features between the participant and the avatar is especially pronounced in the face area. Future support for continuous eye and mouth tracking in HMDs could mitigate these concerns. Furthermore, there are design opportunities to design illusions of body ownership in VR. In such environments, participants could observe their virtual bodies without the direct presence of mirrors, such as through reflective surfaces, through virtual video recording, or from tasks that systematically guide the participant's gaze across body parts.

For agency, in contrast, the presence of a mirror does not seem to demonstrate a negative effect. While any conclusions must remain speculative due to the variety of agency measurements across mirror-using studies and the modest number of these studies ($N = 25$), the mean size of the effect on agency is higher in these studies ($g = 1.07$, 95% CI [0.35; 1.78]) than in those without mirrors ($g = 0.80$, 95% CI [0.12; 1.47]).

Recent evidence suggests that virtual embodiment of different-gendered avatars can have specific behavioral effects, but that the effects are not consistently aligned stereotypically with the gender of the avatar (e.g., the authors observed an increase in selfishness for both male and female gender swaps [19], however, with an increased effect for women embodying a male avatar). Peck et al. [135] successfully demonstrated induction of a stereotype threat, wherein female participants were embodying male avatars, hence demonstrating a stereotype lift considering working memory. Schwind et al. [159] reported subjective differences attributable to gender, from embodying an avatar with gender-swapped hands. In this study, females reported less acceptance of male hands, compared to males who accepted and experienced presence with avatar hands of both genders [159]. Our data suggest that gender likely does not affect the likelihood that participants will accept a virtual body as their own. There is therefore little validity gain from restricting recruitment to one gender only if it is not strictly imperative given the domain of study, such as through mismatch between the participant's and an avatar's gender. There might still be practical benefits from recruitment of one gender related to avatar creation, rigging, and for adjusting body-worn equipment. We further encourage researchers to consider the underrepresented in empirical VR research, which, however, appears to have a more fair representation for embodiment VR research compared to other areas of VR research [139]. To this end, Peck et al. [139] report 39% female participants in the IEEE VR conference proceedings, while our data show 49.7% female participants.

In characterizing the commonly used embodiment questionnaires, their origins, and related statistical treatment, we found that the practices of measuring subjective embodiment are heterogeneous and rarely follow validated procedures. Furthermore, the analysis showed that the employed questionnaires in most cases refer to questions developed for the rubber-hand illusion. On these bases, we see great scientific potential in validating these processes and in requiring scientists to adhere to stricter protocols when working with subjective embodiment. Some recent work has tackled this issue (e.g., [136, 155]), but for practical reasons, we too see great potential in developing cross-laboratory validated scales with few items.

We found that participants tended to report higher levels of agency than body ownership for virtual bodies; that is, participants generally feel in control of virtual avatars, but less so experience the avatars' bodies as *theirs*. While this potentially could be an artifact of the employed psychometric tool—this could also point to various areas of profitable improvements in tracking equipment and kinematics algorithms to foster body ownership on par with agency scores in BOI studies.

6.2 Issues facing Embodiment VR research

A critical assessment of the embodiment VR research shows multiple areas where there are opportunities to improve empirical practices related to study design, recruitment of participants, and dissemination of data. We have documented a variety of empirical issues within the literature. These relate to subjective instruments and their analysis, small sample sizes, and terminological confusion. Below, we point towards opportunities for further advancing the scientific quality of BOI research.

6.2.1 Replication and Open Science. We examined correlations of subjective embodiment scores to other dependent measurements, grouped into subjective, cognitive, motor, and physiological ones. Some of these links have been thoroughly investigated and replicated; however, many such connections to embodiment still hold potential for scientific confirmation.

