Embodiment, Presence, and Their Intersections: Teleoperation and Beyond

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Subjective experience of human control over remote, artificial, or virtual limbs has traditionally been investigated from two separate angles: presence research originates from teleoperation, aiming to capture to what extent the user feels like actually being in the remote or virtual environment. Embodiment captures to what extent a virtual or artificial limb is perceived as one's own limb. Unfortunately, the two research fields have not interacted much. This survey intends to provide a coherent overview of the literature at the intersection of these two fields to further that interaction. Two rounds of systematic research in topic-related data bases resulted in 414 related articles, 14 of which satisfy the deliberately strict inclusion criteria: 2 theoretical frameworks that highlighted intersections and 12 experimental studies that evaluated subjective measures for both concepts. Considering the surrounding literature as well, theoretical and experimental potential of embodiment and presence are discussed and suggestions to apply them in teleoperation research are derived. While increased publication activity is observed between 2016 and 2018, potentially caused by affordable virtual reality technologies, various open questions remain. To tackle them, human-in-the-loop experiments and three guiding principles for teleoperation system design (mechanical fidelity, spatial bodily awareness, and self-identification) are suggested.

CCS Concepts: • **General and reference → Surveys and overviews**; • **Human-centered computing → Collaborative interaction**; **Interaction design theory, concepts and paradigms**; *User studies*; • **Computer systems organization → Robotics**;

Additional Key Words and Phrases: Embodiment, presence, teleoperation, human-robot interaction

Portions of this survey were conducted while the author was student at Technische Universität Darmstadt.
This work received support from the German Research Foundation (DFG) through the project "Users' Body Experience and Human-Machine Interfaces in (Assistive) Robotics" under Grants No. BE 5729/3 and No. BE 5729/11.
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2573-9522/2020/05-ART28
https://doi.org/10.1145/3389210

ACM Reference format:
Nicolas Nostadt, David A. Abbink, Oliver Christ, and Philipp Beckerle. 2020. Embodiment, Presence, and Their Intersections: Teleoperation and Beyond. *Trans. Hum.-Robot Interact.* 9, 4, Article 28 (May 2020), 19 pages.
https://doi.org/10.1145/3389210

1 INTRODUCTION

Teleoperation allows humans to operate in a remote, hostile, or otherwise inaccessible environment, e.g., due to distance or scale [87]. Early teleoperators were solely mechanical and used to manipulate dangerous products over a safe distance [22]. Recent use cases comprise robotic systems in medicine, space applications, and remote maintenance as well as humanoid robots [32, 38]. During teleoperation, the user is presented with artificially rendered cues based on sensors in the remote environment, e.g., visual cues, tactile and proprioceptive cues, auditory cues, and vestibular cues, which are rendered by display devices and integrated into a virtual reality. The respective input devices allow for bilateral and anthropomorphic interaction with that reality, by mapping movement between user and robot or virtual agent. A large body of literature focuses on quantifying the quality of such teleoperation devices regarding interface transparency [17, 54, 69, 102] and human-in-the-loop task performance such as task-completion time or accuracy [17, 68]. The understanding of underlying mechanisms of sensorimotor integration in terms of optimizing performance as well as subjective user experience are crucial for the design of teleoperational systems. Subjective presence and embodiment can be measured via self-report questionnaires. This survey aims at understanding how those two related psychological concepts overlap and delineate from a theoretical perspective as well as their practical application.

Presence, which is often described as the sense of "being there" [41], describes the extent to which users feel they are actually in the remote environment, interacting with it [42, 56, 84]. Since Minsky coined the term telepresence in 1980 [65], it has been defined and refined in ambiguous ways [60]. Self-report questionnaires are mostly used to dissociate subcomponents of presence and for measuring presence in experimental studies. Objective measures include performance, physiological variables, postural responses, and social responses [16]. However, with differences in laboratory settings and the lack of a consistent definitional framework, there is yet no systematic method for the assessment of presence [16]. The working definition considered in this article is based on the notion that

> when feeling present, one's "perceptual, vestibular, proprioceptive, and autonomic nervous systems are activated in a way similar to that of real life in similar situations" [91].

This definition highlights the strong requirements of the technological factors, i.e., interface design and sensor fidelity, over personal and content dependent factors [106]. One refinement is the subconcept of self-presence, defined as "the effect of virtual environment on the perception of one's body (i.e., body schema or body image)" [15] that may influence physiological and emotional states, perceived traits, as well as identity [15]. Self-presence describes how the self is extended into virtual environments through virtual self representations [77]. The distinct subconcept of spatial presence focusses on the perceived self-location and action possibilities in a mediated or virtual environment [40, 105], which essentially constitutes as an experience or state in which individuals feel bodily or physically situated in that space [40, 105]. The meaning and importance of the noted body representations, the self, and the perceived location is further emphasized on by defining embodiment in the following.

Embodiment is the term that refers to the sense of one's own body and is intimately related to the sense of self [61]. A general framework of embodiment is provided by dissociation between body representations [61]. Neuropsychological evidence suggests that at least two internal body representations exist, i.e., body schema and body image [47]. While the body image is considered to incorporate semantic knowledge of the body regarding its attitudes and beliefs [35, 47], the body schema appears to be a subconscious, neurophysiological, and multisensory representation of the characteristics of one's body [36, 62]. It is suggested to be constructed and continuously updated through sensorimotor integration and to facilitate successful tool use [39]. Embodiment is a broad term in science as well as common parlance. For the sake of clarity, he working definition used in this survey relies on its interpretation in research of the bodily self [45, 62]:

> An artefact is embodied if it is experienced as a part of the body schema due to multisensory integration.

A striking example for the integration of external objects to the bodily self-experience is the Rubber Hand Illusion (RHI) [18]. It demonstrates how humans perceive the integration of a visible rubber hand when being exerted with simultaneous tactile stimulation on their hidden real hand. This effect of embodiment through multisensory integration shows similarities to presence regarding the fusion of visual, tactile, and proprioceptive cues to form an experience [91]. A principal components analysis of empirically obtained RHI data by Longo et al. [61] suggests three subcomponents to describe different aspects of embodiment, i.e., agency, location, and ownership. Agency is related to the feeling of being able to move and control the rubber hand, location describes if the rubber hand and one's own hand are perceived in the same place, and ownership occurs if the rubber hand is interpreted as a part of the own body [61]. Similar illusions have been induced with virtual hands [24], robot hands [3, 13, 21, 46, 82], and even with respect to other body parts or the entire body [12, 23, 27, 31, 57, 73, 93]. All those experiments substantiate the importance of multisensory integration processes and modulate embodiment and its subcomponents through specific experimental paradigms. For instance, embodiment is reduced through asynchronous multisensory feedback or influenced by deviations in robotic limb control [11].

The goal of this survey is to achieve a better understanding of how the psychological concepts of embodiment and presence intersect and how they relate to teleoperation and virtual reality system design. A systematic literature survey identifies and analyses studies that try to connect embodiment and presence in comprehensive, theoretical frameworks. While bilateral, anthropomorphic teleoperation is considered as a key example throughout the article, the derived considerations are related to other mediated scenarios, such as virtual reality applications and non-anthropomorphic interaction, which is further discussed in Section 4. Since the theories of both concepts rely on experimental data, studies evaluating subjective self-report of presence and embodiment are are also part of this review. While alternative subjective and objective measures exist, the above noted inconsistency of definitions and differences in laboratory settings [16] are hindering the comparison between those studies. The methods section is followed by a presentation of results including a narrative description of the key papers. Papers that emphasize potential relations between presence and embodiment, but were not selected due to the very strict selection criteria are considered in the discussion to give a broader overview. Moreover, potential performance and quality improvements that might be reached when considering the obtained insights in future teleoperation systems are forecasted and guiding principles for teleoperation system design are suggested.

2 METHODS

Literature was researched twice, once in early 2016 and another time in late 2018. The examined databases and the search terms are shown in Table 1. The syntax of the search terms in the right

Table 1. Search Terms and Databases

Databases	Search Terms
ACM DL, IEEE Xplore, MIT Press, Pubmed, ScienceDirect	[Embodiment OR "Body Schema"] AND [Presence OR Teleoperation]
MitPress (Presence Journal only)	Embodiment OR "Body Schema"

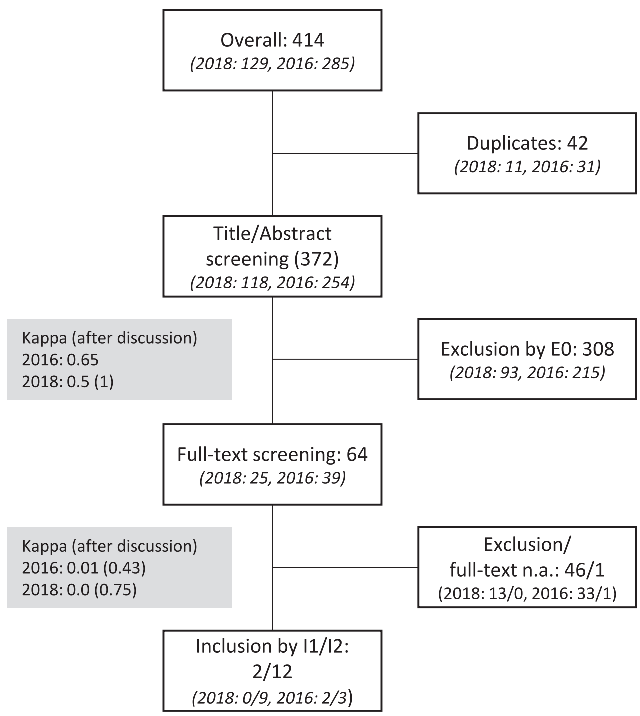

Fig. 1. Overview of the screening process including overall results and subdivided by the 2016 and 2018 search. The grey boxes indicate the obtained Cohen's Kappa values before and after (in brackets) discussion.

column is exemplary and was adjusted to the requirements of each database's search engine to be semantically identical. For the 2018 search, minor changes on the syntax were performed to adapt to the updated search engines of IEEE Xplore and ScienceDirect. Consistency of old and new search was ensured by checking the overlapping subset of papers. In the 2018 screening, all papers that were not screened in 2016 were considered.

