博士論文

Effect of Self-Avatar Anthropomorphism on Perception and Behavior in Virtual Environments

（バーチャル空間の自己アバタの抽象度が
知覚・行動に与える影響）

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Effect of Self-Avatar Anthropomorphism on Perception and Behavior in Virtual Environments

by

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Abstract

Virtual reality (VR) technology enables the creation of self-avatars, the digital representations of a user, in virtual environments (VEs). The illusion that the avatar is one's own body is commonly referred to as the "Body Ownership Illusion (BOI)" and the associated sense is called the "Sense of Body Ownership (SoBO)." Although current VR applications use various appearances of self-avatars, anthropomorphism (i.e., visual human resemblance) is a key factor of the BOI; the closer the appearance of the avatar and human bodies, the stronger the BOI. Despite a considerable body of literature on the effects of self-avatar anthropomorphism on the SoBO, little is known about its effects on users' experiences—how they perceive and behave—in VEs. Therefore, the thesis investigates the effect of self-avatar anthropomorphism on users' perception and behavior in VEs with respect to the following three aspects: how to process sensory information from one's own actual body (i.e., visuo-proprioceptive integration) and from the environment (i.e., object size perception), and how to respond to the received information (i.e., behavior). The results provide compelling evidence that anthropomorphism influences the user experiences in VEs, in accord with the hypothesis that the human-like self-avatars not only strengthen the BOI but also alter one's perception and behavior in VEs such that they rely more on the virtual body representation than the physical body representation. At the same time, the exploration of these aspects also addresses three distinct issues faced by VR applications by providing a perspective in which the self-body representations play a common and important role in all these issues. Specifically, the thesis addresses the spatial limitation in hand interaction techniques that exploit visual dominance over proprioception, the distortion in the spatial perception in VEs, and the issue that users behave unrealistically in VEs such that they walk through the virtual boundaries, which they are not supposed to do. Elucidating the effect of self-avatar anthropomorphism contributes to proposing a novel solution, namely, navigating users' perceptions and behavior in VEs by controlling the appearances of the avatar.

List of Publications

This dissertation includes first-authored peer-reviewed material that has been or will be published as follows:

Chapter 3:

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Chapter 4:

Nami Ogawa, Takuji Narumi, and Michitaka Hirose (2019). Virtual Hand Realism Affects Object Size Perception in Body-Based Scaling. *In Proceedings of 2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR'19)*. pp.519–528. IEEE.
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Chapter 5:

Nami Ogawa, Takuji Narumi, Hideaki Kuzuoka, and Michitaka Hirose (2020). Do You Feel Like Passing Through Walls?: Effect of Self-Avatar Appearance on Facilitating Realistic Behavior in Virtual Environments. *In Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (CHI '20)*. ACM. (to appear)
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[2] IEEE. *IEEE Copyright Policy.* 31 Mar. 2010: https://www.ieee.org/publications/rights/copyright-policy.html

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List of Abbreviations

1PP First Person Perspective.

BOI Body Ownership Illusion.

CG Computer Graphics.

HMD Head Mounted Display.

RE real environment.

RHI Rubber Hand Illusion.

SCR Skin Conductance Response.

SoA Sense of Agency.

SoBO Sense of Body Ownership.

SoE Sense of Embodiment.

VE virtual environment.

VHI Virtual Hand Illusion.

VR Virtual Reality.

Chapter 1

Introduction

1.1 Background

The goal of Virtual Reality (VR) technology is to let users experience a computer-generated world as if it were real [1]. Since the early days of VR research, the creation of a virtual environment (VE) indistinguishable from reality has been a central interest of researchers and developers. Indeed, a considerable amount of VR research has been carried out on *presence*, i.e., the feeling of "being there" in a VE, to improve and measure the subjective quality of a given VE, emphasizing an aspect of VR-experience as a place [2, 3].

On the other hand, the development of VR technology enables users to experience not only a virtual *environment* but also a virtual *body* as if it were real. Over the last decade, advances in body tracking technologies and display systems have resulted in a growing interest among VR researchers on how (and to what extent) we can experience a virtual body representation (i.e., avatar; see Subsection 1.4.1 for a definition) as our own body in a VE [4]. Such illusory experience and the accompanying sense are commonly referred to as a Body Ownership Illusion (BOI) and Sense of Body Ownership (SoBO), respectively, and have been extensively studied in the fields of neuroscience, psychology, and philosophy in the exploration of bodily self-consciousness [5, 6].

One of the most common types of BOI is the well-known Rubber Hand Illusion (RHI) [7]. In RHI, watching a rubber hand being stroked synchronously with one's own unseen hand causes the rubber hand to be attributed to one's own body, such that it feels like one's own hand (i.e., one feels the SoBO over the rubber hand). The RHI is generally inhibited when the rubber hand is stroked asynchronously with the real hand [8] or replaced by a non-corporeal object such as a wooden block [9]. That is, the SoBO emerges from a combination of bottom-up and top-down information, allowing incorporation of a non-corporeal entity into our self-body representation [5]. Here, bottom-up information refers to the spatio-temporal congruency of continuously updated multisensory and motor information, whereas top-down information consists of the existence of sufficient human likeness to presume that an artificial body can be one's own body.

Similarly, experimental findings from BOIs using VR have shown that the closer the appearance of a self-avatar is to our own bodies in terms of structural and morphological aspects (e.g., shape, texture, and anatomical plausibility), the stronger the SoBO (Figure 1.1; see [10] for review). For example, existing research on a BOI using virtual hands has shown that a realistic virtual human hand elicits a stronger SoBO than nonhuman hands (e.g., robotic, cartoon) [11–13] and non-anthropomorphic objects (e.g., sphere, block, and arrow) [11,12,14]. Analogously, a stronger SoBO was elicited when participants had a First Person Perspective (1PP) view of a full-body mannequin instead of a 1PP view of a rectangular body-sized object [15], and the BOI is easier to elicit using a full-body avatar of a realistic human rather than when using a plastic mannequin [16]. Such visual resemblance of an avatar to a human, i.e., the top-down constraints of a BOI over the avatar, is referred to as *anthropomorphism* in avatar research both in and outside of the context of BOIs [17, 18]. In the thesis, anthropomorphism refers to visual human-likeness (vs. object-likeness) as one of the components of visual realism, or fidelity of avatars. This is distinct from other components such as photorealism, truthfulness, and visibility (see Subsection 1.4.2 for details).

In addition, the BOIs not only induce subjective SoBO but also alter the processing of sensory events such that an artificial or virtual body that is incorporated into our body representations can be the source of associated bodily sensations [10]. This is considered to be true because the BOIs "deceive" the central nervous system, which distinguishes self-produced sensations from sensations arising from external causes, into experiencing sensory information actually attributed to the altered self-

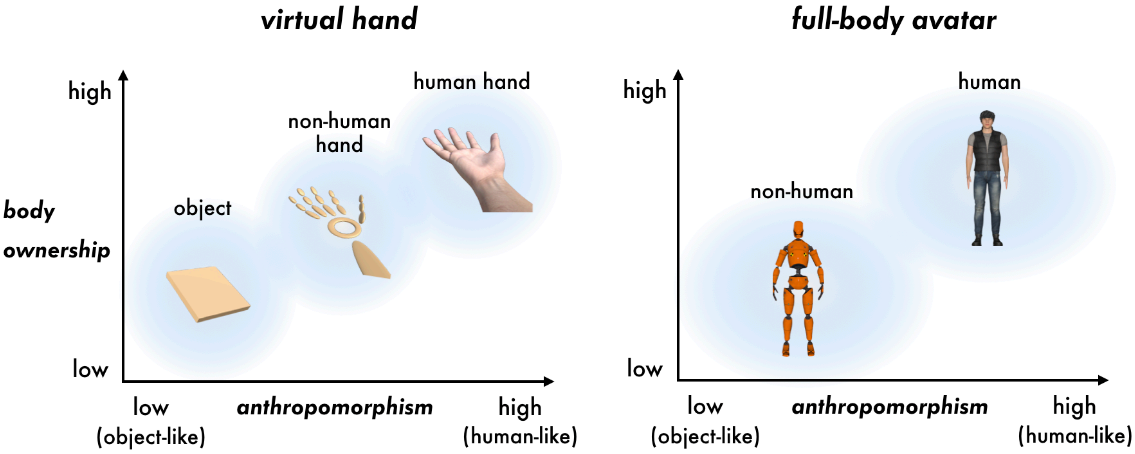

Fig. 1.1: Relationship between avatar anthropomorphism and sense of body ownership. The illustrated avatars are used in Chapter 4 (virtual hand) and Chapter 5 (full-body avatar).

body representation as originating from one's own body [19]. For example, in the RHI, when participants are asked to indicate the felt (proprioceptive) position of their real hand, they typically estimate the position to be shifted toward the rubber hand after the synchronous visuo-tactile stimuli [7]. Similarly, when the rubber hand is threatened by a knife, participants usually exhibit autonomic responses such as enhanced sweating and withdrawal of the real hand [8]. In fact, RHI has been shown to induce changes in two types of body representations, namely, the body image that is used for perception and the body schema that is used for motor actions [20,21][1]. Recent evidence suggests that the RHI attenuates the self-generated tactile sensations by affecting the motor system that generates sensory predictions [19]. Furthermore, self-body representations play a crucial role in perceiving the environment. It especially helps to construct the external space representation because it is defined by the body-centered spatial reference frame [24] In fact, when a full BOI was induced over a tiny doll instead of a rubber hand using the RHI paradigm, participants per-

[1]Schettler et al. [22] define the *body image* as the conscious beliefs regarding one's own body and the *body schema* as the unconscious knowledge of one's own body and its capacities. Moreover, Vignemont [23] defines the *body image* as perceptual, conceptual, or emotional identification and recognition concerning one's body consciousness and the *body schema* as a sensorimotor representation of the body that unconsciously guides actions.

ceived objects to be larger and farther away; the BOI influenced the perceived scale of the entire external world [25]. These perceptual consequences of the BOIs have also been shown in the case of VR-induced BOIs (e.g., [26–28]).

Although existing studies have demonstrated that the use of realistic human self-avatars facilitates the BOIs, which is consistent with our intuitive understanding, little attention has been paid to the influence of the BOIs on users' VR experiences. The thesis considers that user experience can be largely divided into perception and behavior, because humans experience either virtual or real worlds by receiving (e.g., inputting, organizing, identifying, and interpreting) sensory information from either one's own body or the environment (i.e., perception) and by responding to the received information (i.e., action or behavior). In other words, previous studies on self-avatar anthropomorphism have predominantly focused on whether the user perceives the avatar as their own body, but did not focus on how the anthropomorphism influences the way they experience—perceive and behave—in the virtual worlds with their avatar.

Meanwhile, in current VR applications, self-avatars with various levels of anthropomorphism, from abstract (object-like) to realistic (human-like), are used. One of the most significant reasons for such diversity may stem from the fact that realistic avatars generally cost more in terms of computation. In fact, according to documentation [2] for developers provided by Leap Motion, which manufactures hand tracking sensors for VR systems, avatar design is recommended as follows: *"Abstract or stylized hands and bodies are often preferable and less resource-intensive."* Consequently, VR developers are often faced with the question of how anthropomorphic the avatars should be with respect to the balance between computational costs and psychological effects such as SoBO. To keenly balance cost and effect, there is a need for knowledge about the extensive influence of self-avatars not only on the SoBO but also on users' entire experiences in VEs. Therefore, the effect of self-avatar anthropomorphism on user perception and behavior should be investigated to provide

[2] Leap Motion. *Documentation.* 8 May. 2017. https://developer.leapmotion.com/documentation/

evidence-based guidelines for selecting appropriate self-avatar representation that take a wide range of the psychological effects of user experiences into consideration.

1.2 Research Objectives

This background has resulted in the thesis addressing the following research question: *How does the representation of a self-avatar, specifically its anthropomorphism, influence how users perceive and behave in VEs?* As BOIs alter our self-body representation to incorporate an artificial or virtual body and, in that the body representation plays an important role in processing and reacting to sensory information, it can be a rational assumption that under the strong induction of a BOI, one is likely to perceive and behave based on one's altered self-body representation. In other words, it can be hypothesized that the use of highly anthropomorphic (i.e., human-like) self-avatars not only strengthens the SoBO, but also, possibly unconsciously, alters the way one perceives and behaves in VEs such that one's perception and behavior rely on virtual body representation rather than physical body representation.

Therefore, by conducting psychological experiments, the thesis investigates the effect of self-avatar anthropomorphism on users' perception and behavior in VEs with respect to the following three aspects: how to process sensory information from one's own actual body (1) and from the environment (2), and how to respond to the sensory information (3). To this aim, the thesis specifically focuses on the following: how proprioception from one's own body is processed in conjunction with visual information from the virtual body (1. visuo-proprioceptive integration), how external space representation is reconstructed based on the altered self-body representation (2. object size perception), and whether users react realistically to the virtually generated information in VEs using their virtual body as if they would react to the corresponding actual information using their own body in the real environment (RE) (3. behavior).

At the same time, the exploration of these aspects also addresses three specific and apparently distinct challenges commonly faced by VR applications by hypothesizing that the self-body representations play a common and important role in all three. Specifically, fostering visuo-proprioceptive integration is the key to overcoming spatial limitation in a series of hand interaction techniques in VR (e.g., hand retargeting [29]) that exploit visual dominance over proprioception to remap physical hand movements onto different virtual hand movements. Next, the perception of the scale of the external space is closely related to the well-known problem of egocentric distances appearing to be compressed in VEs [30]. Finally, navigating users' behavior can address an issue that users sometimes behave"unrealistically" in VEs such that they walk through virtual boundaries (e.g., walls) which they are not supposed to do [31]. The elucidation of the effect of self-avatar anthropomorphism can enable a novel solution of navigating users' perception and behavior in VEs to solve these issues by controlling the appearances of the avatar.

1.3 Contributions

The thesis extensively investigated the hitherto unexplored influences of self-avatar anthropomorphism on perception and behavior in VEs. The studies revealed that anthropomorphism influences how users interact with VEs at multiple levels of human information processing: processing of sensory information from one's own body (visuo-proprioceptive integration; Chapter 3), processing of information from the environment (object size perception; Chapter 4), and the way one responds to the information (behavior; Chapter 5).

Specifically, Chapter 3 shows that anthropomorphic appearances of a virtual hand affect visuo-proprioceptive integration when virtual (i.e., visual) and physical (i.e., proprioceptive) hand positions are in conflict. In a psychophysical experiment, participants repeatedly executed reaching movements with their right hand while their virtual hands are remapped onto horizontally shifted positions. The proprioceptive drift (i.e., the displacement of proprioceptive self-localization toward a virtual hand) and the detection thresholds for hand remapping (i.e., how large the remapping can be until the user becomes aware of it) were measured. The results reveal that proprioceptive drift was larger with realistic avatars (i.e., human hands) than with abstract avatars (i.e., spherical pointers), showing that realistic avatars can give greater weight to visual information during visuo-proprioceptive integration. In addition, realistic avatars increased the detection threshold (i.e., lowered sensitivity) by 31.3% than abstract avatars, showing that remapping is less noticeable for larger mismatches between virtual and physical movements; self-attribution of the hand is also associated with the self-attribution of the movements. These effects were only observed when the leftward shift was applied (i.e., when the actual hand moved right-forward) and not for the rightward shift. The findings reveal that the more visual dominance over proprioception can be exploited by manipulating the anthropomorphism of self-avatars.

Second, Chapter 4 reveals that the level of anthropomorphism (realistic, iconic, and abstract) influences the effect of the size (veridical and enlarged) of the virtual hand on the perceived size of a virtual cube. The experiment results reveal that only in the case of a realistic human hand, the size of the cube is perceived to be smaller when the virtual hand is enlarged compared to when it is veridical. The findings indicate that the sizes of objects are perceived based on the size of the virtual hand only when the appearance of the virtual hand is easy to be incorporated into a self-body representation; a stronger BOI fosters scaling of the size of objects using the virtual body representation as a fundamental metric. The study sheds new light on the importance of self-avatar representation in the problem whereby spatial perception in VEs appears to be different from that in the RE.

Finally, Chapter 5 shows that realistic self-avatars make users behave in VEs as if they would behave in the corresponding REs. The experiment examines how anthropomorphism (realistic or abstract) and visibility (full-body or hand-only) of self-avatars affect participants' behavior when incentives to walk through walls are provided in room-scale VEs. By analyzing the number of the participants who walked through walls and the time until they do so according to their avatar types, the realistic full-body self-avatar was shown to be the most effective in discouraging the participants from penetrating the walls; it makes users behave in VEs as if they would behave in the corresponding REs. The results suggest that simply changing the self-avatar appearances can implicitly encourage users to behave realistically or unrealistically depending on the situation.

Taken together, these studies provide compelling evidence that the anthropomorphism of self-avatars influences a wide range of user experiences in VR. In fact, one of the major challenges concerning VR studies is determining the predominant factors and parameters influencing user experience in VEs [32]. The thesis addresses this challenge with respect to self-avatar anthropomorphism. In addition, the experimental findings from the three independent studies concur, corroborating the hypothesis that the more human-like the self-avatars, the more easily the BOIs are induced and the more the self-avatars are incorporated into one's self-body representation. The result is that the users' perception and behavior becomes more based on virtual body representation rather than on physical body representation.

Furthermore, in contrast to the existing findings that realistic avatars are the best for inducing strong BOIs, while they generally have high computational cost, the findings provided in the thesis do not imply that the realistic avatars always produce the best perceptual effects considering the implications on a wide range of users' experiences in VEs; rather, they suggest that avatars of appropriate levels of anthropomorphism should be used depending on the situation and purpose by taking their perceptual effects into consideration.

1.4 Scope, Definitions, and Delimitations

The main focus of the thesis is to investigate the effect of the anthropomorphism of self-avatars on how users perceive and behave in VEs. Therefore, the independent variables of the thesis, i.e., the variables used in the experiments from Chapter 3 to Chapter 5, are the level of anthropomorphism of self-avatars. However, as the terms "(self-)avatar" and "anthropomorphism" have not been defined consistently in the literature, there is a need to be explicitly define them in the thesis. In this section, the usage of these terms in the thesis as well as the general definitions is described to clarify the focus of the thesis, followed by methodological limitations of the study that might affect the generality of the findings.

1.4.1 Avatar

The term “avatar” is widely used across multiple scholarly disciplines as well as in daily life. Despite–or perhaps because of--its widespread use, the term has not been consistently used and lacks a universal and consistent definition. Nevertheless, most scholars seem to endorse a definition that avatars are digital representations of the user in a digital environment [33]. Although this conceptual definition acknowledge several aspects of avatars such as social identity expression and emotional icons, the thesis is particularly concerned with an avatar as a digital substitute for a physical body (part) through BOI in immersive VEs. When highlighting the bodily potential of avatars, the term “embodied avatar” is sometimes used to describe representations that have a bodily form to control via naturally mapped users’ movements, often viewed from 1PP [33]. Hence, when the thesis refers to avatars, it usually means embodied avatars. Nevertheless, the “bodily form”, which is included in the above definition of embodied avatar, does not necessarily mean human-like appearance in the thesis because anthropomorphism is a subject of interest. For example, a spherical pointer that moves correspondently to the tip of the index finger of a user is used as a low-anthropomorphic avatar in Chapter 4. In addition, the focus of the thesis does not limit the visibility of avatars. Hence, both full-body avatars and avatars of a body part, specifically virtual hands, are used in the thesis. In Chapter 5, the effect of avatar visibility (i.e., full-body vs hands) as well as anthropomorphism is explored. Furthermore, the thesis focuses on the psychological effects of individual experiences of BOIs independent of a social context, in contrast to avatars as an entity of symbolizing social identity or self-expressions in computer-mediated communications. Thus, although recent research focusing on social aspects of avatars indicates that the appearance of the others’ avatars might affect user perception of their avatar [34], the social contexts where the user interacts with avatars of others are beyond the scope of the thesis. Consequently, even though avatars can be either of a user's own or of other users, the thesis only treats the former, which is called a "self-avatar" when emphasizing the distinction.