Experimental virtual body manipulations (e.g., changes to visuo-motor synchrony, avatar perspective, or the limbs) influence subjective embodiment scores, and the literature offers abundant documentation of this. Likewise, such manipulations' effects on subsequent behavior and social attitudes are frequently referred to. Yet, these effects are rarely replicated. In most cases, any given specific finding is reported once in the entire literature. Hence, while there is solid empirical support for the methodology behind BOIs, the specific behavioral and cognitive effects identified lack definitive verification (most findings are *one-of*, see Table 4). This is especially troublesome in light of the relatively low power that tends to characterize studies in this field. To this end, the long list of variables empirically found to connect to embodiment shown in Table 4 could serve as a starting point for initiating replications attempts to verify embodiment correlates.

Pre-registration is considered methodologically necessary in many disciplines, most notably psychology, but is currently rarely used in BOI research (we found 26 pre-registrations on Open Science Framework by querying `("embodiment" OR "body ownership") AND ("virtual reality" OR "VR")`; 18 of these were from 2021 and 2022). To this end, even as pre-registration counts are still modest, the recent increase provides aspirations for adoption of open science practices within BOI research. Increasing use of preregistration in BOI research would not only alleviate concerns about statistical practices, but could also serve as a repository for description and reason for procedures and tasks, that could aid standardization.

The BOI field as a whole could benefit from stricter scientific rigor, for mitigating problematic publication practices. For instance, adopting standards from *open science* will yield benefits. These standards prescribe pre-registering hypotheses, specifying the analysis plans, and conducting *a priori* power analyses for estimation of the required participant numbers.

Any part of empirical science can gain from adopting open science principles. VR studies, and BOI in particular, are well suited for conducting replication studies, as study procedures, group assignment, data collection, etc. can be encoded into the application. This way, researchers across labs can share materials, and expect to collect consistent data. We therefore foresee that VR technology, and BOIs in particular can be a driver for replication attempts in behavioral science.

6.2.2 Measures. Our review has documented the disparate use of subjective measures in embodiment research to quantify (sub-dimensions) of embodiment. While standardizes questionnaires are emerging (e.g., Peck and Gonzalez-Franco [136], Roth and Latoschik [155]) the prevalence of ad-hoc measures, or adaptations that do not follow original sources is high. Picking suitable subjective measures for quantifying embodiment is non-trivial, taking, among other things, procedures, time, language, and experimental design into consideration. To this end Table 2 can serve as inspiration, showing the complexity, standardization, and suggested statistical treatment for a number of commonly used scales.

6.2.3 Power. For the weighted mean effect size of $g = 0.50$ for subjective body ownership that we estimated in our meta-analysis across embodiment/disembodiment studies and a power of 0.95, there must be 25 participants per group (or more, depending on the specifics of the power analysis). Such estimations contrast the documented median employed participant count of 30 (per study, per group the median is 20). Note that while this participant count would normally be considered a precondition for declaring significant effects on body ownership, it is not necessarily enough to uncover subsequent behavioral or cognitive effects produced by changes to the virtual body. Recent studies have successfully recruited large samples by conducting remote VR studies [121, 122, 152].

7 LIMITATIONS

In most respects, the data obtained from the 111 papers demonstrate heterogeneity; procedures, methods, measurements, scales, and statistical analyses vary greatly between studies. Therefore, even providing descriptive statistics that encompass this corpus has required a fair amount of sophistication in computational techniques (e.g., for estimating means and rendering the scales compatible). Conclusions drawn from this material should take into account that the source data represent diverse scientific practices and have been post-processed for visualization purposes.

Most commonly, subjective embodiment scores are collected as ordinal data. Describing said data with means and standard deviations or conducting parametric statistical tests is not recommended, since the assumptions behind such analyses (e.g., as to normality) are violated. For our meta-analysis, we nonetheless estimated means of embodiment scores from the available statistics and conducted some parametric tests, when deemed necessary. We chose this method because estimating medians from a mean score provides less precision than doing the reverse.