Since both the terms presence and embodiment are defined very broadly, often used in other disciplines, or indeed in everyday language without relation to teleoperation or virtual reality technology, full-text search would deliver high numbers of irrelevant hits. Therefore, abstract search was conducted. Depending upon the database, abstract searches may have included title, keywords, and research highlights.

Four exclusion (E) and two inclusion (I) criteria were defined by all authors to judge the relevance of the papers. The screening and assessment process is shown in Figure 1. In the first step, only the abstracts were screened and non-related papers were filtered out cautiously regarding E0. In the subsequent full-text screening, the additional five criteria were considered as well (step 2). Studies were included if one or more inclusion criterion was met, but excluded as soon as any exclusion criterion was fulfilled.

> **E0**: Embodiment and/or Presence, respectively, their subcomponents, are not used in terms of psychological concepts to describe and evaluate experiences with teleoperation or VR-technology.
> **E1**: No inclusion criteria met.
> **E2**: Studies are presented that did not measure embodiment and presence at all, but only use the terms to label for instance experimental conditions, e.g., authors are referring to different embodied interfaces, robots or avatars that are said to induce different degrees of presence.
> **E3**: Conclusions about embodiment and presence are only drawn based on observable behavior, performance measures, and so on.
> **I1**: A connection between embodiment and presence, respectively, their subcomponents, is pointed out originally based on examination of theory or a comprehensive framework of embodiment and presence is proposed, e.g., body schema integration is described as related or even necessary for presence.
> **I2**: Studies are presented that measure both subjective embodiment and subjective presence, respectively, their subcomponents, with dedicated questions, subscales, or questionnaires.

Inclusion criteria I1 and I2 separately cover theoretical and experimental contributions, which prepares the structure of the subsequent survey and result presentation. E1 excludes all works that do not contain or connect the two investigated concepts at all and E2 excludes experiments using similar labels in different contexts. E3 accounts for missing assessment of the subjective presence experience. As outlined earlier, this requirement is set, since it seems currently not feasible to compare or even dissociate the two psychological concepts only by measures such as physiological variables. Despite certain redundancies with E0, the criteria E2 and E3 are more rigorous when applied to the full-texts due to the consideration of detailed content information such as the measured variables. While the strict inclusion/exclusion criteria were set to point out research focusing on relations between presence and embodiment, unselected papers that emphasize potential relations are considered in the discussion to give a broader overview.

All papers were screened by the first and fourth author separately for inclusion and exclusion. The inter-rater agreement of the screening results is assessed by calculating Cohen's Kappa [25], a concept popular in human sciences. Depending on the overall agreement in the particular steps of the screenings, papers with conflicting ratings were discussed and decisions were revised. Papers were only included if both authors agreed to include them. The goal of this approach is to ensure appropriate application of the criteria by each rater to prevent premature exclusion and inflationary inclusion. To qualify the obtained Cohen's Kappas, the comparative values from [7, 52] are considered. The screening process was designed and supervised in collaboration with the third author. The second author remained neutral until research was finished and critically reviewed the validity and results of the process.

3 RESULTS

An overview of the screening steps and results is given in Figure 1. Out of 285 papers obtained in 2016,[1] 31 are duplicates and excluded. From the remaining, 184 are excluded by both authors and 31 by one author each, which results in 39 papers being included in the second screening step.

[1]Date of final search: February 9, 2016.

Cohen's Kappa of $\kappa = 0.65$ suggests "good" [7] or "substantial" [52] inter-rater agreement. As the definition of exclusion criterion E0 suggests, the high exclusion rate in the first step is due to the fact that both embodiment and presence are terms that are often used in common language and search consequently delivers hits in all kind of non-relevant research areas. In the second step of the screening process, one of 39 papers could not be obtained and was excluded. Additionally, 15 papers were excluded upon agreement and 18 upon disagreement. The high number of papers with disagreement resulted in "poor" [7] or "slight" [52] inter-rater agreement ($\kappa = 0.0087$). While high Cohen's Kappa values were harder to achieve in the second screening due to the lower number of rated papers, this is also caused by a looser interpretation of I1 by one author. This author argued that papers like Reference [15] should be included, since they originally relate presence with body schema and body image. The authors discussed and concluded that those papers contribute too little to the research goal to be included, which is also in line with the strict selection criteria. Hence, 10 conflicting papers were rated with E1 retrospectively based on consensus, resulting in a "moderate" [7, 52] Cohen's Kappa of $\kappa = 0.43$. All papers that led to conflicts in the second screening step of the 2016 search are listed in Table 3.

In the second search in 2018,[2] 406 papers including 129 new publications, for a total number of 414, were identified. Eight of the original 285 hits were not reproducible, six of which stemming from data bases that were subject to search engine changes. Two out of those missing papers went past the first screening stage and are considered ([6, 70] in Table 3). It appears that the 2016 IEEE Xplore search engine did not differentiate between the formulation "tele-operation" with hyphen and "teleoperation" without, whereas the 2018 version does, which explains why they are missing. Out of the 129 additional papers, 11 duplicates were excluded and abstract screening via E0 led to a Cohen's Kappa of $\kappa = 0.5$, suggesting "moderate" [7, 52] agreement. In a subsequent discussion the screening authors developed consensus regarding papers with different votes to avoid premature exclusions, which yielded the inclusion of 25 papers after the abstract screening ($\kappa = 1$). As in the 2016 screening, the second step of the screening, which is prone to lower Cohen's Kappa values, yielded "poor" [7] or "slight" [52] inter-rater agreement ($\kappa = 0.00$). After discussing the conflicted papers, consensus was reached for all papers expect two, resulting in "good" [7] or "substantial" [52] inter-rater agreement ($\kappa = 0.75$). Those two papers with conflicting reviewer judgement are included in Table 3. One of those papers was theoretical, but not considered comprehensive enough to be included via I1 by the one author, similar to those in 2016. The other was experimental, but descriptions of methods and questionnaire were not sufficient for one author to agree to include it via I2.

Finally, the 14 papers listed in Table 2 are included in the main analysis. In the following subsections, the 2 theoretical papers that satisfy criteria I1 and the 12 papers that have been included mainly because of I2 are presented.

3.1 Theoretical Frameworks (I1)

Haans and Ijsselsteijn [39] propose an embodiment and presence framework in which they applied Metzinger's [64] approach to define three orders of embodiment, namely, morphology, body schema, and body image. As visualized in Figure 2, first-order embodiment is assumed to consist of morphology only, which even applies to simple Braitenberg vehicles [39]. Morphology can be extended physically, e.g., in properties like mass or form, but those extensions cannot be used proficiently as tools, since no dynamic body schema exists. The latter is what comes with second-order embodiment and allows for fluent interaction with the environment. Third-order embodiment requires a body image and "the kind of higher order consciousness that enables humans to hold a

[2]Date of final search: September 27, 2018.

Table 2. Papers Included in the Main Analysis of This Review

Study	I1	I2	Type
Haans and Ijsselsteijn [39]	X	—	Theoretical Framework
Kilteni et al. [49]	X	—	Theoretical Framework
Bourdin et al. [19]	—	X	Experimental Study
Leonardis et al. [58]	—	X	Experimental Study
Lankoski [53]	—	X	Experimental Study
Pritchard et al. [76]	—	X	Experimental Study
Steed et al. [95]	—	X	Experimental Study
Pitarello [74]	—	X	Experimental Study
Regenbrecht et al. [79]	—	X	Experimental Study
Aitamurto et al. [2]	—	X	Experimental Study
Brizzi et al. [20]	—	X	Experimental Study
Cortes et al. [26]	—	X	Experimental Study
Herz and Rauschnabel [43]	—	X	Experimental Study
Shin [88]	—	X	Experimental Study

The "X" marks the inclusion criterion (I1, I2).