1.4.2 Anthropomorphism

In the thesis, anthropomorphism refers to visual human-likeness as one of the components of visual realism or fidelity of avatars, distinct from other components such as photorealism, truthfulness, and visibility (Table 1.1; see Section 2.1 for detail). Although the questions of what constitutes visually perceived anthropomorphism and how humans judge human-likeness (e.g., which has more human-like appearance, a robot and an animal?) are challenging and open themselves, they are beyond the scope of the thesis. Instead, the levels of anthropomorphism in the existing literature of BOIs (e.g., [12–14, 35, 36]) can broadly be classified into three: abstract (e.g., object), iconic (e.g., humanoid but non-human), and realistic (e.g., human). Hence, the models actually used in the experiments were chosen based on these classifications (see Figure 1.1), which have been shown to produce different levels of perceived realism from high to low [12]. Although human-likeness is further classified into shape, texture, and anatomical plausibility in the studies of BOIs [10], the thesis does not focus on such sub-components; rather, it manipulates the levels of anthropomorphism based on the classification as ordinal scales. In fact,

Table 1.1: Components of Realism (Fidelity) of Avatar

Realism/Fidelity of Avatar	
Visual (Form) – anthropomorphism (object-like – human-like) – photorealism (stylized – visually detailed) – truthfulness (does not resemble – resembles user) – visibility (no/parital body – full-body)	Behavioral (Movement)

avatars with different levels of anthropomorphism usually differ in terms of their texture, anatomical plausibility, and shape. For example, a robot avatar generally has a metallic texture, and human-skinned spheres would look eerie. Therefore, in the thesis, although the manipulation of anthropomorphism largely relies on shape characteristics, it is also accompanied by changes in the texture and anatomical plausibility of the avatars so that they exhibit anthropomorphic fidelity. Throughout the thesis, the adjectives realistic, iconic, and abstract are used to describe an anthropomorphic spectrum, instead of high-anthropomorphic and low-anthropomorphic or human-like and object-like, as anthropomorphism eventually contributes to realism (abstract–realistic) if a human avatar is supposed.

It should also be emphasized that the term anthropomorphism in the thesis refers to visual aspects rather than the behavioral (movement) aspects, although some literature in avatar communication research deals with behavioral anthropomorphism [33], In the case of self-avatars, the visual and behavioral aspects of realism are considered to largely correspond to top-down and bottom-up factors of BOIs, respectively. Hence, as the thesis focuses on the top-down aspects, behavioral realism of self-avatars, which mainly corresponds to the visuomotor spatio-temporal correspondence between the avatar and one's own movements, are not the main scope of the thesis. Yet, abstract avatars generally have reduced freedom of movement compared with human avatars. The visuomotor correspondence is related to the concept of Sense of Agency (SoA) which is, in turn, considered to interact with the SoBO if they co-occur [37,38] (see Subsection 2.3.2 for details). Hence, to avoid any influence of behavioral aspects (e.g., controlability or functionality), all the avatars used in the thesis were specifically assured to maintain the same functionality with respect to the experimental tasks in spite of their different anthropomorphism. For example, for the task of pushing the button with the fingertip, a spherical pointer that moved in correspondence with the participant's fingertip position was used as an abstract avatar while a human hand model was used as a realistic avatar. Although the SoA is also not the main scope of the thesis, Chapter 3 discusses the results in relation to the SoA because it deals with a self-avatar whose movements are remapped from the user's own.

In addition, the effect of other components of the visual realism of self-avatars, namely photorealism, truthfulness, and visibility, is also beyond the scope of this study although Chapter 5 does do some investigation into the effect of visibility. In terms of photorealism, the potential aversive reaction of a user to a mismatch in photorealism between the environment and the character has been noted [39]. Hence, in terms of render styles, the self-avatars were designed to match the VEs as much as possible in the experiments. Furthermore, although the semantic aspects of highly anthropomorphic self-avatars (e.g., skin color [40] and attractiveness [41]) have been shown to affect users' attitude and behavior through stereotype or memory (i.e., Proteus effect), these are also beyond the scope of the thesis because they occur in social, cognitive contexts rather than in individual, perceptual experiences of BOIs.

1.4.3 Methodological Delimitations

Finally, methodological specifications and constraints should also be noted. To display the VEs, a consumer Head Mounted Display (HMD) that is cutting-edge in the late 2010s (i.e., Oculus Rift CV1[3] and HTC Vive[4]) is used. Both Oculus Rift CV1 and HTC Vive offered 1,080 x 1,200-pixel resolution for each eye, 90Hz refresh rates, and a 110-degree field of view. The experiments were carefully designed and conducted to reduce bias as much as possible. Nevertheless, sampling biases were inevitable owing to practical constraints, although the conclusions were statistically delivered under the assumption of random sampling. Specifically, the participants consisted of Japanese people and the experiments were conducted in Japanese. They were recruited through social media (i.e., Twitter) from the public. Hence, although they were naive as to the purpose of the experiment, they were biased in the way that they were interested in participating in the experiment or VR experiences.

[3] manufactured by Oculus VR, a division of Facebook Inc., released in March 2016

[4] manufactured by HTC and Valve, released in June 2016

1.5 Overview

The thesis consists of a total of 7 chapters. **Chapter 1** states the background and purpose of the thesis. **Chapter 2** first reviews the avatar research with a focus on anthropomorphism. Next, it summarizes the existing literature on BOI by classifying its factors into bottom-up and top-down processes. Then, it discusses the concepts related to the SoBO; sense of embodiment, SoA, and sense of presence. Lastly, it also identifies the perceptual and behavioral consequences of BOI. **Chapter 3** describes an experiment for investigating the effect of self-avatar anthropomorphism on *visuo-proprioceptive integration*. **Chapter 4** describes an experiment for investigating the effect of self-avatar anthropomorphism on *object size perception*. **Chapter 5** describes an experiment for investigating the effect of self-avatar anthropomorphism on *behavior*. **Chapter 6** summarizes the findings in Chapter 3, 4, and 5, discusses limitations and future studies, and revisits the design implications of self-avatar appearances in VR applications. **Chapter 7** concludes the thesis.

Chapter 2

Literature Review

In this chapter, the avatar research is first reviewed with a focus on anthropomorphism. Next, the existing literature on the SoBO is summarized by being classified into bottom-up and top-down processes. Then, several concepts that are closely related to the SoBO are introduced. The accompanying perceptual and behavioral phenomena with the BOIs are also identified depending on the process levels: physiological reaction, multisensory integration, spatial perception, and cognition/action/behavior. Lastly, a summary of literature is stated in the context of the thesis.

2.1 Avatar anthropomorphism

Anthropomorphism is generally defined as the perception or assignment of human traits or qualities such as mental abilities, cognitions, intentions and emotions, or behavior to entities that may or may not be human [33]. Although the term was originally used by psychological scholars when referring to the manner of attributing human reasoning to nonhuman beings such as plants and animals (e.g., [42, 43]), it has been commonly used in recent human-computer interaction research to mean having a human like form of features or the degree to which something resembles a human with regards to artificial entities such as avatars (e.g., [17, 18]), humanoid robots (e.g., [44, 45]), and agents (i.e., virtual characters controlled by a computer; e.g, [18,46]). In avatar research, anthropomorphism has mainly been used for avatars of others. Yet, recent studies have started to use the term for self-avatars (e.g., [17, 36, 47, 48]).

Nevertheless, when discussing the anthropomorphism of avatars, especially full-

Table 2.1: Selected list of literature using realism or anthropomorphism and usages

Literature	Term	Subject	Models
Latoschik et al. [34]	Realism	Avatar (self and others)	Wooden mannequin 3D scanned human
Bailenson et al. [49]	Realism	Avatar (self and others)	Blockie avatar Video image
Garau et al. [50]	Realism	Avatar (self and others)	Iconic avatar Human avatar
Argelaguet et al. [11]	Realism	Virtual Hand	Sphere model Robotic hand Human hand
Lin and Jörg [12]	Realism	Virtual Hand	Wooden block Robot hand Zombie hand Human hand
Chaminade et al. [51]	Anthropomorphism	Animated character	Dot Ellipse Robot Alien Clown Human
Nowak et al. [18]	Anthropomorphism	Avatar and agent	Iconic face image Human face image
Lugrin et al. [17]	Anthropomorphism	Self-avatar	Robot Block-man Realistic Human
Ebrahimi et al. [52]	Anthropomorphic fidelity	Self-avatar	End effector Joint positions Full body

body avatars, the term realism is often used confusedly or interchangeably with anthropomorphism (Table 2.1). Realism is defined as the perception that something could realistically or possibly exist in a non-mediated context [53]. Consequently, while realism can be used for a wide variety of subjects other than avatars, such as virtual environments (e.g., [54,55]), when mentioning a virtual representation that is supposed to be human, realism and anthropomorphism can almost interchangeably refer to being “human-like”. However, while most studies have used either of the terms to refer to apparently similar concepts, Yee et al. [56] distinguishably used them by positioning anthropomorphism as one of the dimensions of realism. They stated that realism of human representations are constituted by several aspects such as behaving realistically, being photographically realistic, and being anthropomorphic. The thesis also follows this standpoint. In this case, where realism of human avatars includes anthropomorphism and other components, the term “fidelity” is often interchangeably used with realism (e.g., [57]).

As shown in Table 1.1, realism (fidelity) is often divided into two categories: visual or form (i.e., appearance) and behavioral (i.e., animation or movement) [49, 57, 58]. In addition, according to Garau’s definition [58], the visual fidelity of virtual characters[1] is further classified into three dimensions of anthropomorphism, photorealism (i.e., the level of detail of meshes and textures of 3D models [59]), and truthfulness (i.e., the similarity of the appearance between the user and the virtual character [58]). What can be confusing is that realism is sometimes used as an abbreviation of photorealism (e.g., [48, 59]). Nevertheless, although terminological confusion exists in the literature around the definitions of anthropomorphism and related concepts, there appears to be some agreement that anthropomorphism refers to human-likeness as one of the components of the visual realism or fidelity of avatars, distinct from other components such as photorealism and truthfulness. Interestingly, similar to Garau’s classification, Schwind et al. [35] found three levels of deviation of virtual hands from real hands that affect the feeling of presence from qualitative feedback provided by think-aloud protocols: deviations from common human appearance, the user’s gender, or the user’s body. Note that their implications could reflect the main

[1]Virtual characters consist of avatars (i.e., a digital representation whose actions are controlled by humans) and agents (i.e., a digital representation whose actions are controlled by computers) [18, 58]. Usually, virtual characters do not refer to self-avatars, that is, they implicitly mean representations of others. When virtual characters are humanoid, they are sometimes called virtual humans.

focus of the study: the effect of gender. In addition, whereas Garau [58] enumerated the three components of visual fidelity of virtual characters, in cases of embodied avatars in particular, visibility appears to be also considered to be one of the major components (e.g., [60–62]). To summarize, the relationship between anthropomorphism and the often-confused terminologies can be summarized as Table 1.1.

Nevertheless, the question of what are the exact features of an image that determine the perceived anthropomorphism or realism of a CG human is still challenging and open themselves. How a human perceives the realism of avatars has been studied mainly in the field of Computer Graphics (CG) with a close relationship to the film industry in the pursuit of how to render virtual characters realistically, attractively, or expressively, with an intensive focus on facial expressions (e.g., [63–65]). A number of studies have investigated these topics in the context of the Uncanny Valley theory [66] such that even small imperfections can trigger negative responses [67]. This theory suggests that a person's response to a robot could shift from empathy to revulsion if the highly realistic model tried to achieve a life-like appearance but presented inconsistencies [48]. The Uncanny Valley effect is also observed in recent studies of BOIs over full-body avatars (e.g., [17], see Subsection 2.2.2 for details). In addition, VR technology has raised another concern: whether virtual characters are perceived and treated as if they are human (e.g., [18, 57]). For instance, Nowak et al. [18] examined the influence of anthropomorphism of an avatar and agent on presence in a VE. The results showed that participants interacting with a less-anthropomorphic 3D facial image reported more copresence and social presence than those interacting with either no image or a highly anthropomorphic image, indicating that the more anthropomorphic images set up higher expectations that lead to reduced presence when these expectations were not met.

In this context, interactive effects between the categories of realism (i.e., visual and behavioral) and the components of realism are identified [51, 57, 64]. For example, Chaminade et al. [51] found that the anthropomorphism of virtual characters influenced the perception of the characters' animation. In addition, Zell et al. [65] evaluated how any combination of anthropomorphism (i.e., shape) and photorealism (i.e, material style) affects the perceived realism, appeal, and expressivity of a virtual character performing several basic facial expressions, and found that shape is the dominant factor when rating realism and expression intensity, while material style is the key component for appeal. They also revealed that realism alone is a bad predictor for appeal, eeriness, or attractiveness. Rather, they illustrated the importance of consistency between the stylization level of characters' shapes and materials. Indeed, inconsistencies negatively impacted appeal and attractiveness of virtual characters, making them look eerie. Taken together, these studies indicate that how human-likeness of human avatars is defined and judged is highly complex and is still open to interpretation. Nevertheless, as stated in Subsection 1.4.2, the thesis does not go any further into these questions but treats them as future studies. Instead, it considers anthropomorphism as a component of realism and manipulates the levels of anthropomorphism based on the existing literature of BOIs.

2.2 Body Ownership Illusion (BOI)

When one immerses oneself in a VE and sees an avatar moving as one's body moves, one will feel as if the avatar is one's own body (i.e., feel the SoBO), even though one is aware that the avatar is in fact the CG projected on displays. This fact seems to be taken for granted. Nevertheless, the question of how a brain distinguishes self-bodies from the bodies of others or from objects in the surrounding environment is one of the most profound issues in the fields of neuroscience, psychology, and philosophy [6, 10, 68]. In these fields, "the bodily self" is pursued by using BOIs to reveal the extent to which the SoBO occurs over external objects.

RHI is one of the best known BOIs. In the RHI, watching a rubber hand being stroked synchronously with one's own unseen hand causes the rubber hand to be attributed to one's own body and touches on one's own hand seem to be coming from the rubber hand, such that it feels like it is one's own hand [7]. The RHI is generally inhibited when the rubber hand is stroked asynchronously with the real hand [8]. Inspired by the RHI, a report on the Virtual Hand Illusion (VHI) found that synchrony between visual and motor activity and synchrony with proprioceptive information induces a SoBO over a virtual arm [14, 26]. Previous studies have demonstrated BOIs over a wide range of body parts (e.g., fingers [9], arms [69], upper body [70], legs [71], and full body [28]) as long as spatially and temporally synchronous visuotactile or visuomotor stimuli are provided.

In this way, congruent multisensory stimuli elicit the BOI, whereas incongruent stimuli eliminate the illusion. Nonetheless, a synchronous multisensory stimulation is not a sufficient factor of the BOI as it hardly occurs for objects that do not resemble body parts. In fact, the RHI was not induced when the rubber hand was replaced by a non-anthropomorphic object (e.g., a wooden stick) [72]. Hence, multisensory integration in the interaction with internal models of the body is necessary for the construction of the SoBO in order to incorporate a non-corporeal entity into our self-body representation [73]; these are referred to as bottom-up processes and top-down influences [72]. While the former pertains to the integration of continuously updated current sensory inputs and motor information, the latter is the cognitive process that is contributed to by our semantic memories and knowledge [10].

Since the introduction of RHI, a considerable number of studies have investigated factors influencing the strength of the BOI and how far we can embody artificial or virtual bodies of appearances different from our own bodies (see [5, 10] for a review). In this section, the studies of the BOI are reviewed according to the bottom-up and top-down factors (see Table 2.2 for a summary).

Table 2.2: Factors of Body Ownership Illusions

Top-down	Bottom-up
Human-likeness – shape – texture – anatomical plausibility	– spatial correspondence of multimodal stimuli – temporal correspondence of multimodal stimuli

2.2.1 Bottom-up Factors: Synchronous Multimodal Stimuli

The induction of BOIs depends critically on bottom-up factors, that is, the spatiotemporal congruency between multisensory/sensorimotor stimuli. The classic RHI uses a paintbrush to provide synchronous visuotactile stimulation to the rubber hand and real unseen hand, but, in the absence of tactile stimulation, the SoBO can be induced using only synchronous visuomotor stimulation. For example, both active motor control over the artificial hand [74] and a data-glove that uses sensors transmitting the positions of fingers to a virtually projected hand [26] induce the SoBO, but nowadays the SoBO over a self-avatar in immersive VEs is probably the most common form of BOIs under the visuomotor congruency. Typically, visuomotor congruency along with visuo-proprioceptive congruency are the keys in a BOI using VR, whereas synchronous visuotactile stimuli are used in a classic RHI.

In both visuotactile and visuomotor stimuli, spatial and temporal correspondence is considered an important condition for the induction of the BOI. It is widely accepted that the BOI is usually eliminated or inhibited under "asynchronous" conditions when the real and the fake body (or body part) are touched asynchronously (e.g., [8, 15, 75, 76]) and the avatar's movement is not a reflection of one's body movement but a random animation (e.g., [26, 27, 71]). Nevertheless, recent studies have suggested that when the fake body is realistic and is seen superimposed onto its real counterpart from 1PP, BOIs could occur even in presence of asynchronous visuotactile or visuomotor stimulation [16, 37]. Similarly, Kokkinara et al. [77] have shown that participants can feel SoBO even when virtual arm movements are distorted in an immersive VE; they investigated the SoBO under velocity- dependent (spatiotemporal) distortions of arm movements, and found that spatiotemporal manipulations of 2 and 4 times faster did not affect the perceived SoBO. Such human traits of attributing the distorted virtual arm movements as their own are exploited in a number of hand interaction techniques in VR (see Chapter 3).

While congruent visuotactile and visuomotor stimulation is necessary for inducing BOIs, spatial congruency of visuo-proprioceptive cues (i.e., spatial coincidence) is considered to be a sufficient condition for eliciting BOIs [10]; different degrees of visuo-proprioceptive spatial mismatch modulate the strength of the BOIs. In fact, the BOI was reported to be attenuated when the artificial or virtual hand was located too far away from the physical hand [78–80], whereas it continues to be elicited as long as the displacement is under a certain threshold (e.g., movement distortion with 22° [77] and spatial displacement is within 30 cm [79]). Lloyd [79] investigated the spatial limits of the RHI by systematically varying the placement of the rubber hand (at a distance of 17.5-67.5 cm horizontal from the participant's own hand). The results revealed a significant nonlinear relationship in the strength of the illusion with the strongest ratings given when the two hands were closest and decaying significantly after a distance of 30 cm. Furthermore, the time taken to elicit the illusion followed a similar trend. In contrast, when the entire scene including an avatar was rotated by 15 degrees upwards in an immersive VE, perceived ownership of the avatar was only slightly diminished [81].

2.2.2 Top-down factors: Anthropomorphism

The BOI is driven by an interplay between bottom-up and top-down factors; besides continuously updated bottom-up information, BOI is also influenced by higher-order top-down cognitive processes. This is because our semantic memories and knowledge contribute toward shaping an abstract body model that contains information about the general and non-self-specific visual, postural, and structural properties of the human body [10]. Kilteni et al. [10] regarded top-down factors of BOIs as semantic constraints; the seen artificial or virtual body (or body part) should be semantically congruent with the real body. That is, the closer the artificial or virtual body appearances are to a non-self-specific human body (part) in terms of structural and morphological aspects, the stronger is the SoBO [10]. Although the term anthropomorphism has rarely been used in the context of BOIs except for recent studies of BOIs over self-avatars (e.g., [17, 36, 47, 48]), it can be said that anthropomorphism is the top-down factor underlying BOIs, especially in the case of

BOIs using VR.

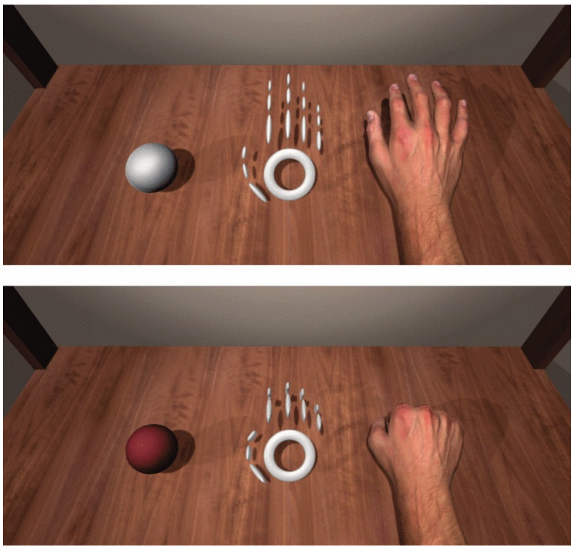

Fig. 2.1: Virtual hand representations used in [11], reprinted from [11]. Abstract (left), iconic (center), and realistic virtual hands (right). Each virtual hand had its own visual feedback when the grasping operation is triggered (bottom). The abstract virtual hand changes color, the iconic virtual hand abruptly changes shape (there is no smooth animation), and the realistic virtual hand is animated from the user's finger motions. © 2016 IEEE.