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A STATISTICAL PRACTICE

A.1 Estimation of means and standard deviations

For comparison across studies and for computing effect sizes, we normalized the descriptive statistics. Where means (*M*) and standard deviations (*SD* values) were reported, we used them in the meta-analysis directly; otherwise, we converted the standard-error (*SE*) values reported into *SD*s: $SD = SE \times \sqrt{N}$. As the availability of descriptive statistics allows, we provide per-study estimates of means and *SD*s for each common variable here, using the methods formulated by Wan et al. [184]. For instance, if the first and third interquartile range, Q_1 and Q_3, are known, *M* and *SD* are obtained via the following estimations (note that the source scale's min. and max. values are used for this operation):

$$M \approx \frac{min + max + 2Med + 2Q_1 + 2Q_3}{8} \tag{1}$$

$$SD \approx \frac{max - min}{4\Phi^{-1}\left(\frac{n-0.375}{n+0.25}\right)} + \frac{Q_3 - Q_1}{4\Phi^{-1}\left(\frac{0.75n-0.125}{n+0.25}\right)} \tag{2}$$

A.2 Mean-of-means estimates

To provide a field-wide overview of the response ranges for the most commonly employed embodiment variables, we plot estimated means across all studies for the four most typical constructs (see Figure 5). For compatibility, measurements have been scaled to the [-3; 3] range as necessary: $x = (b - a)\frac{x - min(x)}{max(x) - min(x)} + a$, where $min(x)$ and $max(x)$ are the limits of the source scale and where a and b are -3 and 3, respectively. This scale was chosen as its commonplace throughout BOI research (hence not requiring any scaling), and as it offers a compelling direct explanation as 0 represents neither embodied or disembodied.

A.3 Outliers

Examining the magnitude of the embodiment manipulations' effects on the central dimension of interest, body ownership, yields a weighted mean Hedges' g of 0.50. Most studies (94%) fall within the range of $-0.25 > g < 2.0$ (see Figure 7). Since only five papers present effect sizes outside this range, we introduced a simple outlier criterion of $g > 2.0$ to reduce the distorting influence of individual studies' extreme values on the results. For the sake of completeness, outliers are retained in the plots, but they are filtered out for reporting of descriptive statistics. To limit the influence of individual findings further, we report weighted means whenever possible, with each study's statistical power determining the weight (computed by the `R` function `stats::power.t.test`).

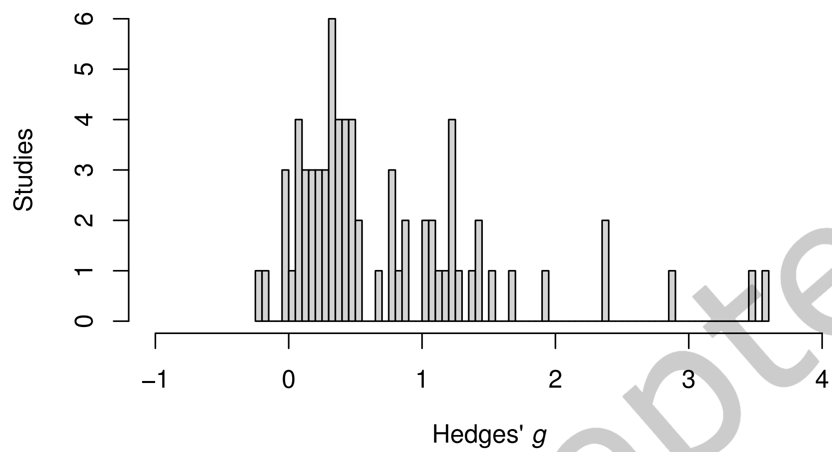
B RISK OF PUBLICATION BIAS

Publication bias. To assess the possibility of publication bias, we looked at funnel plots, constructed for each of four key embodiment constructs using the `R` package `metafor`[181] (see Figure 8). Asymmetry in funnel plots that compare effect size and study precision can suggest publication bias. Consistently, we found no evidence of systematic publication bias for any of the four funnel plots; some few studies showing large effect size are most prominent towards the lower end of standard errors; we deal with such extreme effect sizes as outliers, as described above.