Table 3. Papers Excluded Due to Conflict between Raters

Study	E0	E1	E2	E3	I1	I2	Comments
Alimardani et al. [4]	X	—	—	—	X	X	Presence not mentioned
Almeida et al. [6]	—	—	X	X	X	—	No presence measure
Arnold and Farrell [8]	X	—	—	—	X	—	No comprehensive link
Bayliss [10]	—	X	X	—	(X)	—	No comprehensive link
Biocca [15]	—	X	—	—	(X)	—	No comprehensive link
Cuddihy and Walters [29]	—	—	X	X	(X)	—	No study conducted
Evans [30]	—	—	X	—	(X)	—	No comprehensive link
Franca and Soares [33]	—	X	X	X	(X)	—	No comprehensive link
Kenderline et al. [48]	—	X	X	—	—	X	Results incomplete
Koo et al. [51]	—	—	X	—	—	X	Unclear questionnaire
Mennecke et al. [63]	—	X	X	—	(X)	—	Linked, but not originally
Mohler et al. [66]	—	—	X	—	X	—	No subjective measures, no comprehensive link
Pamungkas and Ward [70]	—	—	—	X	—	X	No presence measure
Paulos and Canny [72]	—	X	—	—	(X)	—	No comprehensive link
Paulos and Canny [71]	—	X	—	—	(X)	—	No comprehensive link
Riva et al. [80]	—	X	—	—	(X)	—	No comprehensive link
Tecchia et al. [97]	—	—	—	X	X	X	No subjective measures
Watanabe and Tachi [101]	—	—	X	X	X	X	No presence measure
Willans et al. [103]	—	X	—	—	X	—	No comprehensive link
Wölfel and Gehmann [108]	—	X	—	—	(X)	—	No comprehensive link

The "X" marks the application of exclusion (E0 to E3) or inclusion (I1, I2) criterion by at least one author. Parenthesis marks that criteria was revoked retrospectively on consensus. The comments in the last column indicate why the studies were excluded. For most of them the link between the concepts is not comprehensive enough to be considered as a framework. One framework focuses on social presence, which is out of scope of this article, but does not thoroughly link general aspects and underlying processes of the concepts in an original way. Some experimental studies were lacking subjective measures or description of results or questionnaires.

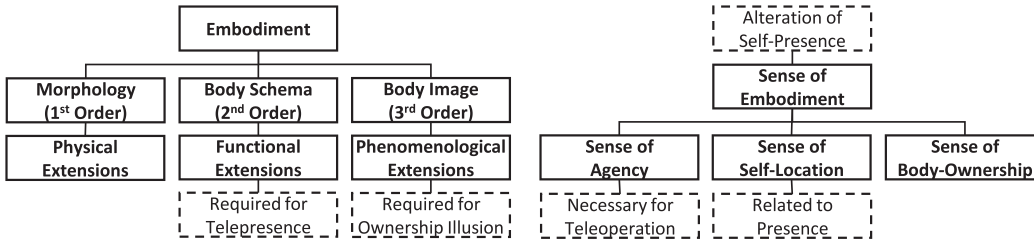

Fig. 2. The authors' depictions of the theoretical frameworks by Haans and Ijsselsteijn [39] (left) and Kilteni et al. [49] (right). Dashed blocks highlight relevant links to related psychological concepts.

concept of their own body over time" [39]. This self-consciousness allows for phenomenological extensions of the body, which can result in ownership over an artificial limb. The authors conclude that presence requires fluent interaction with the mediated environment and therefore an adapted body schema. It is argued that body image incorporation does not necessarily require interaction, which is required for presence. Nevertheless, it is suggested that presence experience might include a feeling of ownership as well, which cannot be explained by incorporation into the body schema alone [39].

Kilteni et al. [49] present a working definition for the Sense of Embodiment (SoE) to address issues of bodily experiences in virtual environments. The framework is shown in Figure 2 and briefly described in this paragraph. SoE toward a body B is defined as "the sense that emerges when B's properties are processed as if they were the properties of one's own biological body" [49]. The underlying structure of the SoE framework is based on three subcomponents: sense of self-location, sense of agency, and sense of body ownership. Comparing presence and self-location, they suggest that self-location refers to the spatial experience of being inside a body whereas "presence would be the feeling of one's self being located in a physical or virtual room, even if this does not require a body representation in the form of an avatar" [49]. It is suggested that self-location and presence address different questions of spatial representation, but it is also proposed that a more extended approach to embodiment could potentially include presence as a subcomponent. In terms of distinguishing the subcomponents of the SoE, Kilteni et al. [49] state that a remote-controlled robot as an advanced tool might be embodied based on agency while self-location and body ownership are not necessarily required for this use case. Finally, it is suggested "that self-presence based on Biocca [15] and Lee [55] is the alteration of the user's behavior or emotional state because of induced SoE toward the given virtual body representation" [49].

3.2 Experimental Studies (I2)

An overview of the identified experimental studies discussed subsequently is given in Table 4. The table contains information about the technology used as well as the considered experimental conditions to give a general idea of the studies. Further, it details the length, structure, and origin of the questionnaires used, if they were not fully customized. Finally, it is noted to what extent the respective study compares the two concepts.

In terms of technology, it is noteworthy that all studies used VR instead of real teleoperation. Most studies used head-mounted displays (HMDs) either as hardware alone or as part of their setup. Two studies [19, 26] used so-called Cave Automatic Virtual Environment (CAVE) systems consisting of four screens. Five studies used additional body or motion tracking and four used some form of haptic or tactile feedback. Arguably, the most extensive setup was used by Leonardis et al. [58]. They present a novel, multi-sensory "Embodiment Station" to study walking experiences. In addition to a HMD, vestibular feedback was provided by a hexapod platform under the seat.

Table 4. Experimental Studies

Study	Technology	Conditions	Questionnaire Items	Comparison of Concepts
Aitamurto et al. [2]	HMD	180° and 360° video vs. flat-screen	10 Presence [1], 12 Embodiment [50, 93]	not explicitly
Bourdin et al. [19]	HMD, Cave, vibrotactile feedback,full body tracking	Haptic feedback (y/n)	1 Presence, 1 Embodiment	not explicitly
Brizzi et al. [20]	HMD, inertial tracking, haptic device	various visual feedback conditions	1 Presence, 1 Embodiment	not explicitly
Cortes et al. [26]	Cave, infrared tracking	different virtual shadows	5 Presence [99], 5 Embodiment	explicitly
Herz and Rauschnabel [43]	Survey without experiment	—	3 Presence, 3 Embodiment	isolated effects and interaction
Lankoski [53]	Ordinary computer games	first-person, third-person, bird's-eye-view	9 Presence [83], 15 Embodiment	overall correlation
Leonardis et al. [58]	HMD, vestibular and proprioceptive feedback	HMD vs. all feedback channels	6 Presence [107], 7 Embodiment	not explicitly
Pittarello [74]	HMD, gesture control	virtual representation of certain body parts (y/n)	3 Presence, 11 Embodiment	not explicitly
Pritchard et al. [76]	HMD, visual-tactice feedback	realistic vs. non-realistic hand, spatial offset (y/n), visual-tactile feedback (no, synchron, asynchron)	3 Presence [85], 22 Embodiment [61, 75]	explicitly
Regenbrecht et al. [79]	HMD, camera tracking	—	8 Presence [78, 86], 6 Embodiment [9, 59]	not explicitly
Shin [88]	HMD	HMD vs. flat-screen	3 Presence [90], 3 Embodiment [89]	overall correlation
Steed et al. [95]	HMD	Avatar (y/n), Induction of body illusion (y/n), other	4 Presence [94], 4 Embodiment [18, 92]	not explicitly

The seat contains actuators near the knee that induce an illusion of knee extension, which then resulted in actual flexion of the participant's knee. One paper [43] is based on a market research survey that did not conduct its own experiment and included only 10.1% of participants who had prior experience with VR glasses and 13.3% who had never heard of such devices before. Regarding experimental conditions, most setups were restricted to change visual information and content of the virtual experience. For instance, they included the influence of virtual body representations or avatars as well as different perspectives. Contentwise, some studies had rather specific scenarios to investigate behavioral cues, such as the willingness to sing in front of an virtual audience [19].

The applied questionnaires varied from having a single question per concept [19, 20] to having a combined 24 [53] or 25 [76]. The latter two had a proportion of 62.5% and 88% embodiment questions. Most of the other studies had a similar number of items per concept. While single-item measures might work in certain cases [44], by definition they do not allow for dissociation between subcomponents of multilayered constructs. Since the questions were often partially or even fully customized it is not always clear if and how they are attributable to one of the concepts. For instance, Reference [19] contained several questions concerning the feeling of being touched, which may be related to embodiment or presence. For a potential future meta-analysis, it would be advantageous were studies to use the same minimally or non-customized questionnaires. In terms of presence, most of the studies collected their items from various well known presence questionnaires and other publications [83, 85, 86, 94, 99, 107]. This is preferable to fully customized questionnaires, however the lack of an agreement on a single standard questionnaire is obvious and still problematic in terms of meta-analysis. While applied embodiment questions may evolve from different references, they mostly can be tracked to the subcomponents of embodiment, i.e., agency, location, and ownership [61], which have been well-studied based on experiments derived from the rubber hand illusion [18].