In VHIs, a realistic virtual human hand elicits a stronger SoBO than nonhuman hands (e.g., robotic, cartoon) [11–13] and non-anthropomorphic objects (e.g., sphere, block, and arrow) [11, 12, 14]. For example, Argelaguet *et al.* [11] compared realistic (human), iconic (robotic), and abstract (sphere) virtual hands, which provided different degrees of visual anthropomorphism[2] but possessed the same control mechanism (see Figure 2.1). They showed that the SoBO was higher for the human virtual hand that provided a direct mapping between the degrees of freedom of the real and virtual hands. Similar to Argelaguet's study [11], most studies investigating the effect of anthropomorphism used a realistic human hand that appears to be connected to the participant's body by a virtual forearm as the highest level of anthropomorphism [12–14, 35] (see Table 2.1 for examples); however, some studies have

[2]Note that they originally used the term "realism" ; see Table 2.1

shown that the truthfulness component (i.e., personalization of avatars) increases the SoBO further than realistic human avatars [34, 82, 83]. In terms of render styles, human hands are usually rendered realistically, although some studies used both realistic and cartoony hands to investigate the effect of photorealism [12, 35].

Analogously, for the BOI over full-body avatars, the stronger SoBO was elicited when participants had a 1PP view of a full-body mannequin instead of a 1PP view of a rectangular body-sized object [15], and the BOI is easier to elicit using a full-body avatar of a realistic human rather than when using a plastic mannequin [16]. Interestingly, Maselli and Slater [16] showed that full-body avatar anthropomorphism (i.e., a realistic human avatar vs a virtual plastic mannequin) favors SoBO when viewed from a first-person perspective, despite the presence of incongruent visuo-motor cues, whereas Ma and Hommel [84] suggested that VHI is influenced by visuomotor synchrony rather than the similarities in the appearances of hands. Furthermore, Yuan and Steed [14] reported that a realistic virtual hand elicited SoBO even when the virtual hand was gradually shifted by 10 cm, but the same was not found for an abstract arrow cursor. Nevertheless, it should be noted that a recent study indicated the presence of the Uncanny Valley effect [66] in the BOIs over full-body avatars and Lugrin et al. [17] showed that machine-like and cartoon-like full-body avatars elicit a slightly stronger SoBO than human avatars.

At the same time, experimental findings have also revealed that our body representations are so plastic and malleable that they can be altered in terms of morphology and semantics [28, 40, 41, 70, 85, 86]. The concept of homuncular flexibility introduced by Lanier [87] illustrates the potential to accept and manipulate morphologically divergent avatars as our own body. For example, VHIs have been shown to occur over morphologically different bodies such as six fingers [88] and long fingers [89] or long arms [69]. In addition, as recent full-body tracking systems enable visuomotor synchrony with high accuracy, BOIs for full-body avatars are found to occur even when there are radical semantic changes in comparison to the true body (e.g., a dramatic increase in belly size [90], another person's body [15], and a body with a tail [91]) when given appropriate visuomotor feedback.

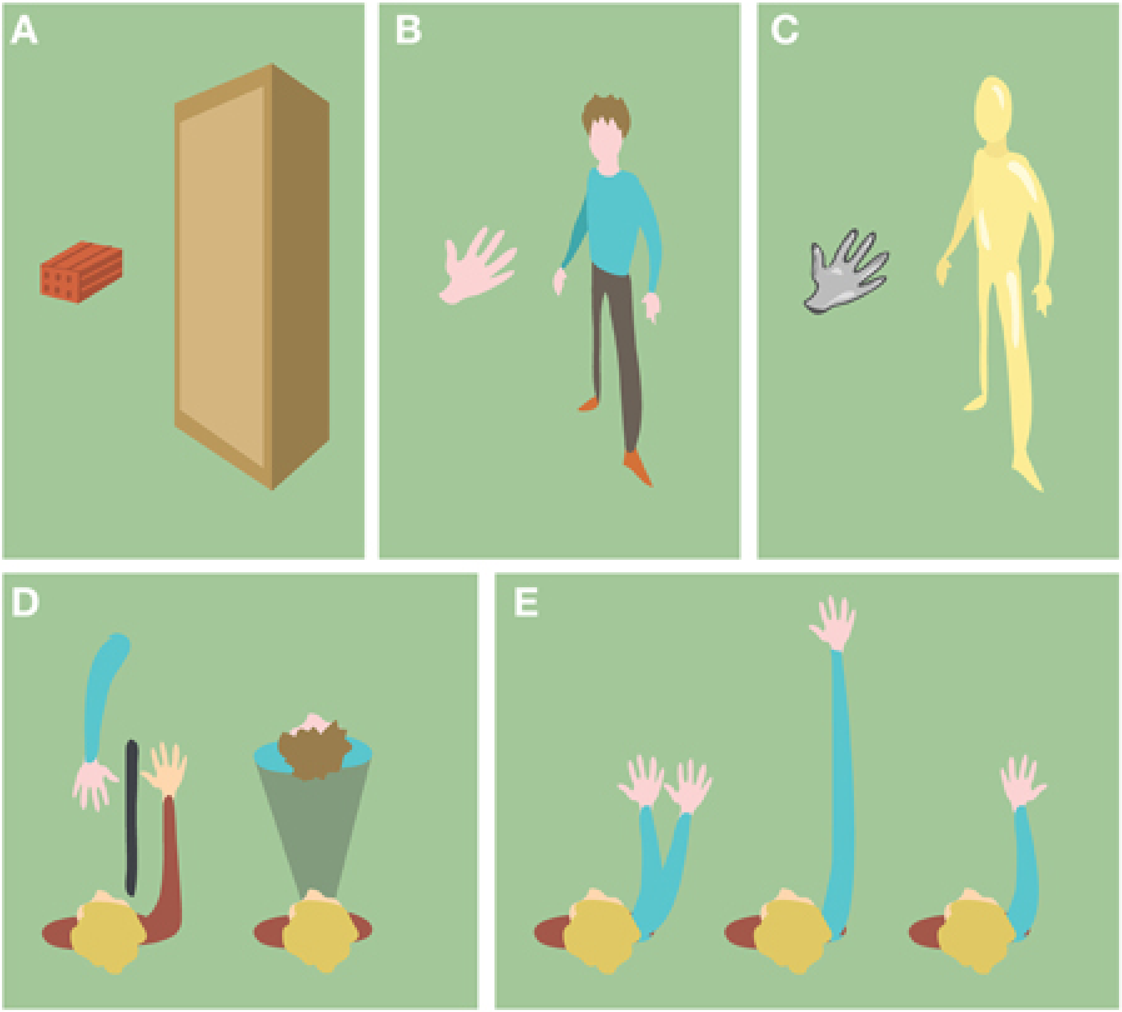

Fig. 2.2: Examples of objects with different semantic information, reprinted from [10]. (A) Objects with non-human body shape. (B) Objects with human body shape. (C) Objects with non-human skin texture (D) Objects (blue) in anatomically implausible spatial configurations with respect to the participant's body (red). (E) Objects (blue) with anatomically implausible structure with respect to the human body. © 2015 Kilteni, Maselli, Kording and Slater.

In terms of the components of anthropomorphism, Kilteni et al. [10] have classified top-down factors of BOIs into the following: shape, texture, the anatomical plausibility of their spatial configuration, and the anatomical plausibility of their internal structure (see Figure 2.2). According to them, in BOIs, whether the object has a human body shape or not is distinguished first, and if it is body-shaped, its semantic information can then be further characterized by its texture and anatomical plausibility, such as the spatial configuration, visual perspectives, and internal structure [10]. In fact, converging experimental evidence suggests that BOIs are shape-sensitive in general, although the influence of texture can be negligible in the case of visuomotor correlations [10, 40]. Nevertheless, as stated in Subsection 1.4.2, the thesis does not focus on each sub-component of anthropomorphism. Instead, it manipulates the levels of anthropomorphism based on the classification as ordinal scales (e.g., abstract, iconic, and realistic) so that shape, texture, and anatomical plausibility should be the natural representation of the real counterpart (e.g., a block, a robot, and a human).

2.3 Concepts Related to Body Ownership

In this section, several concepts that are closely related to the SoBO are introduced: Sense of Embodiment (SoE), SoA, and sense of presence.

2.3.1 Sense of Embodiment (SoE)

The SoE refers to the ensemble of sensations that arise in conjunction with being inside, having, and controlling a body especially in the context of VR studies [5]. According to Kilteni et al. [5], *"SoE toward a body B is the sense that emerges when B's properties are processed as if they were the properties of one's own biological body."*. The SoE seems to be close to the SoBO, but it includes the concept of the SoA and the sense of self-location (SoSL), as well as the SoBO. The SoA refers to the feeling of control over actions and their consequences [92] (see Subsection 2.3.2 for details), and the SoSL refers to one's spatial experience of being inside a body [5]. In VR, the SoA can easily be elicited when the motion of the user is mapped to the virtual body in real-time or near real-time [5]. The SoSL, on the other hand, can be obtained by an immersion from 1PP as it is highly determined by the egocentric visuospatial perspective [5].

Therefore, seeing a virtual realistic body from 1PP with congruent visuo-motor cues is considered sufficient to induce the SoE in VR. In fact, several studies have demonstrated that incongruent visuomotor feedback can attenuate the SoE. In particular, both the SoA and SoBO have been found to be reduced when there is a discrepancy between vision and motor information [26, 93, 94]; however, they can still be induced to some extent. For instance, Kokkinara et al. [95] showed that both the SoBO and SoA can be induced over the walking of a virtual body from a 1PP, even though participants were actually seated and only allowed head movements. Such findings suggest that participants can feel the SoA and SoBO in some situations in spite of visuo-motor discrepancies.

2.3.2 Sense of Agency (SoA)

As stated above, the SoA is considered one of the components of the SoE in the field of VR. However, in the fields of philosophy and psychology, the SoA is considered to form a fundamental aspect of self-awareness together with the SoBO [6]; the SoA refers to the self-attribution of action, whereas the SoBO refers to the self-attribution of body. The SoA is considered to be determined by the comparison between the predicted and actual consequence of an action through sensorimotor processes according to the comparator model [96, 97]. Thus, the SoA has been found to be reduced when there is a discrepancy between vision and motor information [93, 94, 98], as in the case of the SoBO. However, in contrast to the SoBO, the main cue for the SoA is the spatiotemporal contiguity between one's own and observed movements or outcomes [93, 94, 98]. That is, the SoA is hardly influenced by the appearance of the target; it can be felt even over a cursor shape. For instance, Argelaguet et al. [11] investigated the impact of the degrees of freedom of a virtual hand on the SoA. They showed that the SoA was higher with less realistic hands for which there was less of a mismatch between participants' real actions and the animation of the virtual hand. Nevertheless, studies suggest that the SoBO and SoA may strengthen each other if they co-occur [37, 38, 99, 100], although some studies have indicated that both experiences can double dissociate (for a review, see [101]). For example, the SoBO is argued to play a crucial role in modulations of the SoA [38], whereas the SoA was found to be stronger when the hand was perceived to be a part of the body [102]. In addition, it is becoming increasingly recognized that the SoA is based on a combination of internal motor signals and external evidence about the source of actions and effects [103–105]. Thus, although spatial and temporal contiguity between one's own and observed movement are the main cues for the SoA [93,94,98], higher-level cognitive processes such as background beliefs and contextual knowledge relating to the action also influence the induction of the SoA [92, 106].

The measurements of the SoA are generally grouped into implicit or explicit measures [92]. Implicit measures such as sensory attenuation [97], intentional binding [107, 108] and neurophysiological markers [109] assess a correlate of voluntary action about the agentic experience [92]. Alternatively, explicit measures are based on the subjective judgments of the feeling of control (i.e., the authorship or attribution of the actions or their corresponding outcomes) [104, 110–113]. Most studies have used explicit measures, especially in VR [77, 114]. They are typically assessed in paradigms using button presses, which produce sensory feedback [110] or simple movements [77, 93, 94, 113, 115–117]. As for simple movements, a moving cursor associated with a joystick [93, 94] or mouse [115, 116] and visual feedback of hand movements through a mirror [117], a TV-screen [113], or VR [77] are often used.

Although spatial displacement or temporal delay between action and outcome attenuates the SoA [93, 94, 98], illusory SoA over distorted movements can be induced as long as the displacement or delay is under a threshold. In a classic study by Nielsen [117], participants were instructed to draw a straight line to the goal point. After some repetitions, the experimenter secretly inserted a mirror so that the participants were looking at another person's hand in a mirror. Nevertheless, they experienced an illusory SoA and assumed that the hand was their own. Interestingly, when the experimenter distorted their movement so that they drew a curved line, they still attributed the movement to themselves and moved in opposition to the experimenter's movement to compensate for the error between the predicted and actual movement. This means that as long as they attributed a movement to themselves, they tried to control it. In addition, a recent study using VR showed that spatial manipulations that resulted in an offset of 22 angular degrees from 1PP did not attenuate the SoA [77], which showed much lower detection thresholds than previous studies without VR [93, 94]. Moreover, it is possible to cause illusory SoA over bodily movements even when there is no actual corresponding action. In Wegner et al.'s "helping hands" experiment [104], participants watched themselves in a mirror while an experimenter standing directly behind them extended and moved his or her arms as if the participants themselves moved their arms. They reported that participants felt an illusory SoA for another person's hands when they were primed by instructions for that person's movements in advance, although they factually did not move. VR is also used to induce an illusory SoA when passively observing movements of a walking avatar from 1PP [95]. In the field of VR, a number of studies have exploited these facts in order to enhance passive haptics by changing the mapping of movements from the physical to the virtual [29,118,119] (see Chapter 3).

2.3.3 Sense of Presence

In 1980, Marvin Minsky introduced the concept of telepresence, which refers to the phenomenon whereby a human operator develops a sense of being physically present at a remote location through interactions with the system's human interface, user's actions, and the subsequent perceptual feedback they receive via the appropriate teleoperation [120]. Then, Akin et al. [121] introduced the concept to the computing literature by defining telepresence as the condition that occurs when, *"At the worksite, the manipulators have the dexterity to allow the operator to perform normal human functions. At the control station, the operator receives sufficient quantity and quality of sensory feedback to provide a feeling of actual presence at the worksite"*. Over time, the meaning of telepresence was relaxed to include VR (e.g., [122]) and the prefix of "tele-" has been dropped [123].

Although presence has been defined in several ways, it is most commonly defined as the sense of "being there" in a VE [124]. For example, according to Witmer and Singer [125], presence is defined as '*'the subjective experience of being in one place or environment, even when one is physically situated in another"*. On the other hand, according to Sanchez-Vives and Slater [126], if participants within a VE behave as if they were in an equivalent RE, this is a sign of presence. Such "respond as if real" provides an operational definition of the concept of presence, where response is considered at multiple levels: subjectively (e.g., by questionnaire [125, 127]), behaviorally (e.g., through looming responses [128], postural sways [129], and aftereffects [130]), and physiologically (e.g., by heart-rate [131,132], skin temperature [131] and SCR measurements [133]). In other words, to the degree that a VE seems real, it would evoke behavioral or physiological responses similar to those evoked by the corresponding real environment, and that greater presence would evoke a greater response [126]. This definition encompasses their ability to act within the environment created by virtually generated sense data in a manner commensurate with how they would be able to behave if the sensory data were real [124].

To assess presence, a "pit room", where the floor is a narrow ledge around an open hole to another room in a VE, is often used as an arousal-inducing scenario (e.g., [134, 135]). Participants in the pit room usually make their way carefully the sides of the room along the ledge rather than simply gliding across the non-existent virtual pit, even though they know for sure that there is no pit there [3]. Meehan et al. [131] found that participants' heart rate in the pit room was significantly correlated with presence measured by the questionnaire.

In 2009, Slater [3] proposed a theory that presence is composed of two logically orthogonal components, Place Illusion (PI) and Plausibility Illusion (Psi). He defined PI as "illusion of being in a place in spite of the sure knowledge that you are not there," and Psi as "the illusion that what is apparently happening is really happening (even though you know for sure that it is not) [3]." PI corresponds to the traditional conception of (spatial or place) presence as "being there," while Psi represents an entirely different conception of presence, that of believing what you are seeing [2]. Slater [3] also stated that when both PI and Psi occur, participants will respond realistically to the VR and emphasized that Psi does not require physical realism. For instance, in the virtual reprise of the Stanley Milgram obedience experiment, participants exhibited anxiety responses when causing pain to a relatively low fidelity virtual character in terms of both visual appearance and behavior [136]. In contrast, Zimmons et al. [132] exposed participants to the pit room rendered with varying degrees of visual realism and found that the different rendering qualities made no difference to the responses, although Slater et al. [54] showed that greater visual realism induced greater participant presence.

Among various factors that contribute to presence, including frame rate [137] and field of view [138], and visual realism [54], the importance of a self-avatar has long been established (e.g., [61, 139–142]). A self-avatar is especially related to a form of presence called self-presence, which refers to the effect of embodiment in a VE on mental models of the self [143]. SoBO is analogous to self-presence but not limited to VEs [2]. In addition, according to Slater et al. [4], responding to a virtual body as if it were your own body is perhaps the most powerful demonstration of presence. These findings imply that, in a VE, the presentation of a self-avatar lends a stronger sense of presence to the user and elicits the natural behavior of the user.

While the effect that the presentation of a self-avatar has on presence has been widely investigated and accepted [141], few studies have focused on how self-avatar appearances influence presence [34,35,82,144]. Schwind et al. [35] found that the anthropomorphism of virtual hands influenced the presence, but there were significant interaction effects of gender and hands on presence, i.e., presence was perceived by men and women differently. In contrast, Latoschik et al. [34] did not find a significant effect of the anthropomorphism of full-body self-avatars (wooden mannequin vs high fidelity avatars generated from photogrammetry 3D scan) on presence. Similar to anthropomorphism, a few studies have found a significant increase in presence by personalized avatars compared with generic avatars (e.g., full-body avatar [82] and virtual hands [144]).

2.4 Perceptual and Behavioral Consequences of BOI

The BOI provokes a subjective feeling of the incorporation of an artificial or virtual body into self-body representations. Hence, the intensity of the BOI is commonly measured by the subjective scores collected through questionnaires (e.g., [145]). Nevertheless, the BOI not only induces subjective SoBO but it also influences the perceptual judgments and motor actions through the change in self-body representations (i.e., the body image and the body schema); this enables the objective measures of the BOI such as proprioceptive drifts and Skin Conductance Response (SCR) (e.g., [7, 8]). In this section, the accompanying perceptual, cognitive, and behavioral phenomena with the BOI are reviewed according to the levels of the process: physiological reaction, multisensory integration, spatial perception, and cognition/action/behavior.

2.4.1 Physiological Reaction

During the RHI, when the rubber hand is "injured" by a knife or other threatening stimuli, although nothing is done to the real hand, participants usually display autonomic responses such as enhanced sweating [8]. This produces a SCR, which is a widely accepted physiological indicator of autonomic transient sympathetic arousal, either spontaneous or in response to events, specifically responses to changes in the environment, events or surprises. The SCR has been shown to be a reliable physiological index of SoBO when seeing the artificial body under threat (e.g., a hammer [146], a knife [15], a finger being bent into a painful pose [8]). Interestingly, the RHI also leads to a reduction in skin temperature of the actual limb [147]. In addition, a brain imaging study has demonstrated that a threat to an "owned" artificial hand can induce a similar level of activity in the brain areas associated with anxiety as when one's real hand is threatened [148]. They also found that the stronger the feeling of ownership, the stronger the threat-evoked neuronal responses in the areas related to pain anticipation and anxiety. Their results provide objective neurophysiological evidence that the rubber hand is genuinely incorporated into a central representation of the body. In the case of the BOI in VEs, the response to a virtual threat (e.g., a falling object [14,27], fire [11,17,91], or a saw [69]) is often measured behaviorally rather than physiologically, although several studies have validated the physiological measurement (e.g., SCR [14] and heart rate deceleration [85]). For an autonomic behavioral reaction to the threat, see Subsection 2.4.4.