For further assessing the risk of publication bias, we employed weight-function modeling [180] using the `R` package `weightr` [29]. Here, the fit of a publication-bias-adjusted model is compared to that of an unadjusted model. An increase in fit may be indicative of publication bias. The weight-function modeling did not uncover an increase in fit; hence, do not find evidence for publication bias; $\chi^2(1, N = 77) = 0.36,\ p = 0.55$.

We inspected the heterogeneity for study effects for body ownership and agency, respectively. The data showed Higgin's & Thompson's $I^2 = 17\%$ for body ownership and $I^2 = 79\%$ for agency; for body ownership this is

Fig. 7. A histogram of the effect sizes of the embodiment manipulations' effect on body ownership.



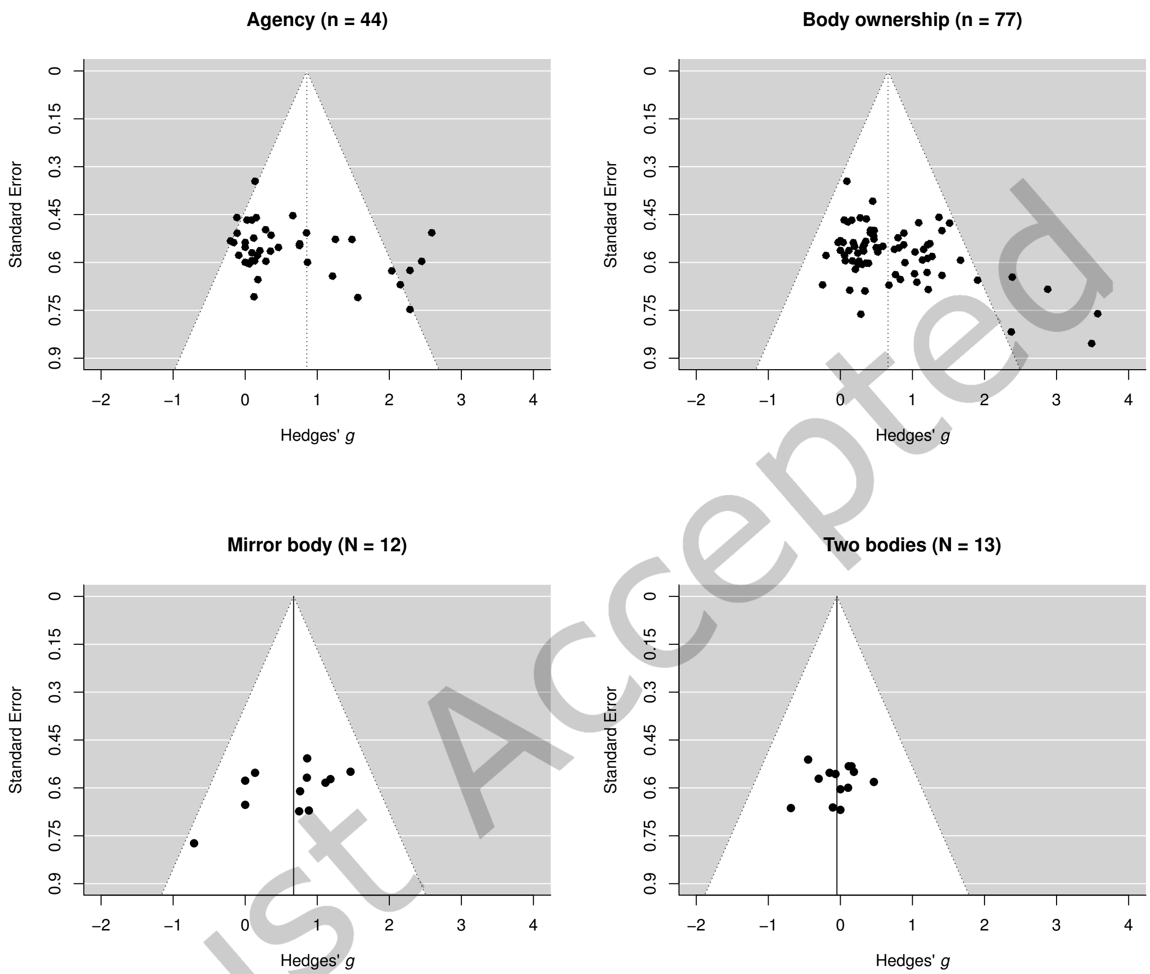
considered *low heterogeneity* and, conversely, for agency it is considered *substantial heterogeneity*. Interestingly, body ownership scores showed a substantial reduction in variation compared to agency, while it should also be noted that agency scores in general are higher compared to body ownership (i.e., it appears easier to induce participant control over virtual limbs, than creating the illusion that the virtual body is theirs.)