As the last column of Table 4 indicates, two studies explicitly calculated the overall correlation between presence and embodiment for which they reported significant correlation [53] as well as a significant effect of presence on embodiment [88]. Two studies [26, 76] drew explicit conclusions about the connection between the two concepts. Cortes et al. [26] found that agency and presence were not influenced by one of the experimental conditions, i.e., the gender of a virtual shadow, whereas ownership was. This suggests that the dissociation of embodiment subcomponents may be useful in such use cases and cannot be captured by the applied presence questionnaire. In Reference [76] it was found that "agency and presence seem to depend on the same multisensory cues that have been found in the embodiment literature," which was seen in the experimental conditions such as hand form, touch, and spatial offset. Further, "presence tends to be influenced by similar cues as embodiment-location ratings" [76]. Both of these observations are in line with the theoretical framework by Kilteni et al. [49]. Most studies however, did not compare the concepts of presence and embodiment explicitly and extensively. For some of those it appears feasible to extract qualitative information out of the charts and tables given. This might suggest correlation between presence and embodiment [58, 79]. In Reference [95], data indicates that presence is generally higher rated and more stable over conditions than ownership. The contrary might be the case in Reference [19], where presence and ownership scored similarly, however with only two questions and two experimental conditions data is not sufficient to rule out dissociation.

4 DISCUSSION

Embodiment and presence both build on multisensory/sensorimotor integration and are connected via body representations and the overall self. The present survey aimed at exploring these connections and shows that only little research has been performed specifically on this topic. Besides discussing theoretical challenges, this section attempts to guide and predict potential performance and quality improvements that could be achieved when considering the corresponding insights in real teleoperation systems in the future.

Considering the existing theoretical frameworks, it becomes evident that they approach embodiment from different points of view. The framework of Haans and Ijsselsteijn is built upon body representations [39], while the framework of Kiltenti et al. upon the sensations of agency, location, and ownership [49]. Despite both frameworks being inherently different, they incorporate some similarities. According to Reference [49], teleoperation requires a sense of agency over the mediated object. Although this connection is not explicitly described in Reference [39], their second order of embodiment seems to encompass it. Specifically, second-order embodiment allows for functional extensions being integrated into the body schema. Both frameworks put body ownership beyond ordinary teleoperation and lower levels of presence. However, advanced levels of presence might in fact induce or be induced by a feeling of body ownership, if the object is becoming a phenomenological extension of the body [39]. From another perspective, self-presence [15] could be a result of the senses of agency, self-location, and body ownership [49]. Presence might be a subcomponent of embodiment, as suggested by Reference [49]. While suggesting this, the authors offer a clear distinction between location (being inside a body) and presence (being in a physical or virtual room) [49]. Overall, both frameworks suggest that different aspects, e.g., levels or subcomponents, of presence may be tied to different aspects of embodiment, which needs to be further explored and tested in experimental studies.

All 12 included experimental studies relied on virtual environments and assessed subjective presence and embodiment with custom questions or established tools, respectively, shortened or modified versions thereof. While comparison between studies is difficult and not all studies explicitly investigated the relationship between presence and embodiment, a few preliminary conclusions can be drawn based on the results. A general correlation between presence and embodiment has been reported in two studies [53, 88] and might explain results in further studies [19, 58, 79]. This would support the aforementioned notion about the potential relation between self-presence or general presence and embodiment suggested by Reference [49]. In particular, agency and location seem to be dependent on similar cues as presence [76]. This supports the claim, that agency seems to be essential in both frameworks. Ownership might not be correlated to presence [26, 95], but still may be a factor that impacts some possible aspects of teleoperation experiences, as reported in a study on avatar genders [19]. This is in line with both frameworks putting ownership beyond ordinary teleoperation and presence. While these first results seem to be supporting the theoretical frameworks, more studies are needed to verify them. In particular, the role of the location component in respect to presence has to be discussed, as suggested by Reference [49].

Despite increasing research activity in the last years, existing experimental studies appear to be too diverse as to provide a basis for meta-analysis. Additionally, this hampers attempts to validate the existing theoretical frameworks or proposing a comprehensive, combined theory of presence and embodiment. Instead, this article hints toward the possible applications of embodiment measures and tries to enable a transfer of existing knowledge to teleoperation research. This seems promising, as embodiment research appears to have a broader and more solid theoretical foundation in psychological research. For instance, recent approaches of researching body illusions follow a bottom-up manner from single, not animated body parts to robotic hands or virtual bodies [11]. Arguably, teleoperation research followed an opposite route, starting on top with the idea of the perfect illusion while developing the theoretical groundwork of the concept only over time, with still mixed results. While this is not to argue that embodiment is able to encompass all parts of presence or generally superior, there are certain aspects of teleoperation that are traditionally related to presence, which might be explained equally well in terms of embodiment. This could especially be the case for highly immersive, anthropomorphic teleoperation as in Reference [96] or telerobotics

[98], but might be expanded to other forms of mediated experience, e.g., non-anthropomorphic teleoperation [81] and the interaction of human individuals with robots teams [67].

To foster efforts toward a comprehensive framework and to support teleoperation system design, the authors propose three guiding principles in Figure 3, which are associated to underlying processes of embodiment and presence:

- mechanical fidelity
- spatial bodily awareness
- self-identification

Mechanical fidelity is suggested as an umbrella term for teleoperation system properties that determine the quality of the representation of interaction between slave and environment, which is related to the sense of agency [49] and to body schema integration [39]. With sensor fidelity, the presence questionnaire by Witmer and Singer [107] evaluates a similar technological factor that appears to determine presence. Telemanipulation is commonly characterized by the performance in physical tasks, making mechanical fidelity a main goal. This is in line with Reference [49] who argue that remote controlled robots can be embodied based on agency, while "sensory evidence for self-location and body ownership is given toward the physical body." Accordingly, many virtual reality applications might benefit from sophisticated haptic feedback despite having close-to-realistic visual or auditory presentation, which underlines the high potential of the mechanical modality. This indicates that future human-in-the-loop experiments might be designed to understand the influence of a physical body (avatar), e.g., by varying sensorimotor contingencies [11] and how the realization of agency should be engineered, e.g., with respect to shared control [14, 17, 34]. Besides measuring agency subjectively, one might also consider paradigms such as intentional binding [21]. Moreover, the technical factors of Reference [106] and other existing presence questionnaires might be used as control variables in upcoming experiments.

Spatial bodily awareness is attributed to the body schema and body image [39] as well as to spatial presence. It is necessary to move and navigate through a mediated or virtual environment and perceive action possibilities, which will influence physical task performance only implicitly. For instance, spatial presence or the sense of self-location may correlate to performance in a teleoperation setup with first-person perspective when controlling a robotic arm and having a camera view in human-like relative position to the arm. However, performance critical information can be presented in other ways, e.g., by bird's eye view, by presenting multiple camera angles, by visual force feedback, or numeric distance-to-target displays. Through such means, both presence and self-location appear less relevant and concepts like situational awareness [37] might be considered for subjective evaluation. Thinking beyond teleoperation, where some kind of remote-controlled machine/body is present, the situation is more complex when considering other forms of "body-less" presence. Being linked to self-location [49], spatial bodily awareness is tightly bound to the body itself as a fixed point of our awareness. That being said, one might still experience such a fixed point even in "body-less" presence scenarios, which could influence a very minimalistic form of embodiment relating to self-location. This accords with the conclusion of Haans and Ijsselsteijn that some kind of body schema is required to experience presence [39] and might also be tackled by future human-in-the-loop experiments juxtaposing the concepts of presence and embodiment. To this end, self-location as well as spatial presence appear to be promising metrics. While self-location is more focusing on bodily experience, spatial presence emphasizes on the relocation into another environment. To contrast both, future experiments could compare the metrics by evaluating both simultaneously juxtaposing established presence [86, 94, 107] and embodiment questionnaires [61] in experimental studies.

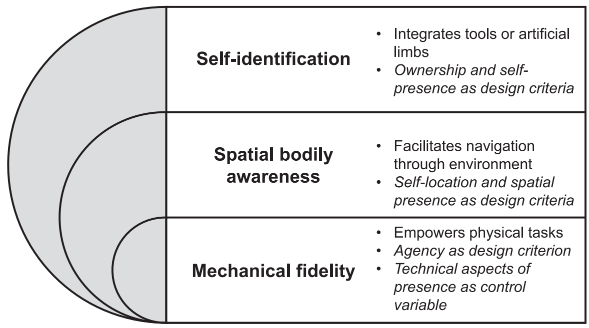

Fig. 3. Three guiding principles to consider presence and embodiment in teleoperation system design. Bullet points indicate the potential of the guiding principles (normal font) as well as which aspects of embodiment and presence could be measured and how they could be employed in the design procedure to test for achieving these principles (italic font).