2.4.2 Multisensory Integration

The inherent tendency of humans to eliminate multisensory conflicts and to bind information across the senses into meaningful perceptions induces a perceptual fusion of visual, tactile, and proprioceptive signals into a unified perception of a single owned body that constitutes the physical self [149]. Thus, the perception of one's own body in space critically depends on multisensory integration [150–152] and the process of the BOI accompanies the dynamic formation of a coherent representation of one's own body in space based on multisensory integration mechanisms [7,19,75,150,151]. Indeed, top-down semantic information has been proposed as an important feature of not only BOIs but also general multisensory integration; it has been shown that the integration of crossmodal stimuli is enhanced when these are semantically congruent [153]. In addition, theoretical frameworks that explain multisensory integration such as the causal inference models [154] and the connectionist models [155] have also recently been used to account for the mechanisms of SoBO [10].

To obtain a coherent multisensory perception in the BOI, the initial conflict between the visual and somatosensory representations of the body and the visual, tactile, and proprioceptive signals is eliminated by incorporating an artificial or virtual body into the self-body representations [150,156]. This alters the processing of sensory events such that one experiences sensory information that is attributed to the altered self-body representation as originating from one's own body [10,19]. For instance, while the rubber and actual hands are placed in different positions during the RHI, participants perceive the position of their hand to be closer to the rubber hand than it really is (i.e., proprioceptive drifts) and feel as if the touch they sense originates from the location on the rubber hand where they see the brush touching the rubber hand, rather than from their real hand [7]. Moreover, evidence also suggests that the RHI attenuates the self-generated tactile sensations by affecting the motor system that generates sensory predictions [19].

The proprioceptive drift has been classically considered an implicit, objective measure of the BOI [5,7,10]. Indeed, several studies have confirmed that the magnitude of proprioceptive drift correlates with the questionnaire scores (e.g., [7,37]), although the relationship between them is a matter of debate [157–161]. The proprioceptive drift has been observed in a variety of BOIs including both the RHI and VHI when synchronous visuo-tactile [7,76] or visuomotor [26,100,102,162–164] stimuli are provided. According to a recent report, the perceived positions of the real and artificial hands converge towards each other [165]. This contradicts the common notion of perceptual substitution of the real hand by the artificial or virtual hand in the BOI. Rather, they are in line with the view that vision and proprioception are fused into an intermediate perception. This is further evidence that the perception of our body is a flexible multisensory construct that is based on integration principles.

As for the proprioceptive drift, the effect of the anthropomorphism has been shown; a non-anthropomorphic object reduces the amount of the proprioceptive drift, compared to realistic virtual [161] and artificial [9] hands. Nevertheless, little is known about the effect of anthropomorphism on other sensory modalities. Recently, Schwind et al. [13] investigated whether the integration of conflicting visual and haptic signals can be influenced by the anthropomorphism of virtual hands when they detect surface irregularities (e.g., bumps and holes). Their results revealed that visuo-haptic integration is influenced by the appearance of virtual hands among human, robot, cartoon, abstract, and invisible hands, although the changes do not correlate with the degree of perceived SoBO.

On the other hand, as bodily self-consciousness results from the integration of two fundamental sources of body-related information, namely, signals arising from the body as perceived from the outside and external environment (i.e., exteroception, such as vision and touch) and from within the body (i.e., interoception) [166][3], it suggests that in the absence of accurate interoceptive representations, one's model of self is predominantly exteroceptive. It is considered that individuals with low interoceptive sensitivity rely mainly on exteroceptive signals (e.g., vision and touch) during body perception; hence, they are easily misled by the BOI. In fact, individual differences in the susceptibility to BOIs (i.e., malleability of body representations) are shown to be related to interoceptive sensitivity, which refers to an individual's ability to sense the internal physiological conditions of the body [169, 170]. Interoceptive sensitivity is usually considered an individual trait and is measured by a task wherein a user detects or counts their own heartbeat [171]. Tsakiris *et al.* [169] showed that interoceptive sensitivity predicts the malleability of body representations; specifically, people with low interoceptive sensitivity experienced a stronger SoBO during the BOI, indicated by both questionnaire and proprioceptive drift [169].

2.4.3 Spatial Perception

The self-body representations play a crucial role in perceiving the environment. Particularly, they help construct the external, allocentric space representation because they are defined by the body-centered, egocentric spatial reference frame [24, 172] and the BOI process involves the recalibration of body-centered representations of space [150]. In fact, the multisensory integration in space surrounding artificial limbs is modulated by the RHI, as if near-personal space was being defined with respect to the rubber hands [150, 173].

Body-based scaling is a notion that our body representations and their action capabilities are used to scale the spatial layout of the external environment [174]; the body representations act as a metric to scale the external environment. In line

[3] Some scholars categorize proprioception as part of interoception (e.g., [167]), and others distinguish the two (e.g., [168]).

with this theory, Linkenauger et al. [174] found that the change in the perceived size of objects is inversely related to the change in the size of one's virtual hand. In addition, the effect was specific to participants' virtual hands rather than another avatar's hands or a salient object of familiar size. Their account for the body-based scaling is based on Gibson's ecological approach to perception, and thus they emphasized the importance of enhancing action capabilities through the functional morphology of the body more than the change in the perceived body size itself. This approach is supported by the growing body of evidence on the remapping of space by tool use; active tool use is considered to induce morphological updating of the representation of body space in the brain [175–177].

Similarly, Van der Hoort and Ehrsson [25, 178] have shown that when a full BOI was induced over a tiny doll or a fake giant's body instead of a rubber hand using the RHI paradigm, participants perceived objects and distances as smaller and nearer for a larger body and vice versa for a smaller body. In addition, their results showed that the effect was weakened when SoBO was disrupted even though the retinal images were the same, and that the effect occurred even when the bodies were invisible [24]. Furthermore, the stronger the BOI, the stronger the effect across participants [24]. Hence, they refer to this effect as "own-body-size effect," emphasizing the importance of SoBO rather than the action capabilities. These findings indicate that the effect of the body as a fundamental reference in space perception differs from the mere use of the body in sight as a familiar size cue; rather, our implicit body representations are rather used to calibrate our perception of the external world.

On the other hand, Banakou et al. [28] investigated the semantic aspects of self-avatars on the size estimation of objects by using a VR system to induce BOI over a full-body avatar of a child or an adult. Their results showed that the object size was overestimated with the child avatar as compared with the adult avatar even though the adult avatar was scaled to the same height as the child and the elimination of the BOI under the visuomotor asynchrony control condition weakened the influence of the avatar on the size estimation. These results suggest that the semantic aspects of self-avatars have enhanced effects that trigger past experiences associated with being younger (other than solely body size) through the higher-level cognitive processes.

Moreover, various ways of manipulating the size of one's body representations, such as the manipulation of interpupillary distances or eye height [179–182], have been shown to change how one visually perceives the scales of external environments. For example, Leyrer et al. [182] found that eye height has an impact on the perception of the room's dimensions, suggesting that eye height not only influences egocentric distances, but also the dimensions of the overall environment. Furthermore, the change in the body representation through the BOI has been shown to influence the perceived weight of an object [183, 184] and self-orientation perception [185].

2.4.4 Cognition, Action, and Behavior

As mentioned in Subsection 2.4.1, when the virtual hand is threatened while the SoBO is occuring, participants react behaviorally to it. For instance, Gonzalez-Franco et al. [27] showed that the participants with a full-body self-avatar in the synchronous visuomotor condition avoided collision with the descending fan significantly more often than those in the asynchronous condition. In addition, participants experiencing a SoBO were more likely to attempt to avoid virtual threats [91] and to show a defensive withdrawal movement when the virtual arm was threatened near the distant hand position [69]. In contrast, Argelaguet et al. [11] also measured collision avoidance as a behavioral measurement of the SoBO but did not find any differences among experimental conditions (i.e., different anthropomorphism of virtual hands).

Nevertheless, delving further into the effect of self-avatar appearances on the actions and behavior of a user, it has been found to be complex. In particular, the effect on task performance is well investigated but it appears to be task-dependent. For example, McManus et al. [186] showed that the participants performed the tasks faster and more accurately when they had a self-avatar. In contrast, Streuber et al. [187] did not find an effect of a self-avatar on a locomotion task (moving through the content of the VE), an object interaction task (interacting with the content of the VE), and a social interaction task (interacting with other social entities within the VE). Yet, they speculated that the results were probably because of the limited field of view of the HMD; the self-avatar was not visible in their task even though it was present. In contrast, a self-avatar, compared with when no avatar is displayed, improved the cognitive task performance [61]. Furthermore, another study demonstrated that the anthropomorphism of a full-body avatar had a significant effect on the accuracy of pointing gestures [188]. It showed that human avatars showed high accuracy in pointing and were perceived as the most human-like, although the error in pointing did not correlate with the degree of anthropomorphism. In contrast, Tran et al. [189] have demonstrated that connectivity of hands with a torso (i.e., arm visibility) does not influence the performance of object selection tasks. Recently, Lugrin et al. [60] compared three types of self-avatar representations (controller, hand, or upper body) on players' experience and performance in an action-based VR game. Their results did not reveal any significant differences in the SoBO, immersion, and emotional and cognitive involvements, as well as the perceived control and difficulty of the game.

Several studies have investigated the effect of self-avatar appearances on a user's behavior with respect to affordance judgment, i.e., deciding what they can and cannot do in the environment. Lin et al. [140] showed that the presentation of self-avatars induced a judgment similar to that in an RE when stepping over or ducking under a pole and when stepping off a ledge in a VE. Bodenheimer et al. [190] further compared situations involving no self-avatar, a line-based skeleton avatar, and a realistic human avatar with respect to affordance judgment using a virtual ledge. Their results replicated Lin et al.'s work [140], but they found no effect of anthropomorphism. In contrast, in Alshaer et al.'s study, the presentation of a self-avatar did not influence whether the participant passed through or went around a particular gap, even though it affected the participant's sense of presence [139].

Furthermore, the BOI can even change how one recognizes the appearance of the artificial body. RHI induces cognitive changes over the rubber hand such that participants perceived the rubber hand as being more similar morphologically to their own hand [191]. Moreover, applying the RHI paradigm to a face affects self-face recognition; Tsakiris [192] showed that tactile stimulation while watching another person's face being synchronously touched produced a bias in recognizing one's own face in the direction of the other person as part of one's self-face representation.

As the BOI involves the change in self-recognition, the semantic aspects of self-avatars, such as gender [85], skin color [40, 70], attractiveness [41], and age [28, 86], have been shown to affect users' attitudes through stereotype or memory, which is automatically associated with avatars (i.e., the Proteus effect). For example, the BOI of a white person in a dark-skinned body reduced implicit racial bias [40], virtual alteration of age through the BOI of an elderly person can reduce negative stereotypes toward the elderly [41], and the BOI of a virtual child body causes implicit child-like attitude changes [28]. It also produces behavioral influences such that the use of a self-avatar with the superhero ability to fly increases helping behavior in the real world [193] and the BOI over a casually dressed dark-skinned virtual body increases their movement patterns for a West-African Djembe hand drum [70]. In addition, a recent study indicated that a robot-like avatar tends to produce a certain feeling of security when facing a dangerous situation [36]. Banakou et al. [28] explained that if the body type was not one that had been coded in memory through past experience, the participants might be influenced by socially and culturally derived expectations of how it would feel to have a specific body type.

2.5 Summary

In this chapter, Section 2.1 first reviews the avatar research with a focus on anthropomorphism, which shapes the usage of anthropomorphism in the thesis: anthropomorphism refers to human-likeness as one of the components of visual realism or fidelity of avatars, distinct from other components such as photorealism, truthfulness, and visibility.

Next, Section 2.2 summarizes the existing literature on BOI by classifying its factors into bottom-up (2.2.1) and top-down processes (2.2.2), namely, spatiotemporally synchronous multisensory/sensorimotor stimuli and the visual resemblance of artificial or virtual body appearances to humans (i.e., anthropomorphism). In current VR applications, various levels of anthropomorphic appearances of self-avatars are used. Although highly precise visuomotor synchrony is available between the movements of an avatar and one's own body thanks to the developments in low-cost, high-quality body-tracking systems, the intensity of the BOIs over self-avatars in recent VR systems largely depend on the avatars' anthropomorphism, rather than on visuomotor synchrony. Thus, it is important to investigate how the anthropomorphism of self-avatars influences the users' VR experiences—how they perceive and behave in VEs. Furthermore, as the appearance of the self-avatars can be easily changed by designers and users, clarification of the influences of self-avatar appearance on VR experiences makes it possible to freely design the experiences according to the situation and purpose.

It follows that Section 2.3 introduces the concepts that are closely related to the SoBO. First the SoBO is described as one of the components of the SoE in the field of VR (2.3.1). Then, the studies in Chapter 3 and 4 measured the degree of the SoE, not just the SoBO, using a questionnaire. Next, the SoA is introduced as a concept referring to the self-attribution of action whereas the SoBO refers to the self-attribution of a body (2.3.2). The SoA is deeply involved in the study in Chapter 3, which deals with the self-attribution of remapped hand movements. Then, the sense of presence is introduced (2.3.3). It is related to the study in Chapter 5 dealing with behavior, as "respond as if real" in VEs provides an operational definition of the concept of presence; how realistically users behave in a VE is associated with their felt sense of presence.

Finally, Section 2.4 identifies the accompanying perceptual and behavioral phenomena with the BOIs depending on the process levels. The SCR is first introduced as a physiological measurement of the BOIs (2.4.1). Hence, the study in Chapter 5 provided participants with threatening stimuli and used the SCR to measure.

Next, Subsection 2.4.2 describes the process of the BOI as depending critically on the multisensory integration and as a consequence the BOI induces proprioceptive drift, where proprioceptive self-localization of a hand is shifted toward a virtual hand. Chapter 3 attempts to exploit this fact in virtual hand interaction techniques such as retargeting (e.g., [29]) that leverage visual dominance over proprioception by remapping physical hand movements onto different virtual movements. Hence, it examines whether a realistic avatar can foster the integration of conflicting visuo-proprioceptive information, resulting in further leveraging of visual dominance, thus making the remapping less noticeable. In addition, it also measures participants' interoceptive sensitivity, which is introduced in this subsection as an index that has been shown to predict individual differences in the susceptibility to BOI.

Then, Subsection 2.4.3 states that the changes in the size of body representation caused by BOIs influence the spatial perception, such as object size perception. Still, whether spatial perception is affected by anthropomorphism or not is a hitherto unexplored aspect of avatar representation. Thus, Chapter 4 explores whether a realistic self-avatar better fosters the influence of avatar body size on object size perception in vEs.

Lastly, Subsection 2.4.4 summarizes the influence of BOIs on cognition, action, and behavior. Although the effect of semantic aspects of self-avatars on behavior (i.e., the Proteus effect) have been extensively shown, the effect of self-avatar appearance on actions and behavior are complex, and little is known about the effect of anthropomorphism except that a stronger SoBO induces a more realistic behavioral response to a threat. Hence, Chapter 5 hypothesizes that realistic self-avatars could elicit realistic behavior even when the situation is not threatening and attempts to solve the issues of users walking through virtual walls (i.e., unrealistic behavior) in VEs.

Chapter 3

Effect on Visuo-proprioceptive Integration

In this chapter[1], we investigated whether the anthropomorphism of self-avatars influenced visuo-proprioceptive integration. It is known that vision often dominates over proprioception. Taking advantage of this human nature, previous research has developed a variety of hand interaction techniques that remap physical hand movements onto different virtual movements. However, when the offset between virtual and physical hands increases, the user become aware of the remapping. We hypothesized that realistic avatars can make the remapping less noticeable by fostering a SoBO over the remapped hands. To verify the hypothesis, we investigated the effect of the anthropomorphism on sensitivity to the remapping offset. The results reveal that realistic avatars increased the detection threshold (i.e., lowered sensitivity) by 31.3% compared to abstract avatars when the leftward shift was applied (i.e., when the hand moved away from the body-midline). In addition, the proprioceptive drift (i.e., the displacement of self-localization toward an avatar) was larger with realistic avatars for leftward shifts, indicating that visual information was given greater preference during visuo-proprioceptive integration in realistic avatars. Our findings reveal that the more visual dominance over proprioception can be exploited by manipulating the anthropomorphism of self-avatars.

[1]The content in this chapter will be published as Nami Ogawa, Takuji Narumi, and Michitaka Hirose (2020). Effect of Avatar Appearance on Detection Thresholds for Remapped Hand Movements. *IEEE Transactions on Visualization and Computer Graphics*. IEEE. (to appear) https://doi.org/10.1109/TVCG.2020.2964758 (© 2020 IEEE)

3.1 Introduction

Our perceptual system inherently integrates multisensory information from different sensory receptors to obtain a robust and coherent perception of the environment and our own bodies (see Subsection 2.4.2 for details). When vision signals conflict with other sensory signals, visual information often becomes dominant, even without subjective awareness of the conflict (i.e., visual dominance or visual capture [194]).

In the field of VR, a number of hand interaction techniques, such as retargeting (e.g., [29, 195–200]), redirection (e.g., [119, 201]), pseudo-haptics (e.g., [202]), and control to display (C/D) ratio techniques (e.g., [203]), leverage visual dominance over proprioception. Typically, physical hand movements are remapped onto different virtual movements; thus, the position of the virtual hand is often displaced from the position of the actual hand. However, when the displacement increases, vision and proprioception are no longer integrated. Consequently, the remapped movements cannot be considered as one's own movements, that is, they cannot be self-attributed [204]. In these hand remapping techniques, larger displacement while ensuring that the remapping is less noticeable is a common challenge.

Interestingly, multisensory integration of body parts, which is the basis of the hand remapping techniques, also constructs bodily self-consciousness, specifically the SoBO, i.e., the self-attribution of body [10]. SoBO is elicited by a user's hand and the virtual hand's synchronous movements as long as the displacement of the virtual hand is under a threshold [14]; however, it is weakened when the displacement increases [78], as in the case of hand remapping techniques. However, only a few studies have associated the SoBO with hand remapping techniques despite the fundamental link between them (e.g., [199, 205]). More importantly, SoBO is not only influenced by visuomotor or visuo-proprioceptive congruency but also by the appearances of an avatar (i.e., virtual self-representation); it is attenuated or even eliminated using abstract avatars than using realistic avatars [11–13] Therefore, we hypothesized that realistic avatars can better foster the self-attribution of remapped virtual hand movements than abstract avatars, thus making the remapping less noticeable.

To the best of our knowledge, this study is the first to investigate the unexplored effect of avatar appearance on the self-attribution of remapped movements. To this end, we conducted an experiment to measure the threshold of self-attribution when one's hand movements are remapped onto different virtual movements. In the experiment, we compared two kinds of the avatar appearances: realistic and abstract (i.e., a realistic human hand vs. a spherical pointer; Figure 3.1). Participants executed reaching movements with their right hand while horizontal (left or right) shifts were incrementally applied at different angles in the trials (Figure 3.2). They were asked to discriminate if the remapped movement that they observed matched the movement of their own hand after each reaching movement. The results show that the threshold for remapping detection is approximately 31.3% higher when using realistic avatars than when using abstract avatars when shifts were applied in the left direction (i.e., when the physical hand moved in a direction away from the body-midline). In addition, we measured proprioceptive drift (i.e., the displacement of proprioceptive self-localization toward a perceived virtual hand from the actual hand position; see Subsection 2.4.2 for details), which is a measurement of the strength of the BOI [7]. The results show that the proprioceptive drift was larger with realistic avatars than with abstract avatars in the case of leftward shifts. This finding indicates that visual information is given greater importance in visuo-proprioceptive integration when realistic avatars are used, as compared to abstract avatars. For both measurements, no significant differences were observed between the two avatars when the rightward shift was applied. To summarize, the results show that compared with an abstract avatar, the realistic avatar makes remapping less noticeable and brings the proprioceptive hand position closer to that of the virtual hand. The use of realistic avatars instead of abstract avatars can potentially improve a wide variety of hand interaction techniques because it can mitigate a range of unnoticeable displacements without changing the mapping model itself.