Publication year. Our results show no significant correlation between publication year and effect size; Pearson's $r(75) = 0.03,\ p = 0.81$.

Between- versus within-subjects design. Our results indicate that body ownership illusions emerge both in within-subjects experiment designs (g = 0.97, 95% CI [0.64; 1.31]) and in between-subjects designs (g = 0.45, 95% CI [0.21; 0.69]).

We did find a significantly larger effect of embodiment scores for within-subjects designs, of about twice the size; $t(43.5) = 2.6,\ p = 0.01$. This likely stems from the fact that visuo-motor asynchrony (i.e., incongruence between the participant's and the avatar's movements), which is the most effective manipulation for body ownership, is frequently a within-subjects condition. When comparing only manipulations of visuo-motor synchrony, we did not find a significant difference in body ownership effect sizes across experimental designs; $t(16.1)$ =-0.6, $p = 0.53$.

Fig. 8. Funnel plots for VR body ownership illusion studies, comparing the effect size (Hedges' g) and precision (standard error), for the four main subjective aspects of embodiment measured: agency, body ownership, mirror body, and two bodies.



C COMMON SUBJECTIVE MEASUREMENTS OF EMBODIMENT IN VR

Here we summarize the six most commonly used questionnaires for measuring embodiment (see Table 2, that also summarizes three additional, less commonly employed, questionnaires).

C.0.1 Botvinick and Cohen (1998). In a seminal paper, Botvinick and Cohen [21] presented the rubber-hand illusion (RHI). In the RHI, tactile stimuli are introduced synchronously to an artificial rubber hand and (hidden behind a screen) the subject's real hand. The participants ($N = 10$) anchored the touches at the location of the rubber hand. This indicates interactions between vision, touch, and proprioception. The authors investigated the phenomenon by using a questionnaire with nine items, of which three were considered likely to evoke affirmative responses (e.g., "I felt as if the rubber hand were my hand"). The questions were administered in random order, on a seven-step [-3; 3] visual-analogue scale from "agree strongly" to "disagree strongly." Although the paper does not present any specific guidance on statistical analysis, single-item means and p-values are reported.

C.0.2 Lenggenhager et al. (2007). In their paper "Video Ergo Sum", Lenggenhager et al. [95] described two experiments ($N = 14, 14$) wherein participants experienced themselves through an HMD from a distance, in a so-called out-of-body experience. Using synchronous and asynchronous visual and tactile stimulation to the subject's own, foreign, and fake bodies, the authors showed a disruption of spatial unity between the self and the body. In addition to objective measurements of drift, the authors collected responses to a subjective questionnaire on "self-attribution of the virtual character" adapted from the work of Botvinick and Cohen [21]. The scores reported were analyzed for each of the seven items (which employ a seven-step scale from -3 to 3) by means of parametric repeated-measures ANOVA and subsequent t-tests. The first three questions, related to touch and "my body," show significant differences for the synchrony of stroking.