Self-identification is connected to body image adaptation [39] and to body ownership [49]. Caused by an ownership illusion, it is not a necessary criterion to accomplish physical tasks, but is suggested to influence task execution in anthropomorphic settings [39]. This unclear relationship might be described best by different levels of self-presence, which influence emotional responses or identity [77]. Those are of particular interest in use cases like physical or psychological therapy [38], communication, or entertainment. However, the experience might also influence performance in physical tasks, when a user feels more involved [107] and experiences flow [28]. One study comparing two sets of teleoperated robotic arms reports that the participants who were trained on the more human-like set of arms perceived stronger body ownership for the setup and showed better motor imagery skills in a follow up session with the less human-like robot [5]. As another human-in-the-loop experiment [100] suggests, the relationship between body ownership over a fake limb and performance in a mechanical teleoperation task is not as obvious. In that study, a feeling of ownership lead the user to keep safer distances to obstacles or targets, resulting in less spatial accuracy and reduced temporal performance [100]. This finding may suggest that setups that do not induce ownership illusions are advantageous for certain applications, however more cautious behavior and hence increased involvement might be preferable for safety critical tasks due to lower error rates [100]. Another recent human-in-the-loop study [34] indicates that embodiment might even be used as a measure to assess the quality of shared control.

As indicated in Figure 3, these guiding principles for teleoperation system design may build upon each other, similar to the second and third-order embodiment in the framework of Haans and Ijsselstein [39]. Mechanical fidelity is interpreted to influence sensorimotor interaction. Spatial bodily awareness and self-identification touch higher levels of body experience. As the structure of the figure implies, mechanical fidelity is a fundamental objective of teleoperation, which can be extended by generating spatial bodily awareness and self-identification. Moreover, the three principles are related to increasing levels of embodied cognition [104]. It is possible that achieving mechanical fidelity fosters spatial bodily awareness and self-identification, but not strictly necessary. Exploring the modulating factors and interrelations of the three suggested principles is interesting and challenging from a scientific point of view and also appears promising for human-machine system design, e.g., teleoperation systems or prosthetics, where certain applications might have lower requirements than others with tighter human-robot interaction. Considering the three principles, which are based on the reviewed theoretical frameworks, could foster advancing future experimental paradigms and improve our understanding of the underlying mechanisms of human body experience.

5 CONCLUSIONS

To investigate how the psychological concepts of embodiment and presence intersect and how they can be considered to assess teleoperation and virtual reality systems, we selected 12 experimental studies and two theoretical frameworks from 414 screened papers. The topicality of the reviewed studies and the surge of experimental works since 2016 indicate the relevance and progress of the field.

The biggest theoretical intersection between embodiment and presence is found in the self-presence component. While this was initially suggested twenty years ago, the two selected theoretical frameworks offer concrete and comprehensive descriptions of this intersection, related to recent empirical research. One approach to combine the concepts is to define presence as a pure place illusion and interpret it as a part of the location component of embodiment. Note, this might not be feasible in applications that induce presence without a mediated or virtual body representation and without interactivity.

Reviewing the identified literature shows that there is not yet a consistent approach to research the intersections between presence and embodiment in experimental studies, as the definitions are not standardized and the assessment metrics are different. This hinders comparison between the included studies and further theoretical advancement. Having said that, the theoretical groundwork of embodiment seems suitable to be considered more often in assessment of anthropomorphic teleoperation devices in general.

A major contribution of this article is the introduction of three guiding principles toward embodiment and presence: mechanical fidelity, spatial bodily awareness, and self-identification. Depending on the desired type of human-robot interaction, future teleoperation systems could be designed to address all or only some of these principles. For instance, teleoperation in hazardous scenarios might benefit from providing mechanical fidelity and creating spatial bodily awareness without reaching self-identification.

Future work should include human-in-the-loop experiments to test existing teleoperators, elaborate standardized methods, and prepare novel theoretical frameworks, which might be based on the guiding principles suggested in this article to address user requirements in an application-specific way.

REFERENCES

[1] Sun Joo (Grace) Ahn, Amanda Minh Tran Le, and Jeremy Bailenson. 2013. The effect of embodied experiences on self-other merging, attitude, and helping behavior. *Media Psychol.* 16, 1 (2013), 7–38. DOI:https://doi.org/10.1080/15213269.2012.755877 arXiv:https://doi.org/10.1080/15213269.2012.755877

[2] Tanja Aitamurto, Shuo Zhou, Sukolsak Sakshuwong, Jorge Saldivar, Yasamin Sadeghi, and Amy Tran. 2018. Sense of presence, attitude change, perspective-taking and usability in first-person split-sphere 360° video. In *Proceedings of the CHI Conference on Human Factors in Computing Systems (CHI'18)*. ACM, New York, NY. DOI:https://doi.org/10.1145/3173574.3174119

[3] Maryam Alimardani, Shuichi Nishio, and Hiroshi Ishiguro. 2013. Humanlike robot hands controlled by brain activity arouse illusion of ownership in operators. *Sci. Rep.* 3 (2013), 2396. DOI:https://doi.org/10.1038/srep02396

[4] Maryam Alimardani, Shuichi Nishio, and Hiroshi Ishiguro. 2014. Effect of biased feedback on motor imagery learning in BCI-teleoperation system. *Front. Syst. Neurosci.* 8 (2014), 52. DOI:https://doi.org/10.3389/fnsys.2014.00052

[5] Maryam Alimardani, Shuichi Nishio, and Hiroshi Ishiguro. 2016. The importance of visual feedback design in BCIs; from embodiment to motor imagery learning. *PloS One* 11, 9 (2016), e0161945. DOI:https://doi.org/10.1371/journal.pone.0161945

[6] Luis Almeida, Bruno Patrao, Paulo Menezes, and Jorge Dias. 2014. Be the robot: Human embodiment in teleoperation driving tasks. In *Proceedings of the 23rd IEEE International Symposium on Robot and Human Interactive Communication (ROMAN'14)*. 477–482. DOI:https://doi.org/10.1109/ROMAN.2014.6926298

[7] Douglas G. Altman. 1990. *Practical Statistics for Medical Research.* Chapman & Hall/CRC, Boca Raton, FL.

[8] Paul Arnold and Martin J. Farrell. 2003. Embodiment and spatial behavior in virtual environments: Comments on Durlach et al. (2000). *Presence: Teleoperat. Virtual Environ.* 12, 6 (2003), 658–662. DOI:https://doi.org/10.1162/105474603322955941

[9] Domna Banakou, Raphaela Groten, and Mel Slater. 2013. Illusory ownership of a virtual child body causes overestimation of object sizes and implicit attitude changes. *Proc. natl. Acad. Sci. U.S.A.* 110, 31 (2013), 12846–12851. DOI: https://doi.org/10.1073/pnas.1306779110 arXiv:https://www.pnas.org/content/110/31/12846.full.pdf

[10] Peter Bayliss. 2007. Beings in the game-world: Characters, avatars, and players. In *Proceedings of the 4th Australasian Conference on Interactive Entertainment.* 4.

[11] Philipp Beckerle, Claudio Castellini, and Bigna Lenggenhager. 2018. Robotic interfaces for cognitive psychology and embodiment research: A research roadmap. *Wiley Interdisc. Rev.: Cogn. Sci.* 10(2) (2018), e1486.

[12] Philipp Beckerle, Oliver Christ, Janis Wojtusch, Jochen Schuy, Kerstin Wolff, Stephan Rinderknecht, Joachim Vogt, and Oskar von Stryk. 2012. Design and control of a robot for the assessment of psychological factors in prosthetic development. In *Proceedings of the IEEE International Conference on Systems, Man, and Cybernetics.*

[13] Philipp Beckerle, Albert De Beir, Tim Schürmann, and Emilie A. Caspar. 2016. Human body schema exploration: Analyzing design requirements of robotic hand and leg illusions. In *Proceedings of the IEEE International Symposium on Robot and Human Interactive Communication.*

[14] Philipp Beckerle, Gionata Salvietti, Ramazan Unal, Domenico Prattichizzo, Simone Rossi, Claudio Castellini, Sandra Hirche, Satoshi Endo, Heni Ben Amor, Matei Ciocarlie, Fulvio Mastrogiovanni, Brenna D. Argall, and Matteo Bianchi. 2017. A human-robot interaction perspective on assistive and rehabilitation robotics. *Front. Neurorobot.* 11, 24 (2017).