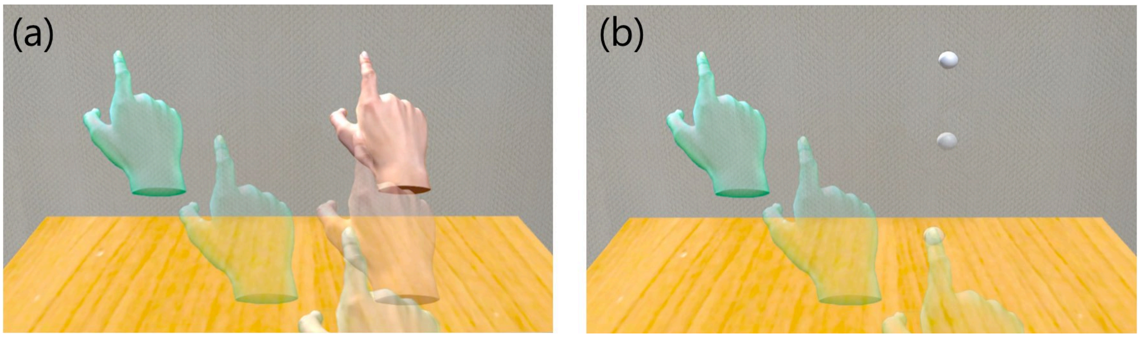

Fig. 3.1: Two avatar appearances used in the experiment. Participants execute a reaching movement with visual feedback of the (a) human hand (*realistic*) or (b) spherical pointer (*abstract*) to which horizontal shits are incrementally applied. The semi-transparent virtual hand represents the physical location of the participant's hand (not displayed in the actual experimental scene). © 2020 IEEE.

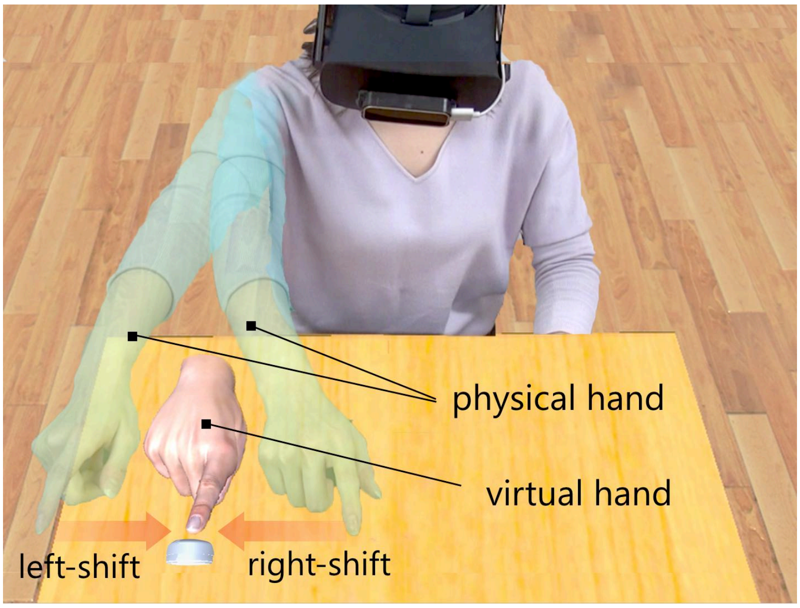

Fig. 3.2: Hand remapping technique. A virtual hand is displayed at the position either in the left or right direction (from a first person perspective) of the physical hand. The participants adjusted their trajectory to compensate for the shift so that the virtual hand could reach the virtual target. © 2020 IEEE.

3.2 Visual Dominance in Hand Interaction Technique

Owing to the nature of human multisensory integration, when vision and other sensory signals conflict moderately, these signals are integrated to generate a single estimate. For instance, in the well known ventriloquist effect, the speech sounds is perceived as coming from the location of the dummy's moving mouth rather than the ventriloquist's unmoving mouth [206]. In such case, vision often dominates other sensory information; thus, the integrated perception relies more on visual information (i.e., visual dominance or visual capture [194]). In such case, vision often dominates other sensory information; thus, the integrated perception relies more on visual information (i.e., visual dominance or visual capture [194]). Visual dominance holds true, particularly over the senses that have lower spatial resolution than vision, such as proprioception [207–211], although this is not always the case, depending on sensory combinations and their relative reliability [149, 152, 212, 213].

In the field of VR, visual dominance over proprioception is often exploited in hand interaction techniques, where the movement of a virtual hand is remapped for a number of purposes (i.e., hand remapping technique). For example, in a series of retargeting techniques, the reaching movements of a virtual hand are mapped to guide the user's actual hand toward haptic props for providing passive haptics for multiple virtual objects [29, 195–197]. On the other hand, hand redirection techniques enable modification of the perceived properties, such as shape, of a physical object when the user continuously touches and explores surfaces [119, 201]. These techniques can also be used to prevent a virtual hand from interpenetrating other virtual objects [196, 214] and to improve the perceived performance of shape displays [200]. Although movement remapping is often combined with passive haptics, it can also be used without haptics to make virtual targets more easily accessible [198] and to make overhead interactions less tiring [199]. Furthermore, pseudo-haptics simulate or enrich haptic sensations such as stiffness, the presence of bumps and holes, and shape without necessarily requiring a haptic interface (for a review see [202]). Lastly, the C/D ratio interaction techniques break the 1:1 mapping between the actual and virtual hands (i.e., control to display ratio) to improve interaction by increasing precision or speed [203].

In hand remapping techniques, making movement remapping less noticeable is a common challenge. In essence, a large discrepancy between the position of the real and virtual hands causes the user to become aware of the remapping (e.g., up to $\approx 4.5°$ [205]). Hence, to apply larger shifts, researchers attempted to find a better mapping between the virtual and real coordinate systems. For instance, in the haptic retargeting [29], the entire virtual world is rotated, as in the redirected walking technique [215–217] as well as the mapping of the bodies. Similarly, Feuchtner and Müller proposed Ownershift, which gradually applies a shift after ballistic movements [199]. However, these solutions have limitations in that they limit the user movements or situations unnaturally. In this study, we aim to alleviate the range of unnoticeable offset by focusing on how we perceive the virtual hand movements as our own, instead of finding better mappings.

Hand remapping techniques in VR are often explained through visual dominance alone. However, as the techniques inevitably use virtual bodies, the knowledge of bodily self-consciousness should also be incorporated into its theory and evaluation. Indeed, studies in the field of psychology and cognitive neuroscience have also demonstrated that we can self-attribute visual hand movements, which are different from real hand movements (see Subsection 2.2.1 and 2.3.2 for details). For example, SoA and SoBO can occur over drifting avatars [14], movements made by someone else [115, 117], and even over an avatar's autonomous movements without the user's actual movements [95, 218]. Nevertheless, only a few studies have addressed the concept of SoA and SoBO in hand remapping techniques. Only recently, Debarba et al. [204] investigated the effect of the type of remapping (i.e., helping or hindering) on self-attribution of hand movements, and they discussed their results in terms of SoA. In addition, the first study which evaluated the users' SoBO with a hand remapping technique was recently conducted by Feuchtner and Müller [199], who proposed a novel remapping technique for overhead interaction. Zenner and

Krüger [205] also evaluated the SoBO in conjunction with detection thresholds for hand redirection techniques as one of various indicators of subjective impressions.

In contrast, we hypothesize that the induction of a stronger SoA or SoBO can effectively foster the self-attribution of virtual hand movements, despite visuo--proprioceptive discrepancies. That is, the detection threshold for discrepancy can be increased. In this study, we attempted to manipulate the strength of SoBO rather than SoA, as SoBO is greatly influenced by the semantic features of the visual body [10], which can be easily manipulated in VR. In contrast to SoBO, the main cue for SoA is the spatiotemporal contiguity between one's own and observed movements or outcomes [93, 94, 98]; this reduces according to the increase in the shift of remapping. Nevertheless, studies suggest that SoBO and SoA may strengthen each other if they co-occur [37, 38, 99, 100], although some studies have indicated that both experiences can double dissociate (for a review, see [101]). Hence, we consider that strengthening SoBO may influence even the detection thresholds of discrepancy between the virtual and actual movements, although it can be related to the sense of self-attribution of action (i.e., SoA) rather than that of body (i.e., SoBO).

Considering the abovementioned studies on self-body perception, modulating top-down expectations conveyed by avatar appearances also influences the SoBO over a virtual hand, the movements of which are distorted from one's own. Hence, in the case of visuo-proprioceptive integration, the realistic avatar may foster the integration of conflicting information, resulting in further leveraging of visual dominance.

3.3 Hypotheses

Our hypotheses were as follows:

H1 The detection threshold of the movement remapping is higher with realistic avatars than with abstract ones.

H2 The amount of proprioceptive drift is larger with realistic avatars than with abstract ones.

H3 The participants with lower interoceptive sensitivity tend to exhibit higher thresholds.

H4 The participants with lower interoceptive sensitivity tend to be well influenced by avatar appearance in terms of the thresholds.

3.4 Experiment

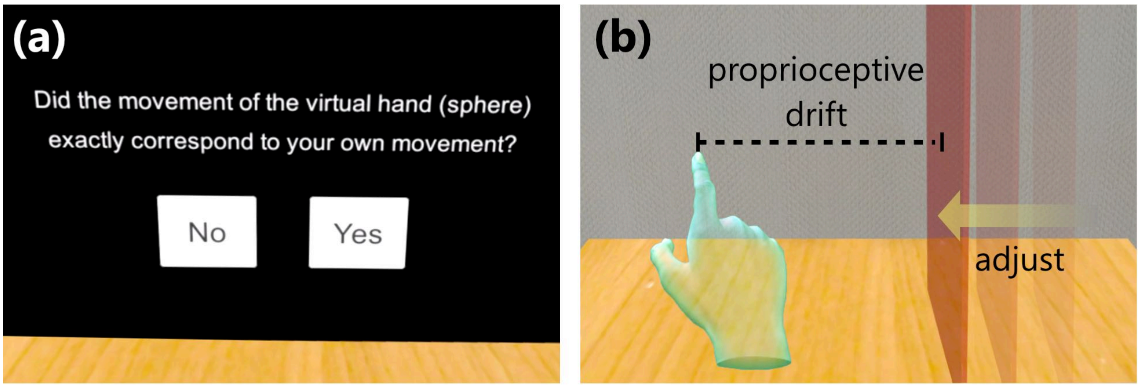

Fig. 3.3: Experimental tasks. (a) In the remapping detection task, participants answered whether the movements of the avatar corresponded to their own movements. (b) In the self-localization task, participants estimated their actual hand position (represented by a semi-transparent hand; not displayed in the actual experimental scene) by shifting the position of a thin board by using a controller. The difference between the estimated and actual positions is referred to as proprioceptive drift. © 2020 IEEE.

The main objective of the experiment was to investigate whether 1) a realistic avatar makes the movement remapping less noticeable compared with the abstract avatar (*remapping detection task*; Figure 3.3 (a)). To further support this objective, we also studied whether 2) a realistic avatar gives greater importance to the visual information for visuo-proprioceptive integration than an abstract avatar (*self-localization task*; Figure 3.3 (b)). In both tasks, participants reached for a virtual button with visual feedback of their right hand; this movement was remapped by different shifts for each trial. The visual feedback was either a realistic or an abstract self-avatar (i.e., realistic hand or spherical pointer; Figure 3.1). In the remapping detection task, we asked the participants to discriminate whether the visual movements corresponded to their own movements to estimate the detection threshold for remapping. In the self-localization task, we asked the participants to estimate the position of their actual index fingertip without observing it to measure the proprioceptive drift. In addition, we investigated whether 3) individual differences in the perception of remapped movements can be explained by interoceptive sensitivity, an index of a personality trait that reportedly predicts the susceptibility to BOIs (*heartbeat counting test*). In the heartbeat counting test, participants silently counted their heartbeat without tracking their pulse to measure interoceptive sensitivity. Finally, we measured the subjective SoBO through a *questionnaire*.

3.4.1 Remapping Model

We used a basic retargeting model that linearly remaps a hand movement by a fixed angle. During a reaching movement, a horizontal shift is incrementally applied to the virtual hand position depending on its distance to the target. The participants were exposed to a continuous directional discrepancy between the virtual and physical hand movements. Therefore, they adjusted their trajectory to compensate for the shift such that the virtual hand can successfully reach the virtual target. This type of remapping model is often accompanied by a physical object to provide passive haptic feedback (e.g., [29, 195, 196]). Nevertheless, we did not provide the participants with haptic feedback so as to verify the effect of avatar appearance by using the simplest model possible.

As shown in Figure 3.4, the model maps the physical position of an index fingertip ($\mathbf{p}$) onto a virtual position ($\mathbf{p}'$) according to a shift (s) when the depth position of $\mathbf{p}$ is between the initial and target positions ($O_z < p_z < T_z$). S_{max} represents the maximum shift applied when $\mathbf{p}$ reaches $\mathbf{T}$, and it changed for every trial. S_{max} takes a positive value for a rightward shift and a negative value for a leftward shift. If D and d are the distance between $\mathbf{O}$ and $\mathbf{T}$ and between $\mathbf{p}$ and $\mathbf{O}$ along the depth

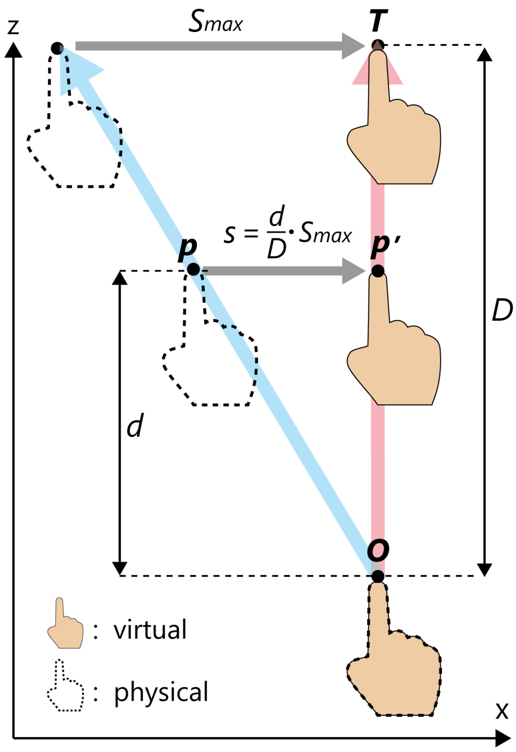

Fig. 3.4: Top view of the retargeting model used in the experiment, illustrating the case with a right-shift and realistic avatar. The abscissa and ordinate represent the horizontal and depth axes, respectively. The position of virtual fingertip (**p'**) was obtained by horizontally shifting the position of physical fingertip (**p**) according to the shift (s) during a reaching movement. S_{max}, which is the maximum shift applied when the virtual fingertip reaches the target, changed for every trial. ©2020 IEEE.

direction, respectively ($D = T_z - O_z$, $d = p_z - O_z$), s is given as $s = \frac{d}{D} \cdot S_{max}$. In addition, to prevent the virtual fingertip from penetrating the button, p_z is restricted to below T_z, whereas the physical and virtual positions are collocated when p_z is smaller than O_z. To summarize, the following equations are used to calculate $\mathbf{p}'$:

$$(p'_x, p'_z) = \begin{cases} (p_x + S_{max}, T_z) & (p_z \geq T_z) \\ (p_x + s, p_z) & (O_z < p_z < T_z) \\ (p_x, p_z) & (p_z \leq O_z) \end{cases}$$

During the experiment, we manipulated the value of S_{max} for every trial while **O**, **T**, and D remained constant ($D = 20$ cm). Hereafter, we refer to S_{max} as *shift*.

3.4.2 Participants

Before the experiment, we performed a power analysis to estimate the necessary sample size using G*Power with regards to the main response variable (i.e., detection threshold). Based on the prior analysis of the informal pilot experiment, we expected the effect size to be large. For an effect size of 0.8, a significance level of 0.05, and a power of 0.8, the minimum sample size was computed as 15. Thus, we set the sample size to 16 and conducted the experiment with 16 participants. However, as we had to exclude the data from one participant (see Section 3.5.1 for details), we recruited another participant. Consequently, a total of 17 individuals participated (14 males and 3 females; 24.53 ± 4.42 (SD) years old; 169.94 ± 7.77 (SD) cm tall). All participants were recruited through social media, unaware of the true purpose of the experiment, and had normal or corrected-to-normal vision. We did not recruit participants with glasses because they could have difficulties in correctly wearing a head-mounted display (HMD). All participants except one self-reported as being right-handed. Nine participants had limited experience with VR, whereas eight were familiar with VR. They signed an approved statement of consent, and they were compensated with an Amazon gift card amounting to approximately \$10. The experiment was approved by the local ethical committee.

3.4.3 Materials

Apparatus

The experimental apparatus included a Windows-based computer (with an Intel i7-8750H, 16 GB RAM, and an NVIDIA GTX1060), a hand-tracking sensor (Leap Motion Controller), an HMD set (Oculus Rift CV1), a controller (Oculus Remote), and a pulse oximeter (KONICA MINOLTA PULSOX-Lite). The experimental program was developed using Unity 3D.

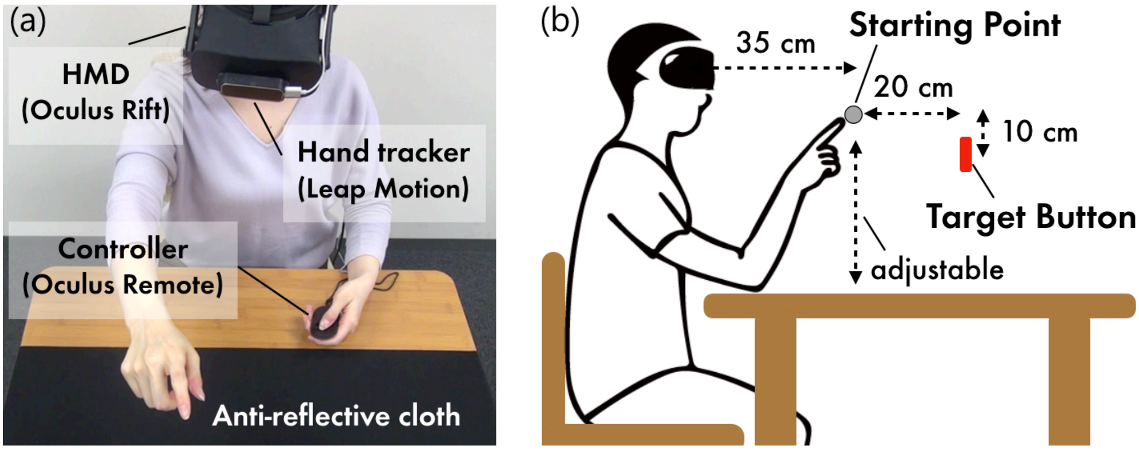

Fig. 3.5: (a) Front view of physical setup. (b) Arrangement of virtual stimulus (side view). The starting point and target button were placed 10 cm to the right of the participants' body mid-line. ©2020 IEEE.

Hand Appearance

In line with the previous studies (e.g., [11–13]), we adopted the Leap Motion Controller as the hand-tracking device. This controller can track the forearm, hand, and fingers of the users within a 1-m radius without the need to wear gloves or markers. Its estimations deviate from the actual positions by 1.2 mm on average [219]. Therefore, we considered it to be sufficiently accurate when tracking hands in this study. Nevertheless, the following two steps were considered to ensure optimal tracking conditions for the leap motion. First, we placed an antireflective cloth on the physical table to limit infrared interference (Figure 3.5). In addition, we asked the participants to hold the controller with their left hands and place the hand on their laps during the tasks. This instruction was intended to prevent detection artifacts by keeping their left hand away from the field of view of the leap motion. In Figure 3.5, the left hand is placed on the table only for clarity.

We used two types of avatar appearances, namely *realistic* and *abstract* (Figure 3.1). For the *realistic* condition, we used a realistic gender-neutral virtual hand. The forearm was not included in the model, as in previous retargeting studies (e.g., [195, 196, 200, 214, 220, 221]). A 3D model of the realistic hand was obtained from the Leap Motion Software Development Kit (SDK). For the *abstract* condition, we chose a sphere that moved in correspondence with the tip position of the participant's index finger as a non-anthropomorphic avatar. One of the reasons for this choice was that proprioceptive drift is commonly measured using the position of the tip of an index finger (e.g., [7, 37]). Thus, it was necessary to use a model for which the position of the tip of an index finger was as obvious as that of the realistic hand model. In addition, task performance is known to influence action-effect integration in SoA [204, 222]. Considering Fitts' law [223], the difference in the cursor size (i.e., the avatar size for pushing the button) could influence the task performance. Thus, for a fair comparison, we had to ensure that both avatars maintained the same functionality in pushing the button despite their different appearances. Thus, we chose a spherical model, the diameter and end position of which corresponded with the width and end position of the index fingertip of the realistic hand model.