C.0.3 Longo et al. (2008). Taking a psychometric approach, Longo et al. [102] investigated the experience of having a body during the RHI. Working with transcripts of qualitative reports from five participants, they developed an initial set of 27 items. Participants in this between-subjects study ($N = 131$) were exposed to two conditions—synchronous and asynchronous tactile stimuli—and then rated their agreement with the 27 randomly ordered items on a 7-point scale from -3 (for strong disagreement) to +3 (for strong agreement). Principal-component analysis (PCA) revealed four major components of having a body, with embodiment being the primary one. Subsequent analysis identified 10 embodiment-related items (e.g., "It seemed like the rubber hand was part of my body") as representing three subcomponents: ownership, location, and agency. Results from ANOVA testing showed a significant effect connected with the condition (synchrony) and for the components, along with an interaction of the two.

C.0.4 Banakou et al. (2013) and Banakou and Slater (2014). Two influential BOI studies by Banakou and colleagues [5, 8] showed that the illusion of ownership over a virtual body yields consequences for subsequent behavior—specifically, expression of child-like attitudes and a changed manner of speech. Alongside objective measurements of these behavior changes, the authors collected subjective embodiment data. Both studies applied four single-item embodiment variables: *VRBody/MyBody*, *Mirror*, *Features*, and *TwoBodies*), with the latter two affording consistency checks. The 2014 article cites the questionnaire used in the aforementioned RHI study as inspiration, and an item addressing agency was included. Beyond these four or five constructs, the researchers utilized a range of study-specific questions related to age perception and room size. While these studies were not intended to recommend a standardized way of measuring embodiment, they have inspired many scholars, who, accordingly, often refer to them in relation to their own embodiment questionnaires; 15 embodiment articles in our review feature such references. The items from both studies use a range of -3 ("strongly disagree") to +3 ("strongly agree"). The results in the 2013 study were obtained with a non-parametric Friedman test, while the second study employed ordinal logistic regression.

C.0.5 Gonzalez-Franco and Peck (2018). More recently, Gonzalez-Franco and Peck [48] presented a questionnaire on VR avatar embodiment, informed by a review of previous experiments' embodiment questionnaires that reference the work of Botvinick and Cohen [21]. The authors found six types of questions to be frequently used in BOI research: items on (1) ownership, (2) agency, (3) tactile sensations, (4) location, (5) appearance, and (6) response, with classes 1, 2, and 4 being the most important. The resulting questionnaire consists of 25 items, with random administration order, divided among the six constructs. The common practice of applying a 7-point scale from "strongly disagree" (-3) to "strongly agree" (3) was followed. The authors recommended analysing responses using non-parametric tests for either sum-of-scores or principal-component scores. A recently published validation of the scale [136] further improves this instrument.

C.0.6 Other practices related to BOIs. Several papers about embodiment in VR by Martini and colleagues [23, 111, 112] have used a one-question operationalization of virtual arm ownership: "Did you feel as if the virtual right arm was your own right arm?" (the most recent study used a similar question about agency as well). In this setting, participants answer the question verbally, using a 7-point (1–7) Likert scale ("not at all" to "yes, completely/totally"), in a repeated-measures design with several within-subjects conditions. The data analysis uses a non-parametric Friedman test after which single comparisons are computed by means of Wilcoxon tests.

Recently, Roth and Latoschik [155] presented a three-dimensional 12-item questionnaire on embodiment, specifically targeted at VR. Through three studies and a validation study, the authors derived their final set of questions and constructs for measuring embodiment in VR. Items are answered on a 7-point scale, and the recommended analysis approach involves means of items and subsequent parametric testing with ANOVA. On account of its recency, the questionnaire was not employed in any studies in our survey.

In a full-body VR illusion incorporating three binary between-subjects manipulations—of perspective, movement, and touch—Slater et al. [166] collected subjective measurements of embodiment (in addition to heart-rate deceleration) from 24 male participants. After the procedure, the experimenters posed eight questions about body ownership, on various aspects of body perspective, touch, and response to a virtual threat. The responses, on an 11-point scale of 0–10 ("not at all" to "very much"), were then mapped to five bins: Very Low (0), Low (1–3), Medium (4–6), High (7–9), and Very High (10). The mapping afforded applying a proportional-odds cumulative logit model (used in addition to parametric ANOVA).