[15] Frank Biocca. 1997. *The Cyborg's Dilemma: Progressive Embodiment in Virtual Environments.* Vol. 3. IEEE Computer Society Press, Los Alamitos, CA. DOI: https://doi.org/10.1111/j.1083-6101.1997.tb00070.x

[16] Jana Birkenbusch and Oliver Christ. 2013. Concepts behind serious games and computer-based trainings in health care. In *Serious Games and Virtual Worlds in Education, Professional Development, and Healthcare*, Klaus Bredl and Wolfgang Bösche (Eds.). IGI Global, 1–14. DOI: https://doi.org/10.4018/978-1-4666-3673-6.ch001

[17] Henri Boessenkool, David A. Abbink, Cock J. M. Heemskerk, Frans C. T. van der Helm, and Jeroen G. W. Wildenbeest. 2013. A task-specific analysis of the benefit of haptic shared control during telemanipulation. *IEEE Trans. Haptics* 6, 1 (2013), 2–12. DOI: https://doi.org/10.1109/TOH.2012.22

[18] Matthew. Botvinick and Jonathan Cohen. 1998. Rubber hands "feel" touch that eyes see. *Nature* 391, 6669 (1998), 756. DOI: https://doi.org/10.1038/35784

[19] Pierre Bourdin, Josep Maria Tomàs Sanahuja, Carlota Crusafon Moya, Patrick Haggard, and Mel Slater. 2013. *Persuading People in a Remote Destination to Sing by Beaming There: Proceedings: Nanyang Technological University, Singapore, October 6-9, 2013.* Association for Computing Machinery, New York, New York. DOI: https://doi.org/10.1145/2503713.2503724

[20] Filippo Brizzi, Lorenzo Peppoloni, Alessandro Graziano, Erola Di Stefano, Carlo A. Avizzano, and Emanuele Ruffaldi. 2018. Effects of augmented reality on the performance of teleoperated industrial assembly tasks in a robotic embodiment. *IEEE Trans. Hum.-Mach. Syst.* 48, 2 (April 2018), 197–206. DOI: https://doi.org/10.1109/THMS.2017.2782490

[21] Emilie A. Caspar, Albert de Beir, Pedro A. Magalhaes De Saldanha Da Gama, Florence Yernaux, Axel Cleeremans, and Bram Vanderborght. 2015. New frontiers in the rubber hand experiment: When a robotic hand becomes one's own. *Behav. Res. Methods* 47, 3 (2015), 744–755. DOI: https://doi.org/10.3758/s13428-014-0498-3

[22] Ryad Chellali. 2010. Tele-operation and human robots interactions. In *Remote and Telerobotics*, Nicolas Mollet (Ed.). InTech, 91–111. DOI: https://doi.org/10.5772/9248

[23] Oliver Christ, Anna Elger, Katharina Schneider, Philipp Beckerle, Joachim Vogt, and Stephan Rinderknecht. 2013. Identification of haptic paths with different resolution and their effect on body scheme illusion in lower limbs. *Technical. Assist. Rehab.* (2013).

[24] Oliver Christ and Miriam Reiner. 2014. Perspectives and possible applications of the rubber hand and virtual hand illusion in non-invasive rehabilitation: Technological improvements and their consequences. *Neurosci. Biobehav. Rev.* 44 (2014), 33–44. DOI: https://doi.org/10.1016/j.neubiorev.2014.02.013

[25] Jacob Cohen. 1960. A coefficient of agreement for nominal scales. *Educat. Psychol. Measure.* 20, 1 (1960), 37–46. DOI: https://doi.org/10.1177/001316446002000104 arXiv:https://doi.org/10.1177/001316446002000104

[26] Guillaume Cortes, Ferran Argelaguet, Eric Marchand, and Anatole Lécuyer. 2018. Virtual shadows for real humans in a CAVE: Influence on virtual embodiment and 3D interaction. In *Proceedings of the 15th ACM Symposium on Applied Perception (SAP'18).* ACM, New York, NY. DOI: https://doi.org/10.1145/3225153.3225165

[27] Simona Crea, Marco DeAlonzo, Nicola Vitiello, and Christian Cipriani. 2015. The rubber foot illusion. *J. NeuroEng. Rehab.* 12:77 (2015).

[28] Mihaly Csikszentmihalyi. 2014. *Flow and the Foundations of Positive Psychology.* Springer Netherlands, Dordrecht. DOI: https://doi.org/10.1007/978-94-017-9088-8

[29] Elisabeth Cuddihy and Deborah Walters. 2000. Embodied interaction in social virtual environments. In *Proceedings of the 3rd International Conference*, Elizabeth Churchill and Martin Reddy (Eds.). 181–188. DOI: https://doi.org/10.1145/351006.351039

[30] Simon Evans. 2012. Virtual selves, real relationships: An exploration of the context and role for social interactions in the emergence of self in virtual environments. *Integr. Psychol. Behav. Sci.* 46, 4 (2012), 512–528. DOI: https://doi.org/10.1007/s12124-012-9215-x

[31] Mareike Flogel, Karl Theodor Kalveram, Oliver Christ, and Joachim Vogt. 2016. Application of the rubber hand illusion paradigm: Comparison between upper and lower limbs. *Psychol. Res.* 80, 2 (2016), 298–306. DOI: https://doi.org/10.1007/s00426-015-0650-4

[32] Terrence Fong, Jennifer Rochlis Zumbado, Nancy Currie, Andrew Mishkin, and David L Akin. 2013. Space telerobotics: Unique challenges to human-robot collaboration in space. *Rev. Hum. Factors Ergonom.* 9, 1 (2013), 6–56. DOI: https://doi.org/10.1177/1557234X13510679

[33] Ana Carol Pontes de França and Marcelo Márcio Soares. 2015. Dialogical self on virtual reality systems: Presence and embodiment in human situated interaction. *Procedia Manufactur.* 3 (2015), 6444–6450. DOI: https://doi.org/10.1016/j.promfg.2015.07.923

[34] Jakob Fröhner, Philipp Beckerle, Satoshi Endo, and Sandra Hirche. 2019. An embodiment paradigm in evaluation of human-in-the-loop control. *IFAC-PapersOnLine* (2019).

[35] Shaun Gallagher. 2005. Dynamic models of body schematic processes. In *Body Image and Body Schema*, Helena de Preester and Veroniek Knockaert (Eds.). Vol. 62. John Benjamins Publishing Company, Amsterdam, 233–250.

[36] Shaun Gallagher and Jonathan Cole. 1995. Body schema and body image in a deafferented subject. *J. Mind Behav.* 16 (1995), 369–390.

[37] Yiannis Gatsoulis, Gurvinder S. Virk, and Abbas A. Dehghani-Sanij. 2010. On the measurement of situation awareness for effective human-robot interaction in teleoperated systems. *J. Cogn. Eng. Decision Mak.* 4, 1 (2010), 69–98. DOI: https://doi.org/10.1518/155534310X495591

[38] Michael A. Goodrich, Jacob W. Crandall, and Emilia Barakova. 2013. Teleoperation and beyond for assistive humanoid robots. *Rev. Human Factors Ergonom.* 9, 1 (2013), 175–226. DOI: https://doi.org/10.1177/1557234X13502463

[39] Antal Haans and Wijnand A. Ijsselsteijn. 2012. Embodiment and telepresence: Toward a comprehensive theoretical framework. *Interact. Comput.* 24, 4 (2012), 211–218. DOI: https://doi.org/10.1016/j.intcom.2012.04.010

[40] Tilo Hartmann, Werner Wirth, Peter Vorderer, Christoph Klimmt, Holger Schramm, and Saskia Böcking. 2015. *Spatial Presence Theory: State of the Art and Challenges Ahead.* Springer International Publishing, Cham, 115–135. DOI: https://doi.org/10.1007/978-3-319-10190-3_7

[41] Carrie Heeter. 1992. Being there: The subjective experience of presence. *Presence: Teleoperat. Virtual Environ.* 1, 2 (1992), 262–271. DOI: https://doi.org/10.1162/pres.1992.1.2.262

[42] Claudia Hendrix and Woodrow Barfield. 1996. Presence within virtual environments as a function of visual display parameters. *Presence: Teleoperat. Virtual Environ.* 5, 3 (1996), 274–289. DOI: https://doi.org/10.1162/pres.1996.5.3.274

[43] Marc Herz and Philipp A. Rauschnabel. 2019. Understanding the diffusion of virtual reality glasses: The role of media, fashion and technology. *Technol. Forecast. Soc. Change* 138 (2019), 228–242. DOI: https://doi.org/10.1016/j.techfore.2018.09.008

[44] Bettina B. Hoeppner, John F. Kelly, Karen A. Urbanoski, and Valerie Slaymaker. 2011. Comparative utility of a single-item versus multiple-item measure of self-efficacy in predicting relapse among young adults. *J. Substance Abuse Treat.* 41, 3 (October 2011), 305–312. DOI: https://doi.org/10.1016/j.jsat.2011.04.005

[45] Nicholas P. Holmes and Charles Spence. 2004. The body schema and the multisensory representation(s) of peripersonal space. *Cogn. Process.* 5 (2) (2004), 94–105.

[46] Mohamad Arif Fahmi Ismail and Sotaro Shimada. 2016. "Robot" hand illusion under delayed visual feedback: Relationship between the senses of ownership and agency. *PloS One* 11, 7 (2016), e0159619. DOI: https://doi.org/10.1371/journal.pone.0159619

[47] Marjolein P. M. Kammers, Ineke J. M. van der Ham, and H. Chris Dijkerman. 2006. Dissociating body representations in healthy individuals: Differential effects of a kinaesthetic illusion on perception and action. *Neuropsychologia* 44, 12 (2006), 2430–2436. DOI: https://doi.org/10.1016/j.neuropsychologia.2006.04.009

[48] Sarah Kenderdine, Jeffrey Shaw, and Anita Kocsis. 2009. Dramaturgies of PLACE: Evaluation, embodiment and performance in PLACE-Hampi. In *Proceedings of the International Conference on Advances in Computer Enterntainment Technology.* 249–256.