Experimental Scene

The experimental scene was designed to display a realistic room composed of a wooden table and shelves. A virtual button with a diameter of 8 cm and a semitransparent virtual sphere with a diameter of 2.5 cm represented the target and initial positions, respectively. Their spatial configurations are shown in Figure 3.5 (b). They floated 10 cm to the right of the body mid-line so that the participants' right arm should be natural and comfortable to touch the initial point while keeping their elbow on the table. To personalize the height of the initial point depending on the arm length, the participants wore the HMD and were asked to adjust the height of the initial point by pushing the buttons of the controller to reach a comfortable posture when touching the initial point with the tip of their index finger at the beginning of the experiment. The height of the button was also changed according to the adjusted height of the starting point, to keep the relative positions identical. The above-mentioned values and procedures were determined through the informal pilot study to retain the participants' comfort and eliminate the influence of fatigue.

3.4.4 Remapping Detection Task

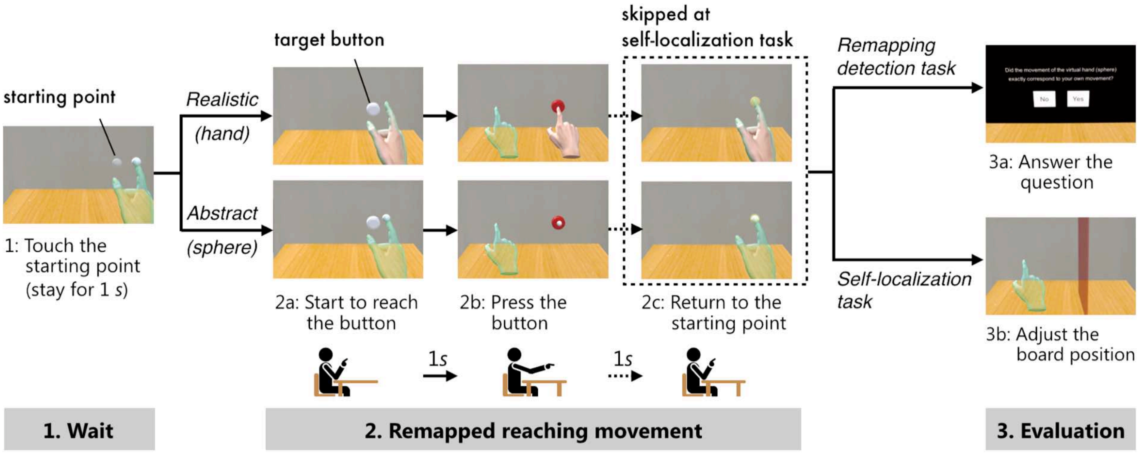

Fig. 3.6: Illustrations of a trial. The semi-transparent virtual hand represents the physical location of the participant's hand (not displayed in the actual experimental scene). 1a) The participants placed the index fingertip of the hand inside the marker of the initial point. 1b) They kept the fingertip at this point for 1 s. 2a) They start a reaching movement with remapped visual feedback of the human hand (*realistic*) or spherical pointer (*abstract*). 2b) They press the target button. At that moment, the avatar's displacement from the actual hand is the exact amount of *shift*, which changes for each trial. 2c) They returned the fingertip to the initial point with remapped visual feedback only for the remapping detection task. 3a) The participants answered whether the visual movements corresponded to their own movements. 3b) The position of the board was adjusted to correspond with the perceived location of their invisible index finger. ©2020 IEEE.

This task was aimed at estimating the detection thresholds (i.e., the lowest levels of discrepancy that can be detected) of the movement remapping. To this end, we used a two-alternative forced choice (2AFC) task with an adaptive staircase method [224]. The task followed a 2 × 2 factorial design (within-subjects), and the independent variables were avatar appearance (*realistic and abstract*) and shift direction (*left and right*). Further, the dependent variable was the detection threshold.

The participants first executed a reaching movement with their right hand in each trial. To start each trial, the participants were asked to place their right index fingertip at an initial position (Figure 3.6, 1). Before starting the trial, they could view the same sphere model as in the abstract condition without any movement remapping. When the trial started, the program proceeded to beep every 1 s. This was introduced to ensure that the movement speed was almost constant among trials and to avoid the influence of speed on the task. Participants were asked to maintain a still posture at the initial position for 1 s until they heard the next beep. Then, the mark at the initial position disappeared, and a button appeared at the target position. Simultaneously, either the realistic or abstract avatar, which moved according to the remapping model, was displayed (Figure 3.6, 2a). The shift of the model changed for every trial. The participants reached the button in 1 s such that they could push it with the virtual tip of the index finger immediately upon hearing the beep (Figure 3.6, 2b). When they successfully pushed the button to a depth of 2 cm, the button disappeared.

In the remapping detection task, the participants instantly retracted their hand in another second so that they could move back to the initial position when they heard the next beep (Figure 3.6, 2c). During the retraction, the self-avatar was still visible, and its movement followed the retargeting model. The self-avatar disappeared when the participants successfully touched the marker at the initial point. Then, they answered a 2AFC task (yes/no) (Figure 3.6, 3a). The displayed question was a Japanese-translation of "Did the movement of the virtual hand (sphere) exactly correspond to your own movement?". They could select the answer by pressing the left or right button on the controller held in their left hand, and they confirmed it by pressing the center button. They proceeded with the trials consecutively, although they could freely rest during the interval of trials if they needed.

Staircase Procedure

In the remapping detection task, the shift amount was varied between trials according to a simple up–down staircase procedure (Figure 3.7). When the participant was aware that the movement was remapped (i.e., a "no" response) at a trial, the staircase reduced the shift amount by 1.5 cm for the next trial. Likewise, in the case

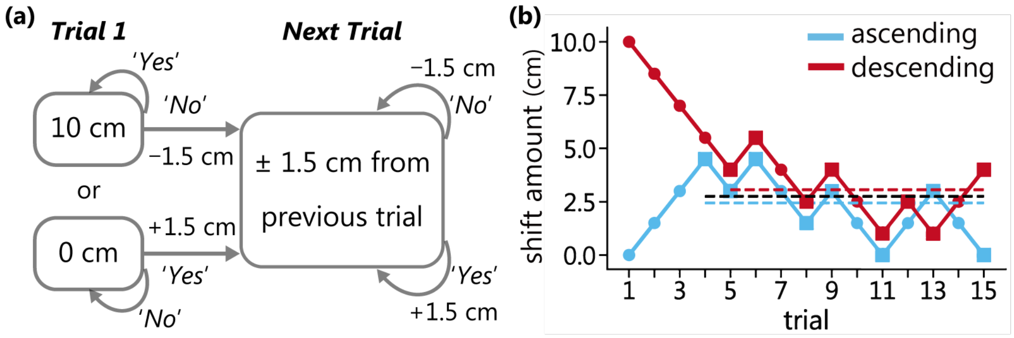

Fig. 3.7: (a) The staircases increase or decrease the shift amount by 1.5 cm for every trial according to the answer. (b) An example panel represents the trial histories for two interleaved staircases that converged from above and below the expected threshold region (descending and ascending staircases, respectively). The dashed lines indicate the mean of staircase reversals (represented by square markers), which approximates the detection threshold (blue: ascending, red: descending, and black: mean of both staircases). ©2020 IEEE.

of response "yes", the procedure raised the shift amount by 1.5 cm. This stepping rule converged to the 50% point of the psychometric function, which corresponds to the detection threshold at which remapping can barely be detected. As typically used in the staircase method, to prevent participants from being aware of the scheme and to exclude any possible biases resulting from this awareness, two staircases were interleaved for each condition. The descending and ascending staircases began sufficiently above (10 cm) and below (0 cm) the expected threshold region, respectively, the values of which were estimated during the informal pilot study. In any trial, the shift amount cannot take a negative value (i.e., remapping to the opposite direction of the condition). For example, in case the participant's response was "no" when the shift amount was 0 cm (i.e., the movement was not remapped), the shift amount did not change to -1.5 cm but remained 0 cm for the next trial. Similarly, when their response was 'no' to the 1-cm-shift trial in the descending staircase, the shift changed to 0 cm rather than −0.5 cm for the next trial. In this case, after they answered "yes" to the 0-cm-shift trial, the shift was increased to 1 cm and not 1.5 cm.

Eight unique types of staircases (two levels of avatar appearance $\times$ two shift directions $\times$ two initial shifts) were alternately performed in a randomized order until 14 trials were completed for all the staircases. That is, the participants proceeded through eight staircases in parallel; they first completed the first trials from all eight staircases in a randomized order and then moved to the next eight trials in another randomized order. This design is aimed at preventing the influence of adaptation. Each participant performed a total of 112 trials. Note that when the participant completed the 14th trial, the staircase could determine the shift amount for the 15th trial. The average of the reversal points (i.e., the point at which the response changes from "yes" to "no" or vice versa) is typically used to estimate the detection threshold.

3.4.5 Self-Localization Task

This task was aimed at assessing proprioceptive drift, that is, the degree to which the perceived hand location drifted toward the self-avatar. We hypothesized that the proprioceptive drift as well as the thresholds of self-attribution of remapped movements was influenced by the avatar appearance. The proprioceptive drift can not only be used as a measurement of SoBO but also of how vision dominates proprioception.

The proprioceptive drift was measured through the visual estimations of the perceived finger position, as in previous studies (e.g., [72, 160, 162, 225]). We used an adjustment method; the participants continuously changed the position of the virtual thin board until its position was perceived as the same as their finger position. To eliminate the influence of anchoring effects, we used two directions of adjustment: the board appeared at either 25 cm to the left or right from the center of the virtual button for each trial. We assumed that the positions were sufficiently far from the participants' perceived hand location.

The task followed a 2 $\times$ 5 factorial design (within-subjects). The independent variables were the avatar appearance (*realistic and abstract*) and shift (-10 cm, -5

cm, 0 cm, 5 cm, and 10 cm). Moreover, the negative and positive values indicate leftward and rightward shifts, respectively. Based on our informal pilot study, we anticipated that the thresholds with respect to the shift amount in the remapping detection task would be approximately 5 cm on average and seldom exceed 10 cm. Hence, by setting the shift factor to ±5 and ±10, we expected that we could collect data of proprioceptive drifts for both cases in which the participants easily noticed the discrepancy (±10 cm) and experienced difficulty in realizing the discrepancy (±5 cm). The dependent variable was the proprioceptive drift, which was measured by recording the horizontal position of the virtual board from the actual finger position.

In each trial, the participants first executed a reaching movement as in remapping detection task. The difference was that they kept their arm still after completing the one-way reaching movement. When they pushed the target button (Figure 3.6, 2b), the button and self-avatar disappeared. Instead, a virtual thin board appeared (Figure 3.6, 3b). Then, the participants adjusted the horizontal position of the board to match the position with the perceived location of their own index finger. They could continuously move the board with a precision of 1 mm by pressing the left and right buttons on the controller held in their left hand. When they were satisfied, they pressed the center button to finalize the answer. While estimating their perceived index finger position, they were not allowed to move their arm. Then, they retracted their arm to the initial position for the next trial. During the retraction, the self-avatar was still invisible because the visible position would provide feedback for the correct answer. When the tip of the actual index finger approached the starting position within a 5-cm radius from the center, the sphere model was displayed at the tip of the index finger.

Twenty unique types of trials (two levels of avatar appearances $\times$ five levels of shift amounts $\times$ two adjustment directions) were successively performed in a randomized order. These 20 unique trials constituted a block, and the task constituted of two blocks. Thus, each participant performed 40 trials.

3.4.6 Heartbeat Counting Test

There are individual differences in detecting visuomotor or visuo-proprioceptive discrepancies over remapped movements. Yet, the cause of these differences has not been well understood. Thus, we conducted this test to assess individual interoceptive sensitivity, which reportedly predicts the susceptibility to BOIs (see 2.4.2 for details), to determine if it could also predict the individual differences in the self-attribution of remapped movements.

The susceptibility to BOI has two aspects in this experiment: how much the threshold is increased, i.e., decrease in the sensitivity to the visuomotor discrepancies, irrespective of avatar appearance, and how susceptible one is to the avatar appearance, that is, how one's response in each measurement differed between the levels of avatar appearance. Hence, we expected that interoceptive sensitivity may account for one's sensitivity to the remapping or susceptibility to avatar appearance.

We used the mental tracking method [226], which has been widely used to assess interoceptive sensitivity (e.g., [169, 171]). The test was conducted without using the HMD. The participants were asked to count their heartbeat as follows: "Without manually checking, e.g., touching your heart or vein, silently count your heartbeat from the time you hear 'start' until you hear 'stop'. At the end of each interval, please verbally report the number of counted heartbeats." This process was repeated for three time intervals of 25, 35, and 45 s, presented in a random order. The participant was informed of the length of the time interval. No feedback regarding their performance was given to the participant. After one brief training session (15 s), the actual experiment started. There were 20-s breaks after every interval. During the task, the actual heart rate was monitored with a pulse oximeter attached to the participant's left index finger.

The interoceptive sensitivity was estimated by calculating the normalized difference between their estimated and actual heart rates. Each participant's interoceptive sensitivity score was calculated as the mean score of three trials according to the following transformation [226, 227]:

$$\frac{1}{3}\sum_{i=0}^{3}(1-\frac{|recorded-counted|}{recorded}) \tag{3.1}$$

The score could vary between 0 and 1, with higher scores indicating small differences between recorded and counted heartbeats (i.e., higher interoceptive sensitivity).

3.4.7 Questionnaire

The subjective evaluation of embodiment for virtual avatars was assessed through a questionnaire. Although we were interested in SoBO in particular, we measured the sense of embodiment [5], which consists of SoA, SoBO, and the sense of self-location (i.e., one's spatial experience of being inside a body), as they are closely related to each other. We used Gonzalez–Franco and Peck's VR-specific avatar embodiment questionnaire [145], supplemented by a Japanese translation. We omitted items that were not applicable to our study context, such as the question regarding tactile sensation. Consequently, the questionnaire consisted of nine items and three subsets of questions: body ownership (Ownership), agency and motor control (Agency), and

Table 3.1: Questionnaire items to measure the sense of embodiment based on [145]. Items in italics represent control questions. ©2020 IEEE.

Subscale	Question
Ownership	1) I felt as if the virtual hand (sphere) was my hand. 2) *It felt as if the virtual hand (sphere) I saw was someone else's.* 3) *It seemed as if I might have more than one hand.*
Agency	4) It felt like I could control the virtual hand (sphere) as if it was my own hand. 5) The movements of the virtual hand (sphere) were caused by my movements. 6) I felt as if the movements of the virtual hand (sphere) were influencing my own movements. 7) *I felt as if the virtual hand (sphere) was moving by itself.*
Location	8) I felt as if my hand (fingertip) was located where I saw the virtual hand (sphere). 9) *I felt out of my body.*

body location (Location) (Table 3.1). Each response was scored on a seven-point Likert scale (-3 = strongly disagree; $+3$ = strongly agree). The evaluation was performed for each level of avatar appearance.

The questionnaire was performed within the HMD. During the questionnaire, the participants could see the avatar of their right hands. The avatar appearance was either realistic or abstract, and the avatar moved in exact correspondence with their real movements. They could freely move their right hand. A question from the questionnaire and a slider with numbers from -3 to $+3$ were displayed. The questionnaire was simultaneously shown in English (original) and in Japanese (translated). The participants were instructed to answer each question based on the impression of the avatar they were observing (i.e., the movement-correspondent avatars) but not based on the recall of the main tasks. Each question was answered twice for the two types of avatar alternately in a randomized order. They could choose the answer by pressing the buttons on the controller held in their left hand. Once they answered the question regarding the observed virtual avatar, the appearance changed to the other, while the question remained the same. After they answered the same question for two types of avatar appearances, the next question was shown, which was randomly chosen from the nine items.

3.4.8 Procedure

The basic procedure of the experiment was (a) remapping detection task, (b) heartbeat counting test, (c) self-localization task, and (d) questionnaire. The whole experiment took approximately 1 h to complete. The overall flow of each experiment is described as follows. The steps in italics were conducted while the participants' wearing the HMD. The participants

1. read and signed an experimental consent form.
2. received instructions and an overview of the task.
3. *completed the training and the main trials of remapping detection task (10–15 min).*

4. completed the heartbeat counting test (3 min).
5. *completed the training and main trials of self-localization task (10–15 min).*
6. *completed the embodiment questionnaire (5–10 min).*
7. took off the HMD and filled out a demographic questionnaire.

During training of remapping detection task, the participants completed a minimum of eight trials with the same stimulus type as the first trial for each unique staircase. For each training trial, the expected answer was given to the participant as feedback. Through the course of training, all the participants were able to correctly distinguish between nonremapped (i.e., 0-cm shift) and remapped (i.e., 10-cm shift) movements. For self-localization task, the training trials consisted of a few trials without feedback to practice the procedure.

3.5 Results

For continuous variables, analysis of variance (ANOVA) was conducted when the normality assumption (Shapiro–Wilk's normality test) was not violated ($p > .05$). When the sphericity assumption was violated (Mauchly's sphericity test), the degrees of freedom were corrected using the Greenhouse–Geisser correction. In addition, η_p^2 were provided to quantitatively compare the effect size. Finally, Tukey's post-hoc tests ($\alpha = .05$) were conducted to check the significance of pairwise comparisons of the parametric data. When the normality assumption was violated, or the measurement did not use continuous variables, a Wilcoxon signed rank test was conducted.

3.5.1 Detection Threshold of Remapping

To test [H1], i.e., the threshold for detecting if the remapping of movements is higher with the realistic avatar than with the abstract avatar, we analyzed the data from remapping detection task. As described in Subsection 3.4.4 and Figure 3.7, the average of the reversal points, including the data point from the 15th trial, was used to estimate the threshold for each staircase. We excluded three data points from reversals as they were possibly mistakes and outliers; two participants answered "no" in the first trial of one of the ascending series (i.e., a 0-cm shift) and one participant answered "yes" for a descending series (i.e., a 10-cm shift). The average value of the thresholds of the ascending and descending series for each condition was used as a representative value from each participant because they were expected to converge to the same values. As described in Section 3.4.2, the data from one male participant was excluded from the analysis because his thresholds for two out of four conditions exceeded 10 cm. Considering he understood the instruction during the training session that the expected response to 10-cm shift was "no" (see Subsection 3.4.8), it is rather unlikely that he actually could not notice the remapping with a 10-cm shift. Rather, it is reasonable to suppose that he did not properly complete the task. Thus, we used a total of 16 participant datasets for the following analysis.

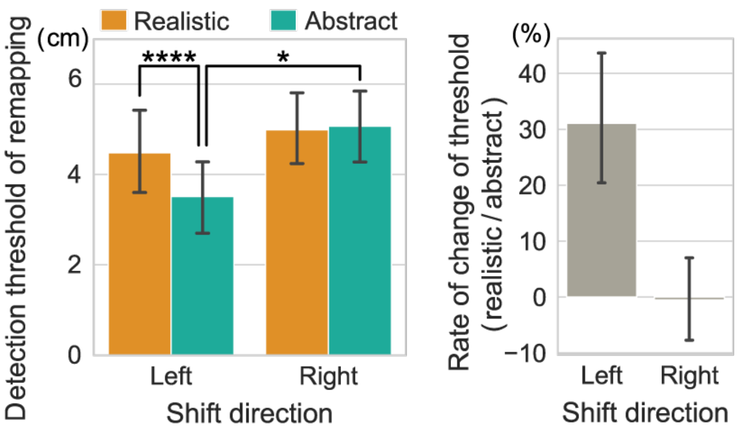

Fig. 3.8: Results of remapping detection task. (Left) Bar plot of detection threshold of remapping determined by the shift amount (cm) considering avatar appearance and shift direction. (Right) Bar plot of the rate of change of the threshold from abstract to realistic considering shift direction. The error bars indicate 95% confidence intervals (CIs). *: $p < .05$, ****: $p < .0001$.