[49] Konstantina Kilteni, Raphaela Groten, and Mel Slater. 2012. The sense of embodiment in virtual reality. *Presence: Teleoper. Virtual Environ.* 21, 4 (2012), 373–387. DOI: https://doi.org/10.1162/PRES.a.00124

[50] Elena Kokkinara, Mel Slater, and Joan López-Moliner. 2015. The effects of visuomotor calibration to the perceived space and body, through embodiment in immersive virtual reality. *ACM Trans. Appl. Percept.* 13, 1 (Oct. 2015). DOI: https://doi.org/10.1145/2818998

[51] Kyo-in Koo, Dae Kwon Park, Yoon Seok Youm, Sung Do Cho, and Chang Ho Hwang. 2018. Enhanced reality showing long-lasting analgesia after total knee arthroplasty: Prospective, randomized clinical trial. *Sci. Rep.* 8, 1 (2018), 2343. DOI: https://doi.org/10.1038/s41598-018-20260-0

[52] J. Richard Landis and Gary G. Koch. 1977. The measurement of observer agreement for categorical data. *Biometrics* 33, 1 (1977), 159. DOI: https://doi.org/10.2307/2529310
[53] Petri Lankoski. 2016. Embodiment in character-based videogames. In *Proceedings of the 20th International Academic Mindtrek Conference (AcademicMindtrek'16)*. ACM, New York, NY, 358–365. DOI: https://doi.org/10.1145/2994310.2994320
[54] Dale A. Lawrence. 1993. Stability and transparency in bilateral teleoperation. *IEEE Trans. Robot. Autom.* 9, 5 (1993), 624–637. DOI: https://doi.org/10.1109/70.258054
[55] Kwan Min Lee. 2004. Presence, explicated. *Commun. Theory* 14, 1 (2004), 27–50. DOI: https://doi.org/10.1111/j.1468-2885.2004.tb00302.x
[56] Sangyoon Lee and Gerard Jounghyun Kim. 2008. Effects of haptic feedback, stereoscopy, and image resolution on performance and presence in remote navigation. *Int. J. Hum.-Comput. Studies* 66, 10 (2008), 701–717. DOI: https://doi.org/10.1016/j.ijhcs.2008.05.001
[57] Bigna Lenggenhager, Tej Tadi, Thomas Metzinger, and Olaf Blanke. 2007. Video ergo sum: Manipulating bodily self-consciousness. *Science* 317, 5841 (2007), 1096–1099. DOI: https://doi.org/10.1126/science.1143439
[58] Daniele Leonardis, Antonio Frisoli, Michele Barsotti, Marcello Carrozzino, and Massimo Bergamasco. 2014. Multi-sensory feedback can enhance embodiment within an enriched virtual walking scenario. *Presence: Teleoperat. Virtual Environ.* 23, 3 (2014), 253–266. DOI: https://doi.org/10.1162/PRES.a.00190
[59] Joan Llobera, Maria Victoria Sanchez-Vives, and Mel Slater. 2013. The relationship between virtual body ownership and temperature sensitivity. *J. Roy. Soc. Interface* 10, 85 (2013), 20130300. DOI: https://doi.org/10.1098/rsif.2013.0300 arXiv:https://royalsocietypublishing.org/doi/pdf/10.1098/rsif.2013.0300
[60] Matthew Lombard and Matthew T. Jones. 2015. Defining presence. In *Immersed in Media*, Matthew Lombard, Frank Biocca, Jonathan Freeman, Wijnand IJsselsteijn, and Rachel J. Schaevitz (Eds.). Springer International Publishing, Cham, 13–34. DOI: https://doi.org/10.1007/978-3-319-10190-3.2
[61] Matthew R. Longo, Friederike Schuur, Marjolein P. M. Kammers, Manos Tsakiris, and Patrick Haggard. 2008. What is embodiment? A psychometric approach. *Cognition* 107, 3 (2008), 978–998. DOI: https://doi.org/10.1016/j.cognition.2007.12.004
[62] Agnes Mayer, Karen Kudar, Karoly Bretz, and Jozsef Tihanyi. 2008. Body schema and body awareness of amputees. *Prosthetics and Orthotics International* 32 (3) (2008), 363–382.
[63] Brian E. Mennecke, Janea L. Triplett, Lesya M. Hassall, and Zayira Jordan Conde. 2010. Embodied social presence theory. In *Proceedings of the 43rd Hawaii International Conference on System Sciences*. 1–10. DOI: https://doi.org/10.1109/HICSS.2010.179
[64] Thomas Metzinger. 2006. Reply to Gallagher: Different conceptions of embodiment. *Psyche* 12, 4 (2006).
[65] Marvin Minsky. 1980. Telepresence. *Omni* (1980), 45–51.
[66] Betty J. Mohler, Sarah H. Creem-Regehr, William B. Thompson, and Heinrich H. Bülthoff. 2010. The effect of viewing a self-avatar on distance judgments in an HMD-based virtual environment. *Presence: Teleoperat. Virtual Environ.* 19, 3 (2010), 230–242. DOI: https://doi.org/10.1162/pres.19.3.230
[67] Selma Musić and Sandra Hirche. 2017. Control sharing in human-robot team interaction. *Annu. Rev. Control* 44 (2017), 342–354.
[68] Claudio Pacchierotti, Leonardo Meli, Francesco Chinello, Monica Malvezzi, and Domenico Prattichizzo. 2015. Cutaneous haptic feedback to ensure the stability of robotic teleoperation systems. *Int. J. Robot. Res.* 34, 14 (2015), 1773–1787. DOI: https://doi.org/10.1177/0278364915603135
[69] Claudio Pacchierotti, Asad Tirmizi, and Domenico Prattichizzo. 2014. Improving transparency in teleoperation by means of cutaneous tactile force feedback. *ACM Trans. Appl. Percept.* 11, 1 (2014), 1–16. DOI: https://doi.org/10.1145/2604969
[70] Daniel S. Pamungkas and Koren Ward. 2014. Electro-tactile feedback system for achieving embodiment in a tele-operated robot. In *Proceedings of the 13th International Conference on Control Automation Robotics & Vision (ICARCV'14)*. 1706–1711. DOI: https://doi.org/10.1109/ICARCV.2014.7064573
[71] Eric Paulos and John Canny. 16-20 May 1998. Designing personal tele-embodiment. In *Proceedings of the IEEE International Conference on Robotics and Automation*. 3173–3178. DOI: https://doi.org/10.1109/ROBOT.1998.680913
[72] Eric Paulos and John Canny. 1997. Ubiquitous tele-embodiment: Applications and implications. *International J. Hum.-Comput. Studies* 46, 6 (1997), 861–877. DOI: https://doi.org/10.1006/ijhc.1996.0120
[73] Valeria I. Petkova and H. Henrik Ehrsson. 2008. If I were you: Perceptual illusion of body swapping. *PloS One* 3, 12 (2008), e3832. DOI: https://doi.org/10.1371/journal.pone.0003832
[74] Fabio Pittarello. 2017. Experimenting with PlayVR, a virtual reality experience for the world of theater. In *Proceedings of the 12th Biannual Conference on Italian SIGCHI Chapter (CHItaly'17)*. ACM, New York, NY. DOI: https://doi.org/10.1145/3125571.3125596

[75] Vince Polito, Amanda J. Barnier, and Erik Z. Woody. 2013. Developing the sense of agency rating scale (SOARS): An empirical measure of agency disruption in hypnosis. *Conscious. Cogn.* 22, 3 (2013), 684–696. DOI: https://doi.org/10.1016/j.concog.2013.04.003

[76] Stephen C. Pritchard, Regine Zopf, Vince Polito, David M. Kaplan, and Mark A. Williams. 2016. Non-hierarchical influence of visual form, touch, and position cues on embodiment, agency, and presence in virtual reality. *Front. Psychol.* 7 (2016), 1649. DOI: https://doi.org/10.3389/fpsyg.2016.01649

[77] Rabindra Ayyan Ratan and Béatrice Hasler. 2009. Self-presence standardized: Introducing the self-presence questionnaire (SPQ). In *Proceedings of the 12th Annual International Workshop on Presence*.

[78] Holger Regenbrecht, Cristina Botella, Rosa Baños, and Thomas Schubert. 2017. Mixed reality experience questionnaire (MREQ) -Reference. *Info. Sci. Discuss. Papers Ser. No. 2017/01* (2017). Retrieved from http://hdl.handle.net/10523/7151.

[79] Holger Regenbrecht, Katrin Meng, Arne Reepen, Stephan Beck, and Tobias Langlotz. 2017. Mixed voxel reality: Presence and embodiment in low fidelity, visually coherent, mixed reality environments. In *Proceedings of the IEEE International Symposium on Mixed and Augmented Reality (ISMAR'17)*. 90–99.

[80] Giuseppe Riva, Andrea Gaggioli, and Fabrizia Mantovani. 2008. Are robots present? From motor simulation to being there. *Cyberpsychol. Behavior: Impact Internet, Multimed. Virtual Reality Behav. Soc.* 11, 6 (2008), 631–636. DOI: https://doi.org/10.1089/cpb.2007.0265

[81] Carine Rognon, Stefano Mintchev, Fabio Dell'Agnola, Alexandre Cherpillod, David Atienza, and Dario Floreano. 2018. FlyJacket: An upper body soft exoskeleton for immersive drone control. *IEEE Robot. Autom. Lett.* 3, 3 (July 2018), 2362–2369. DOI: https://doi.org/10.1109/LRA.2018.2810955

[82] Daniele Romano, Elisa Caffa, Alejandro Hernandez-Arieta, Peter Brugger, and Angelo Maravita. 2015. The robot hand illusion: Inducing proprioceptive drift through visuo-motor congruency. *Neuropsychologia* 70 (2015), 414–420. DOI: https://doi.org/10.1016/j.neuropsychologia.2014.10.033

[83] Richard M. Ryan, C. Scott Rigby, and Andrew Przybylski. 2006. The motivational pull of video games: A self-determination theory approach. *Motivat. Emot.* 30, 4 (Dec. 2006), 344–360. DOI: https://doi.org/10.1007/s11031-006-9051-8

[84] Eva-Lotta Sallnäs, Kirsten Rassmus-Gröhn, and Calle Sjöström. 2000. Supporting presence in collaborative environments by haptic force feedback. *ACM Trans. Comput.-Hum. Interact.* 7, 4 (2000), 461–476. DOI: https://doi.org/10.1145/365058.365086

[85] Maria V. Sanchez-Vives and Mel Slater. 2005. From presence to consciousness through virtual reality. *Nature Rev. Neurosci.* 6, 4 (2005), 332–339. DOI: https://doi.org/10.1038/nrn1651

[86] Thomas Schubert, Frank Friedmann, and Holger Regenbrecht. 2001. The experience of presence: Factor analytic insights. *Presence: Teleoperat. Virtual Environ.* 10, 3 (2001), 266–281. DOI: https://doi.org/10.1162/105474601300343603

[87] Thomas B. Sheridan. 1995. Teleoperation, telerobotics, and telepresence: A progress report. *Control Eng. Pract.* 3, 2 (1995), 205–214. DOI: https://doi.org/10.1016/0967-0661(94)00078-U

[88] Donghee Shin. 2018. Empathy and embodied experience in virtual environment: To what extent can virtual reality stimulate empathy and embodied experience?*Comput. Hum. Behav.* 78 (2018), 64–73. DOI: https://doi.org/10.1016/j.chb.2017.09.012

[89] Donghee Shin and Frank Biocca. 2018. Exploring immersive experience in journalism. *New Media Soc.* 20, 8 (2018), 2800–2823. DOI: https://doi.org/10.1177/1461444817733133 arXiv:https://doi.org/10.1177/1461444817733133

[90] Donghee Shin. 2013. Defining sociability and social presence in social TV. *Comput. Hum. Behav.* 29, 3 (2013), 939–947. DOI: https://doi.org/10.1016/j.chb.2012.07.006

[91] Mel Slater. 2003. A note on presence terminology. *Presence Connect* 3, 3 (2003), 1–5.

[92] Mel Slater, Daniel Perez-Marcos, H. Henrik Ehrsson, and Maria V. Sanchez-Vives. 2008. Towards a digital body: The virtual arm illusion. *Front. Human Neurosci.* 2 (2008), 6. DOI: https://doi.org/10.3389/neuro.09.006.2008

[93] Mel Slater, Bernhard Spanlang, Maria V. Sanchez-Vives, and Olaf Blanke. 2010. First person experience of body transfer in virtual reality. *PloS One* 5, 5 (2010), e10564. DOI: https://doi.org/10.1371/journal.pone.0010564

[94] Mel Slater, Martin Usoh, and Anthony Steed. 1994. Depth of presence in virtual environments. *Presence: Teleoperat. Virtual Environ.* 3, 2 (1994), 130–144. DOI: https://doi.org/10.1162/pres.1994.3.2.130

[95] Anthony Steed, Sebastian Frlston, Maria Murcia Lopez, Jason Drummond, Ye Pan, and David Swapp. [n.d.]. An "in the wild" experiment on presence and embodiment using consumer virtual reality equipment. *IEEE Trans. Visual. Comput. Graph.* 22, 4 [n.d.], 1406–1414. DOI: https://doi.org/10.1109/TVCG.2016.2518135

[96] Susumu Tachi. 2015. Telexistence. In *Virtual Realities*, Guido Brunnett, Sabine Coquillart, Robert van Liere, Gregory Welch, and Libor Vása (Eds.). Lecture Notes in Computer Science, Vol. 8844. Springer International Publishing, Cham, 229–259. DOI: https://doi.org/10.1007/978-3-319-17043-5_13

[97] Franco Tecchia, Giovanni Avveduto, Marcello Carrozzino, Raffaelo Brondi, Massimo Bergamasco, and Leila Alem. 2014. [Poster] Interacting with your own hands in a fully immersive MR system. In *Proceedings of the IEEE*

International Symposium on Mixed and Augmented Reality (ISMAR'14). 313–314. DOI: https://doi.org/10.1109/ISMAR.2014.6948466

[98] Alexander Toet, Irene A. Kuling, Bouke N. Krom, and Jan B. F. van Erp. 2020. Toward enhanced teleoperation through embodiment. *Front. Robot. AI* 7 (2020), 14. DOI: https://doi.org/10.3389/frobt.2020.00014

[99] Martin Usoh, Ernest Catena, Sima Arman, and Mel Slater. 2000. Using presence questionnaires in reality. *Presence: Teleoperat. Virtual Environ.* 9, 5 (2000), 497–503. DOI: https://doi.org/10.1162/105474600566989

[100] Lloyd V. Wajon, M. M. van Paassen, David A. Abbink, Erwin Boer, and Max Mulder. 2017. Does the projected-hand-illusion help in teleoperation? In *Proceedings of the 19th International Symposium on Aviation Psychology*.

[101] Kouichi Watanabe and Susumu Tachi. 2011. Verification of out of body sensations, attribution and localization by interaction with oneself. In *Proceedings of the IEEE International Symposium on VR Innovation (ISVRI'11)*. 111–118. DOI: https://doi.org/10.1109/ISVRI.2011.5759611

[102] Jeroen G. W. Wildenbeest, David A. Abbink, Cock J. M. Heemskerk, Frans C. T. Van Der Helm, and Henri Boessenkool. 2013. The impact of haptic feedback quality on the performance of teleoperated assembly tasks. *IEEE Trans. Haptics* 6, 2 (2013), 242–252. DOI: https://doi.org/10.1109/TOH.2012.19

[103] Tom Willans, Sue Rivers, and Ekaterina Prasolova-Farland. 2016. Chapter 10—Enactive emotion and presence in virtual environments. In *Emotions, Technology, and Behaviors*, Sharon Y. Tettegah and Dorothy L. Espelage (Eds.). Academic Press, San Diego, 181–210. DOI: https://doi.org/10.1016/B978-0-12-801873-6.00010-8

[104] Margaret Wilson. 2002. Six views of embodied cognition. *Psychonom. Bull. Rev.* 9, 4 (2002), 625–636. https://link.springer.com/content/pdf/10.3758/BF03196322.pdf.

[105] Werner Wirth, Tilo Hartmann, Saskia Backing, Peter Vorderer, Christoph Klimmt, Holger Schramm, Timo Saari, Jari Laarni, Niklas Ravaja, Feliz Ribeiro Gouveia, Frank Biocca, Ana Sacau, Lutz Jancke, Thomas Baumgartner, and Petra Jancke. 2007. A process model of the formation of spatial presence experiences. *Media Psychology* 9, 3 (2007), 493–525. DOI: https://doi.org/10.1080/15213260701283079 arXiv:https://doi.org/10.1080/15213260701283079

[106] Bob G. Witmer, Christian J. Jerome, and Michael J. Singer. 2005. The factor structure of the presence questionnaire. *Presence: Teleoperat. Virtual Environ.* 14, 3 (2005), 298–312. DOI: https://doi.org/10.1162/105474605323384654 arXiv:https://doi.org/10.1162/105474605323384654

[107] Bob G. Witmer and Michael J. Singer. 1998. Measuring presence in virtual environments: A presence questionnaire. *Presence: Teleoperat. Virtual Environ.* 7, 3 (1998), 225–240. DOI: https://doi.org/10.1162/105474698565686

[108] Matthias Wölfel and Ulrich Gehmann. 2015. To be there, or not to be there, that is the question. In *Proceedings of the International Conference on Cyberworlds (CW'15)*. 251–258. DOI: https://doi.org/10.1109/CW.2015.12

Received May 2018; revised March 2020; accepted March 2020