Finally, a two-way ANOVA with repeated measures was conducted considering the within-subjects factors of avatar appearance (two levels: *realistic and abstract*) and shift direction (two levels: *left and right*). As shown in the left part of Figure 3.8, ANOVA showed a significant two-way interaction effect between avatar appearance and shift direction [$F(1,15)=17.39$, $p<.001$, $\eta_p^2=0.54$]. Thus, we conducted Tukey's post-hoc tests for each avatar appearance level and shift direction. When comparing the values for each shift direction, the threshold was significantly smaller for the abstract avatar than for the realistic avatar only for the leftward shift (left: $p < .0001$, right: $p = .67$). In contrast, when comparing the value of each avatar appearance level, the threshold was significantly smaller in the leftward shift than in the rightward shift only in the case of the abstract avatar (abstract: $p < .05$, realistic: $p = .42$). The detailed statistical values are shown in Table 3.2.

Table 3.2: Results of remapping detection task. Mean and standard error values of the thresholds of distortion determined by the amount of maximum shift (cm) are given according to each combination of conditions (Avatar anthropomorphism and distortion direction). The difference and ratio between the thresholds in the left and right conditions for each distortion direction are also provided ($M \pm SE$).

	threshold (cm)		p-value	difference (cm)	ratio (%)
	Hand	Sphere			
Left	4.50±0.49	3.51±0.42	p <.0001	0.99 ± 0.16	131 ± 5.8
Right	4.99±0.42	5.07±0.41	p =.67	-0.08 ± 0.18	99.5 ± 3.9
p-value	$p = 0.43$	$p < .05$			

These results indicate that the participants were less sensitive to remapping with realistic avatars than with abstract avatars when leftward shifts are applied. To reveal how much the realistic avatar increased the detection thresholds of visuomotor discrepancy accompanied by leftward shifts, we calculated the threshold ratio of realistic to abstract for each shift direction, for each participant (Figure 3.8 right). Note that the average of the ratios can be different from the ratio of the averages. As a result, the threshold was found to be 31.3±12.5% higher and 0.5±8.2% lower (95%CIs) for realistic avatars than abstract avatars on average for the left- and right-shift conditions, respectively.

In addition, all the participants had a larger threshold with realistic avatars than with abstract avatars in the left-shift condition. This finding means the effect was applicable to anyone for leftward shifts, further supporting the robustness of the effect. In contrast, for the rightward shifts, half of the participants reported a positive effect with the use of the realistic avatar in terms of threshold; the other half reported a negative effect. To summarize, these results partially supported [**H1**] in the sense that the detection threshold of the remapping was higher when using realistic avatar than when using abstract avatar, only in the case of the leftward shifts depending on the direction of remapping.

3.5.2 Proprioceptive Drift

To test [H2], i.e., the amount of proprioceptive drift is larger for the realistic avatar than for the abstract avatar, the results of self-localization task were analyzed. The value of the drift indicates how far the proprioceptive self-location was perceived toward visual self-location (i.e., where the self-avatar was located) from the actual hand position. The average of the four repeated measurements (including both adjustment starting points of -25 cm and 25 cm) for each condition was taken as the data point for each participant.

A two-way ANOVA with repeated measures was conducted considering the within-subjects factors of avatar appearance (two levels: *realistic and abstract*) and shift (five levels: *-10, -5, 0, 5, and 10 cm*) (Figure 3.9). Note that the rightward and leftward shifts take a positive and negative value, respectively. ANOVA revealed a significant two-way interaction effect between avatar appearance and shift [$F(2.99, 47.84) = 3.40$, $p < .05$, $\eta_p^2 = 0.18$]. Thus, we conducted Tukey's post-hoc tests for each avatar appearance level and shift (Figure 3.9). When comparing the value for each shift, the proprioceptive drift was significantly smaller with respect to the abstract avatar than that with respect to the realistic avatar in the -5- and -10-cm conditions ($p < .05$ and $p < .01$, respectively). For the realistic avatar, the proprioceptive drifts were not significantly different between 5 and 10 cm ($p = .96$) or

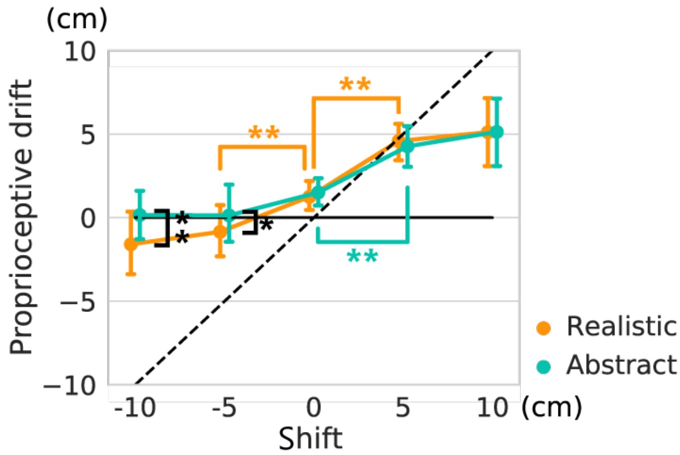

Fig. 3.9: Point plot of the mean proprioceptive drift (i.e., the localization bias of own hand toward the virtual hand) considering avatar appearance and shift during self-localization task. Error bars indicate 95% CIs. The shift takes a positive/negative value for rightward/leftward shift The solid/dotted black lines indicate the relative position of the actual/virtual hands from the actual hand, respectively, for readability. *: $p < .05$, **: $p < .01$. ©2020 IEEE.

between -5 and -10 cm ($p = .84$). The other comparisons produced significant differences ($p < .05$ for 0 cm vs 10 cm; $p < .01$ for the others). For the abstract avatar, the proprioceptive drifts were not significantly different among 0, -5, and -10 cm ($p = .27$ for 0 cm vs -5 cm, $p = .34$ for 0 cm vs -10 cm, $p = 1.00$ for -5 cm vs -10 cm) or between 5 cm and 10 cm ($p = .60$). Moreover, the other comparisons produced significant differences ($p < .01$ for all).

To summarize, these results partially support **[H2]** in the sense that the extent of proprioceptive drift was larger with respect to the realistic avatar than with respect to the abstract avatar, only for leftward shifts.

3.5.3 Sense of Embodiment

To test if the realistic avatar induced a stronger sense of embodiment, including SoBO, than the abstract avatar, the subjective ratings of the questionnaire were analyzed. The subscales of ownership, agency, and location ratings in the question-

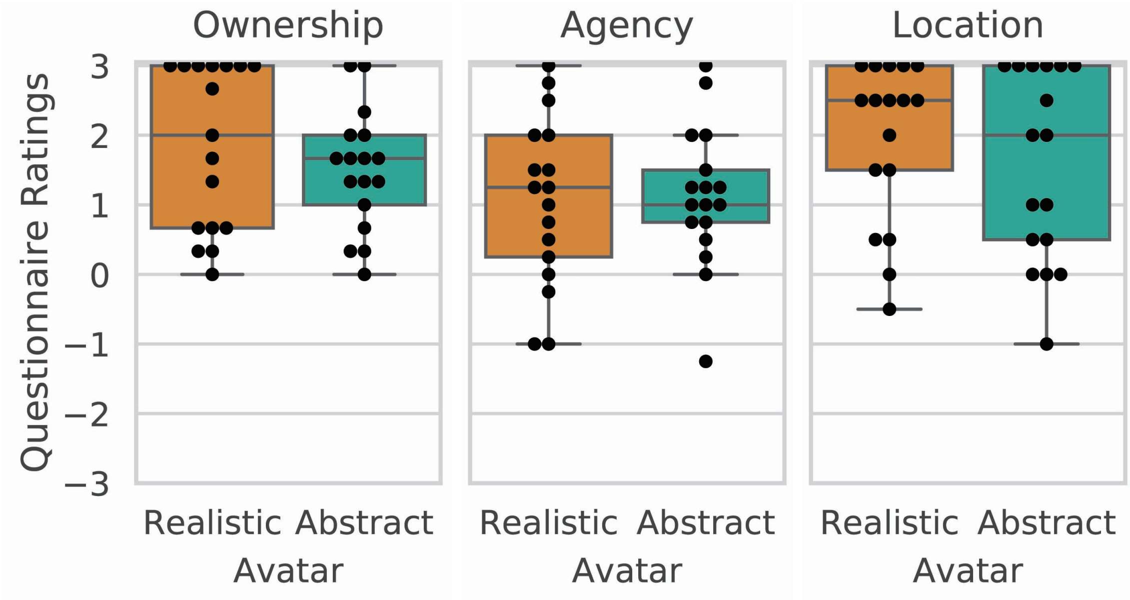

Fig. 3.10: Box plots of the mean subjective ratings of ownership (left), agency (center), and location (right) for each avatar appearance level and gender obtained through the questionnaires (from −3 to +3). ©2020 IEEE.

naire were aggregated and averaged (answers for control items were inverted) to compute the scores for each avatar appearance per participant.

As the Likert scale is regarded as an ordinal scale, Wilcoxon signed-rank tests with the within-subjects factor of avatar appearance (two levels: *Realistic*, *Abstract*) were performed for each subscale. As shown in Figure 3.10, no significant difference was found between the scores of realistic and abstract avatars for Ownership ($p = .20$) or Agency ($p = .72$). The Location score with the abstract avatar was marginally smaller than that with the realistic avatar ($p = .07$). Contrary to our expectations drawing on previous studies that the realistic avatar induces the stronger SoBO (e.g., [11–14]), there was no significant difference between the sense of embodiment with the realistic and abstract avatars.

3.5.4 Interoceptive Sensitivity

We tested [**H3**] and [**H4**], i.e., the participants with lower interoceptive sensitivity tend to have higher thresholds (H3) or tend to be well influenced by avatar appearance (H4). In addition, we tested if the proprioceptive drift and questionnaire scores of ownership subscale, which are both measurements of BOI, can be explained according to interoceptive sensitivity to validate the previous study [169]. Previous studies have suggested that interoceptive sensitivity predicts the malleability of body representation; that is, people with low interoceptive sensitivity experience a stronger BOI [169]. Therefore, we investigated whether interoceptive sensitivity predicted the individual differences of detection threshold of remapping.

As a result of the heartbeat counting test, interoceptive sensitivity scores were derived from Equation 3.1 in 3.4.6. The scores did not satisfy the normality assumption, and the median value was 0.93. As with the previous studies on interoceptive sensitivity [169–171] , a median split method was used to divide the participants into high- and low-interoceptive-sensitivity groups (median = 0.96 and 0.78, respectively).

For the thresholds, we used the average values in the left- and right-shift conditions for each avatar appearance as an index. We then calculated the indices of the threshold and proprioceptive drift for each avatar appearance, which can represent the values regardless of shift. For the proprioceptive drift, we first calculated the normalized ratio of the proprioceptive drift to the shift (i.e., the ratio of the subjective displacement of the self-location to the actual displacement) for each condition (avatar appearance × shift). This ratio can vary from 0 to 1, except for the case of a 0-cm shift. The drift was not meant to occur with this shift because the virtual and actual hands were present at the exact same position. Nevertheless, we observed the proprioceptive drift with a 0-cm shift ($p < .05$ for both avatar appearances; see Discussion). Hence, we eliminated the bias for each participant by subtracting the value in the 0-cm shift as a baseline from the values in each shift for each avatar appearance. We used these adjusted values to calculate the ratio for each condition.

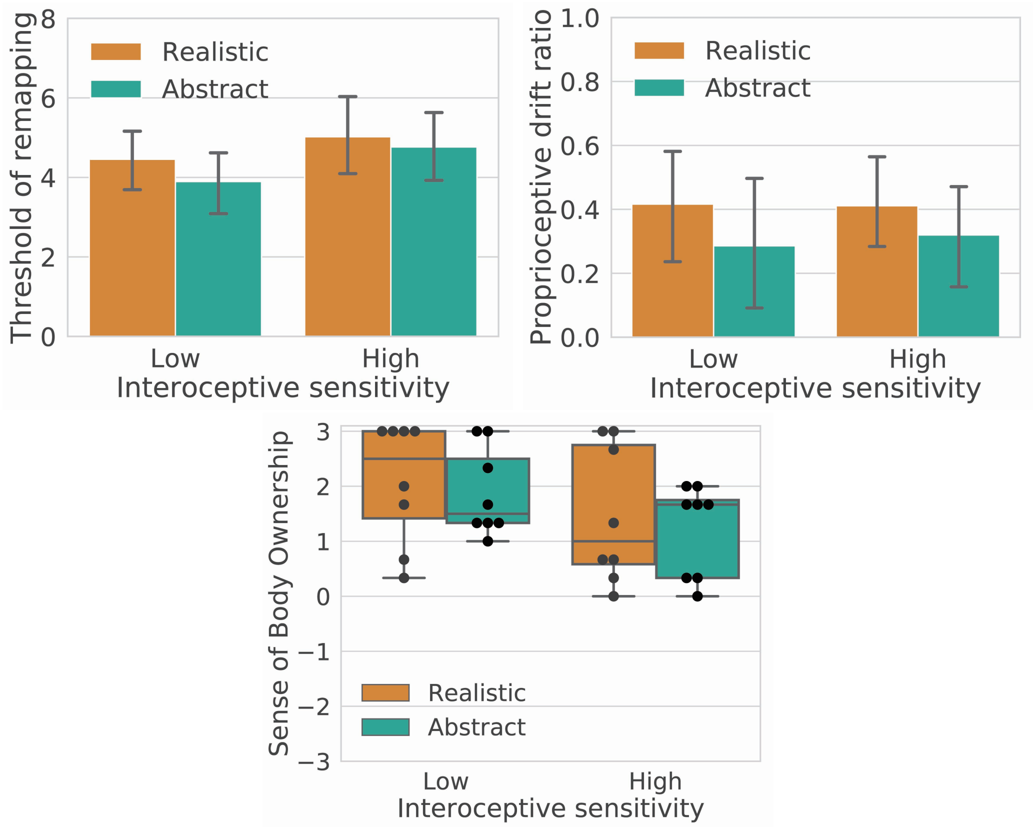

Fig. 3.11: Bar plots of the threshold of remapping (upper left) and the proprioceptive drift ratio (upper right), and box plots of the subjective ratings of ownership (bottom) for each avatar appearance level and interoceptive sensitivity. Error bars of the bar plots indicate 95% CIs. ©2020 IEEE.

Finally, we used the average values of the ratio in all shift conditions, except for the 0-cm shift, for each avatar appearance as an index.

As we were interested in whether the values irrespective of avatar appearance differed according to the interoceptive sensitivity (i.e., the main effect of interoceptive sensitivity) and whether the effect of avatar appearance differed according to the interoceptive sensitivity (i.e., the interaction effect) for each index, we conducted a two-way ANOVA with repeated measures considering the within-subjects factor of avatar appearance (two levels: *realistic* and *abstract*) and the between-subjects factor of the interoceptive sensitivity (two levels: *high* and *low*) for each index except for the subjective SoBO. For the subjective SoBO, we conducted the Wilcoxon signed-rank test instead of the ANOVA as the data was nonparametric. We did not report the main effect of avatar appearance for all the indices as it had been already reported in the analyses in the previous sections.

For the thresholds, ANOVA revealed that neither the main effect of interoceptive sensitivity nor the interaction effect were significant [$F(1,14)=1.20$, $p=.29$, $\eta_p^2=0.08$; $F(1,14)=1.67$, $p=.21$, $\eta_p^2=0.11$]. For the proprioceptive drift ratio, the ANOVA also revealed that neither the main effect of interoceptive sensitivity nor the interaction effect were significant [$F(1,14)=0.01$, $p=.91$, $\eta_p^2=0.0008$; $F(1,14)=0.27$, $p=.61$, $\eta_p^2=0.002$]. For the subjective SoBO, the Wilcoxon signed-rank test showed that the SoBO score tended to be lower in the high-interoceptive sensitivity group than in the low-interoceptive sensitivity group ($W=83, p=.09$), although it was not significant. The other comparisons equivalent to the test of the interaction effect were not significant for the subjective SoBO.

To summarize, we did not find any relationship between one's interoceptive sensitivity and detection thresholds or the proprioceptive drift. Instead, we marginally validated the previous studies, which showed that the participants of lower interoceptive sensitivity tended to score higher SoBO ratings. These results did not support **[H3]** and **[H4]**.

3.5.5 Summary of Findings

The main findings of our experiment are as follows:

- The detection threshold of the movement remapping was approximately 31.3% higher with realistic (i.e., virtual hands) than abstract (i.e., spherical pointers) avatars when the leftward shift was applied.

- The proprioceptive drift (i.e., displacement of the perceived self-location toward the virtual hand) was larger with realistic than abstract avatars when the leftward shift was applied.

- For both measurements, there were no significant differences between the two avatars when the rightward shift was applied.
- The sense of embodiment including SoBO did not differ between 1:1 mapped realistic and abstract avatars.
- The relationship of the interoceptive sensitivity with the individual differences of the threshold and proprioceptive drift was not found.

3.6 Discussion

3.6.1 Main Results

We revealed, for the first time, that avatar appearance influences the self-attribution of the remapped movements in hand interaction techniques that exploit visual dominance. Specifically, the result of remapping detection task showed that compared to abstract avatars, realistic avatars can make remapping less noticeable. With the realistic avatar, the participants could not notice that the movement of the virtual hand was different from that of their own for a leftward shift of up to 4.5 cm (i.e., 12.7° redirection), which is 31.3% higher than that with abstract avatar. In addition, the result of self-localization task showed that a greater importance is given to visual information for visuo-proprioceptive integration when realistic avatars are used than when abstract avatars are used. The finding that the same results were shown with two complementary measurements not only confirms the reliability of our findings but also reinforces our argument that the BOI is closely related to the self-attribution of the remapped movement. This is remarkable because in remapping detection task, we asked the participants about the self-attribution of movements, which is related to SoA and not SoBO. Conventionally, the limitation of the self-attribution of a remapped movement is considered to depend on the mismatch between actual control and visual feedback (i.e., visuomotor or visuo-proprioceptive discrepancy). To the best of our knowledge, this is the first study which showed that avatar appearance changes how one perceives the identical discrepancy between visual and real hand movements.

Our contributions, with respect to the limitation of self-attribution of the remapped movement in hand interaction techniques exploiting visual dominance, can be summarized as follows:

1. We expect that the avatar appearance can influence the sense of self-attribution by associating with BOI

2. We provide quantified evidence that realistic avatars can make the remapping less noticeable for larger mismatches between visual and actual movements.

Given these findings, we recommend that designers of VR applications use realistic rather than abstract avatars to widen the range of unnoticeable displacement for the hand remapping techniques. The use of realistic avatars rather than abstract avatars can potentially improve a wide variety of hand interaction techniques because it can mitigate a range of unnoticeable displacement without changing the mapping model itself.

Nevertheless, there are some unexpected results that must be discussed in detail. First, with both the detection threshold and proprioceptive drift, the effect of avatar appearance was observed only when the leftward shift was applied, i.e., his/her own right hand moves to the right and forward from the right side of the body. The following questions were raised. 1. "What is the difference between the rightward and leftward shifts?" and 2. "Why is the avatar appearance only effective in the leftward shift?". The first question may be hinted at by the notable anisotropy observed in self-localization task. As shown in Figure 3.9, the proprioception was almost fully captured by vision in the 5 cm-shift condition (i.e., rightward shift) for both avatars, and the location was scarcely captured with the -10- and -5-cm shifts (i.e., leftward shift), especially for abstract avatars. A possible explanation for the first question can be the difference in the muscle execution: flexion and extension. As the target was placed 10 cm to the right of the participant's body midline (i.e., where the right hand is naturally located), the arm should be somewhat flexed to touch it. The actual arm was also flexed with rightward shift. However, it was extended in the case of leftward shift. It can be considered that it is difficult to deceive that the arm was flexed when the actual arm was extended. In addition, when we extend the arm to the right, maintaining the posture was more difficult than when reaching for the front of the body. Consequently, it could foster the awareness of proprioception and might result in higher reliability of proprioception in the case of the leftward shift.

Furthermore, similar anisotropy is shown in BOI; the relative distance of the fake hands to the body midline as well as distance between the real and artificial hands modulate the proprioceptive drift [228]. In our cases, the relative distances of the actual hand from the body midline largely differed when the leftward and rightward shifts were applied; they elicited their own movements in the direction toward and away from the body midline, respectively. The distance from body midline influences BOI because the peripersonal space, a representation of the space immediately surrounding the body, plays a key role in BOI and visual-proprioceptive integration [79, 151, 228, 229]. Outside this space (i.e., extra-personal space), multisensory integration is considered to be diminished. Although peripersonal space is considered to be determined by the reaching extent, evidence has been found for a graduated transition between the two spaces, and this transition begins within the reaching space [230]. The theory of peripersonal space explains the first point and helps in the consideration of the second point. Our results indicate that the avatar appearance has an effect on the visuo-proprioceptive integration only when integration scarcely occurs. We conjecture that if the situation already allows for integration (i.e., within peripersonal spaces), the impact of the top–down process is relatively low. Rather, the avatar appearance can foster the integration when the integration hardly occurs. Nevertheless, the above-mentioned studies mostly investigated the effect of the position of artificial hands rather than that of the actual hands. In addition, the actual hand is placed away from body midline in a typical RHI (e.g., [159]). Hence, further investigation would be needed to validate if the peripersonal space could well explain the anisotropy.

Second, in self-localization task, we observed the proprioceptive drift with the 0-cm-shift, where the drift was not supposed to occur because the virtual and actual hands were present at the exact same positions (Figure 3.9). This bias is considered to be a result of proprioceptive recalibration caused by the unexpectedly fast, strong visuomotor adaptation (e.g., [231]) that persisted in the subsequent trial. In particular, the estimated drift to the right in the 0-cm-shift condition might have been influenced by the large proprioceptive drift under the preceding right-shift condition. Another possible explanation for the bias is an artifact of the absolute error in the estimation of hand positions by Leap Motion. Optical imperfections such as perspective distortion could produce the constant horizontal offsets between actual and estimated hand positions.

Third, contrary to the expectation, the results of the questionnaire indicated that avatar appearance does not influence SoBO. The visuomotor synchrony from the first-person perspective enabled by VR was considered to function as a powerful tool for embodiment and resulted in the ceiling effect, regardless of avatar appearance. Nevertheless, the score of SoBO over the spherical pointer in our study was rather high even compared to that of previous studies on SoBO over abstract avatars (e.g., block, board and sphere) in VR [11–13, 232]. This may be because of our experimental protocol. In our experiment, participants evaluated the sense of embodiment over avatars whose movements were completely synchronized with their own after they used the avatars whose movements were remapped in the main tasks. Hence, it is possible that in the questionnaire, SoBO was estimated to be high as completely synchronous visuomotor information was provided compared to the previous avatar. In addition, the proprioceptive drift and subjective scores of SoBO were shown to not always correspond [157–161]. Therefore, we considered that the unexpected results of the questionnaire do not immediately undermine the value of our other results. Furthermore, the sample size of this study was chosen based on the power analysis for the detection threshold. Hence, the supports for the null hypothesis of the questionnaire results might be attributable to the relatively low statistical power for non-parametric tests, which increased the probability of committing a type II error. Thus, further investigations are needed in terms of the mechanism of the effect of avatar appearance.

Lastly, we did not find the relationship between interoceptive sensitivity and threshold of remapping, contrary to the expectation (Figure 3.11). In addition, we could not validate the previous finding that the susceptibility of BOI, measured by proprioceptive drift and questionnaire, is predicted by interoceptive sensitivity. One of the reasons for this is that the interoceptive sensitivity scores indicated the ceiling effect and did not sufficiently vary between participants. In fact, the median was 0.93. Some participants reported in open-ended questions after the experiment that the pulse became apparent owing to the finger being pressured in the pulse oximeter. Hence, finding an alternative method to precisely detect the participant's actual heartbeat would be needed for future studies. If the individual differences are predicted through interoceptive sensitivity, the level of remapping to each user can be adjusted based on the individual traits of how sensitive they are to the sensory conflict without directly measuring it. As a method of predicting one's tendency of visual dominance, it may also be applicable to a wide variety of interaction techniques.

3.6.2 Limitations and Future Work

Herein, we adopted two types of avatar appearances to verify the hypothesis that the more realistic the avatar, the more visual dominance can be exploited. Our results supported the hypothesis for the leftward shift at least in our experimental condition; nevertheless, it remains unclear how far this holds true for different avatar appearances. Hence, a further investigation from at least two aspects may be necessary in future studies. The first being the consideration of how the self-attribution would be affected if the avatar is of medium level of anthropomorphism, such as robotic hand. The other is whether a more realistic virtual hand (e.g., personalized hand in terms of size and texture and a realistic full-body including arm) fosters self-attribution more than a realistic virtual hand without an arm, which we used in this study. It is known that a stronger SoBO can be elicited with a virtual upper limb that appears to be connected with one's torso than a virtual hand without an arm [157]. However, when remapping the movements of the virtual upper limb, the arm may sometimes appear to be obviously detached from the user's torso or protrude unnaturally from the torso, which breaks the connectivity to the body. Indeed, Azmandian *et al.* [29] considered it to be an issue and proposed a body-friendly adjustment method, wherein the virtual hand rotates and shifts to avoid detaching the arm from the torso. Thus, when using a full-body avatar, a technique to maintain the connectivity as well as to investigate the effect of SoBO must be realized.

In this study, we focused on the aspect of SoBO with respect to the self-attribution to identify if the avatar appearance could affect the threshold of the remapping. Similarly, focusing on SoA, which is another aspect of the self-attribution, may also contribute to identifying other factors that could affect the threshold. In fact, higher-level cognitive processes, such as background beliefs and contextual knowledge relating to the action, also influence the induction of SoA [92, 106], although spatial and temporal contiguity between one's own and observed movements are the main cues for SoA [93, 94, 98]. Thus, controlling the context may help increase the threshold without changing the mapping. For example, priming, a method that is often used to modulate the SoA by manipulating prior conscious thought about an outcome [103, 111, 112], would be a promising technique to foster self-attribution. Moreover, task performance is known to influence action-effect integration in SoA [204, 222]. In this study, we used the avatars with the same functionality or controllability in pushing the button so as to investigate the effect of avatar appearance fairly. Conversely, the change in avatar representation including the functionality or controllability as well as its appearance may influence both SoA and SoBO; hence, it may further foster self-attribution.

Furthermore, evidence from several studies indicates the effectiveness of haptic feedback. For instance, Caola et al. [218] found that synchronous visuo-tactile stimulation counteracted the visuomotor inconsistencies (i.e., virtual arms moved while real arms kept still) to induce SoBO. Lee et al. [233] also showed that finger-based cutaneous haptic feedback increased the detection threshold of the visuo-proprioceptive conflict arising from tracking error. To apply these findings to hand remapping technique in terms of SoBO would be an interesting future prospect.

Finally, this study dealt with a basic retargeting model that linearly remaps a hand movement according to a fixed angle as an example of a hand remapping technique exploiting visual dominance. Nevertheless, considering the theory of SoBO, the avatar appearance may influence the self-attribution in more complex remapping techniques as well. Moreover, it may be applicable to visuo-proprioceptive discrepancies, which is unintentionally caused by tracking errors and latency. Futhermore, the investigation of the effectiveness of avatar appearance in combinations of multimodal integration other than visuo-proprioceptive, such as visuo-vestibular (i.e., used in redirected walking techniques [215–217]), is a potentially fruitful area of future work.

3.7 Conclusion

By associating the fact that the avatar appearance affects SoBO with the self-attribution of the remapped hand movements, we hypothesized that realistic avatars (i.e., human hands) can better foster self-attribution than abstract avatars (i.e., spherical pointers). In the experiment, participants executed reaching movements with two types of avatars while horizontal (left or right) offsets were incrementally applied. The results showed that realistic avatars increased the detection threshold (i.e., lowered sensitivity) for remapped movements by 31.3% than abstract avatars when the leftward shift was applied (i.e., when the hand moved in the direction away from the body mid-line). Our findings showed for the first time that avatar appearances influence the self-attribution of the remapping, in the sense that the realistic avatar makes the remapping less noticeable for larger mismatches between virtual and physical movements. In addition, the proprioceptive drift (i.e., the displacement of self-localization toward a virtual hand) was larger with respect to realistic avatars than with respect to abstract avatars for leftward shifts, indicating a greater importance being given to visual information when realistic avatars are used. The finding that the same results were shown with two complementary measurements reinforces our argument that the BOI is closely related to the self-attribution of the remapped movement.

Chapter 4

Effect on Object Size Perception

In this chapter[1], we investigated how the anthropomorphism of self-avatars influenced the perception of VEs. Specifically, this study examines how the anthropomorphism affects perceived object sizes as the size of the virtual hand changes. As the theory of *body-based scaling* suggests that the scale of the external environment is perceived relative to the size of one's body, it can be hypothesized that the anthropomorphism of an avatar affects not only SoBO but also the fidelity of the avatar with respect to "body representations as metrics." Therefore, we conducted an experiment in which we manipulated the level of anthropomorphism (realistic, iconic, and abstract) and size (veridical and enlarged) of the virtual hand, and measured the perceived size of a cube. The results revealed that the size of the cube was perceived to be smaller when the virtual hand was enlarged compared to when it was veridical only in the case of a realistic hand, indicating that the participants perceive the sizes of objects based on the size of a realistic avatar. In contrast, when the participants used an iconic or abstract avatar, the hand size did not affect the perceived size of a cube. Our findings indicate that the more realistic the avatar, the stronger the BOI, which fosters scaling of the size of objects using the size of the body as a fundamental metric. This provides evidence that self-avatar anthropomorphism affects not only SoBO but also how users perceive the VEs, which can address the problem whereby spatial perception in VEs appear to be compressed [30]. This study sheds new light on the importance of avatar representation in a three-dimensional user interface (3DUI) field in terms of how it affects the manner in which we perceive the

[1]The content in this chapter has been published as Nami Ogawa, Takuji Narumi, and Michitaka Hirose (2019). Virtual Hand Realism Affects Object Size Perception in Body-Based Scaling. *In Proceedings of 2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR'19).* pp.519–528. IEEE. https://doi.org/10.1109/VR.2019.8798040 (© 2019 IEEE)

scale of an object in a VE.

4.1 Introduction

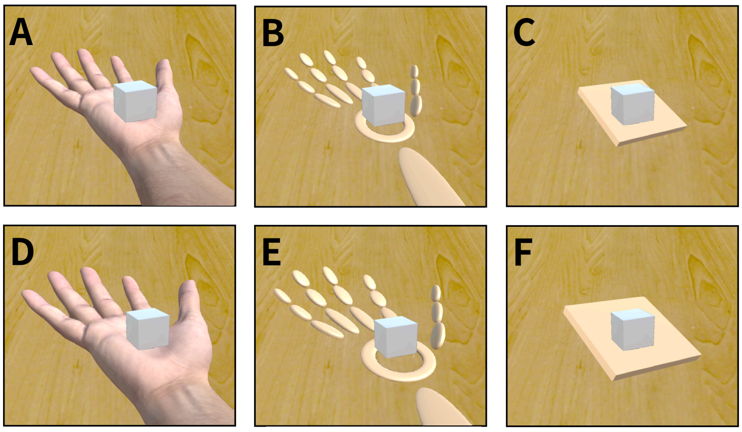

Fig. 4.1: Virtual hands used in the experiment. Participants embodied realistic (A and D; high-anthropomorphism), iconic (B and E; medium-anthropomorphism), or abstract virtual hands (C and F; low-anthropomorphism). The sizes of the virtual hands varied between veridical with the participants' own hands (A–C) and magnified by 1.25 times (D–F). © 2019 IEEE.

How does the representation of an embodied avatar influence the way in which one perceives the scale of a virtual environment? Conventionally, visual space perception has been considered a matter of geometric and optical analysis (e.g., object size is generally considered an intrinsic primary quality of an object). However, recent views emphasize the act of body in space perception [234–237] (see Subsection 2.4.3 for details); object size perception is affected by the perceived size of the body [24, 25, 28, 174, 178, 238]. A notion, called *body-based scaling*, considers that one's own body acts as a perceptual ruler, which individuals use to scale the apparent sizes of objects in their environment [174, 239]. The study by Linkenauger et al. [174] supported this notion by showing that increase in the size of one's virtual hand results in decrease in the perceived sizes of objects. Additionally, they found that this effect was specific to participants' virtual hands rather than extraneous hands or a salient familiarly sized object. Similarly, the scaling effect was found to be greater when they experienced a stronger SoBO over the artificial bodies [24, 178].

Considering these studies, it can be anticipated that if avatar representation is less likely to be embodied, its fidelity as one's own body representation decreases, resulting in decreased influence on body-based scale perception. However, studies on object size estimation have so far not placed much emphasis on avatar anthropomorphism. Indeed, previous studies that investigated the effect of perceived body size on object size perception in VE used realistic human avatars [28, 174]. Thus, it is still unknown if the effect is also verified with less realistic but commonly used virtual avatars. Only recently did Jung et al. [144] investigate the effect of a personalized hand on object size perception as well as SoBO and presence. They compared generic virtual hands of invariant size and appearance, modeled using three-dimensional computer graphics (3DCG), with hands that were personalized in size and appearance and presented using a video-based chroma key approach. They found that the use of personalized hands not only increased SoBO and presence, but also accuracy in object size estimation compared to generic 3DCG virtual hands. This study supports our view that the closer the avatar hand is to one's own, the easier it can be used in size estimation. In contrast to their study, we are interested in the pure effect of visual anthropomorphism of virtual avatars on size estimation rather than the personalization effect because hands with various levels of anthropomorphism are commonly used in current VR systems.

Meanwhile, users often embody avatars, whose representation is not identical to one's own body in terms of its size and appearance in VEs. This may be one of the causes of the commonly known issue of distortion of spatial perception (i.e., egocentric distances appearing to be compressed) in VEs [30, 240]. Indeed, the egocentric distance estimation becomes accurate when the self-avatar is displayed than when no-avatar is displayed, especially if the avatar is self-animated in real time [182, 237, 241, 242]. In addition, the impoverishment of avatar fidelity (e.g., showing either the full body avatar, only joint locations, or end-effector) compromises the improvements in the accuracy of distance estimations in both near field [52] and far distances [243]. Furthermore, showing virtual hands whose sizes are perceived identical to one's own improves the perception of size distortion between real and virtual environments [239]. Therefore, we investigate herein the effect of virtual hand anthropomorphism on the extent to which the size of a virtual object is perceived based on the size of the virtual hand.

4.2 Experiment

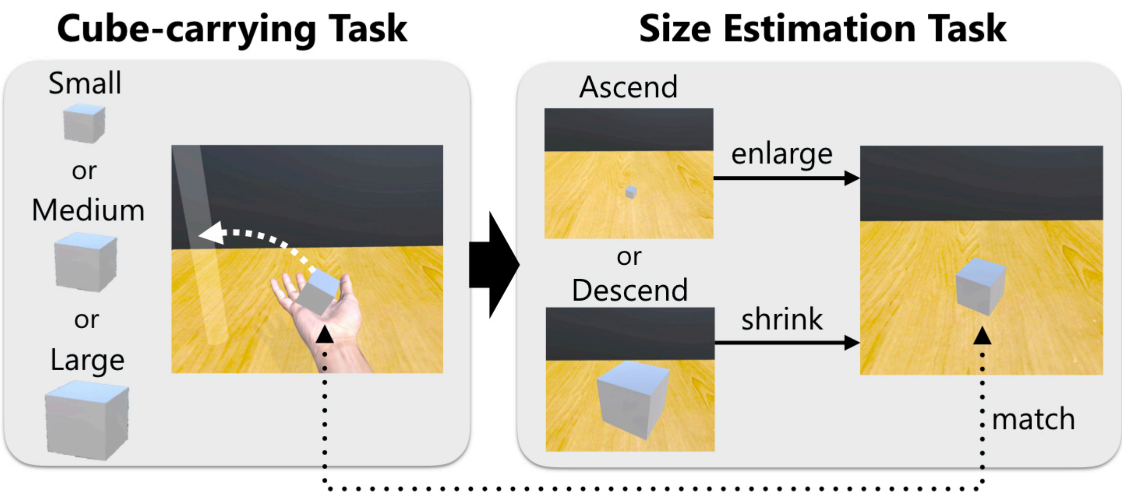

Fig. 4.2: Each trial consisted of a cube-carrying task, where the participants carried a virtual cube to a target cylinder with a virtual hand, and a successive cube size estimation task, where the participants enlarged or shrank a size-adjustable cube using a controller such that its size corresponded to their perception of the cube's size. © 2019 IEEE.

The experiment aims to investigate the effect of virtual hand anthropomorphism on the body-based scaling effect, that is, to what extent the size of a virtual object is perceived based on the size of the virtual hand. The participants performed a cube-carrying task with virtual hands of various sizes and anthropomorphism levels (see Figure 4.1) and estimated the size of the cube by scaling a size-adjustable virtual cube (see Figure 4.2). We hypothesized that the object size is perceived as smaller with the enlarged hand than with the veridical hand for the realistic virtual hand.

We also hypothesized that the less realistic the virtual hands are, the weaker the SoBO is, which makes it harder to scale the size of an object based on the size of one's body.

4.2.1 Participants

A total of 24 individuals (12 males and 12 females; 28.18 ± 8.04 (SD) years old) participated. They were recruited through social media. All participants were naive as to the true purpose of the experiment, had normal or corrected-to-normal vision, and were right-handed. We did not recruit participants with glasses because they tend to have difficulty in correctly wearing a head-mounted display (HMD). Seven participants had no previous experience with VR; 13 had limited previous experience; and four were familiar with VR. The participants signed an approved statement of consent and they were compensated with an Amazon gift card amounting to approximately $10.

4.2.2 Apparatus

Figure 4.3A shows the experimental setup. The experimental apparatus includes a Windows-based computer, a motion sensor (Leap Motion Controller), an HMD set (Oculus Rift CV1), and a controller (Oculus Remote). The experimental program has been developed using Unity 3D. The experimental scene is designed as a simplified room composed of a wooden table, a white cube, and a translucent cylinder to eliminate the possibility of participants using a specific strategy for size estimation, such as a direct comparison with the features of textures or objects.

We adopted the Leap Motion Controller as a hand-tracking device in the same manner as in the previous studies on avatar anthropomorphism [11–13, 35]. It could track the forearm, hand, and fingers of the users at distances of up to 1 m. It automatically detected the hand size for each participant. Its estimations deviated from the actual positions by 1.2 mm on average [219]. Therefore, we considered it to have sufficient accuracy and robustness for scaling and tracking hands for the

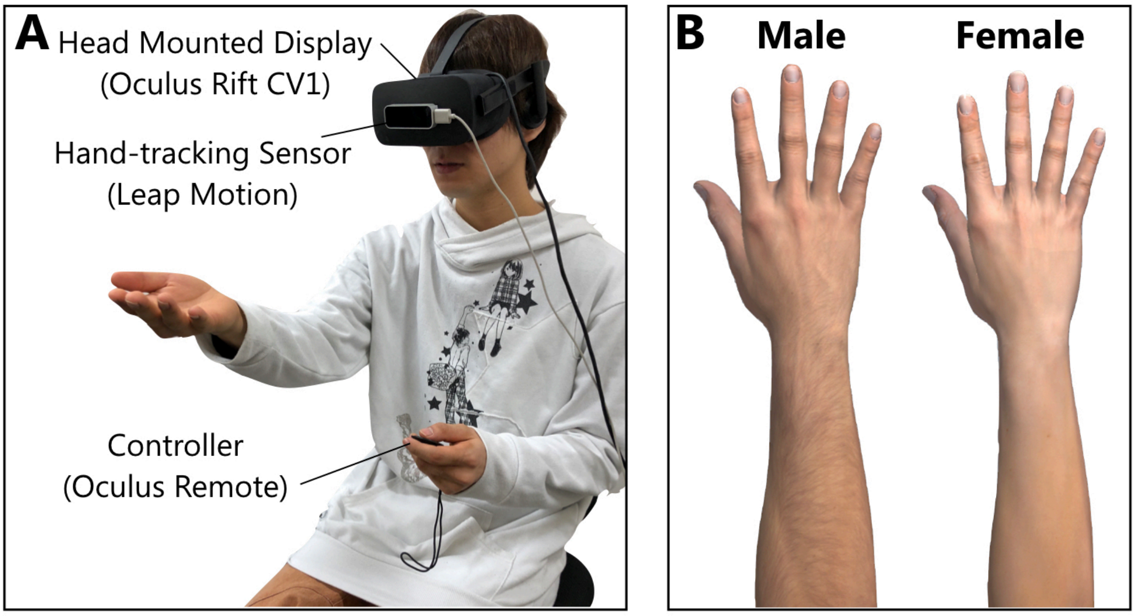

Fig. 4.3: (A) Realistic male and female hands used in the high-anthropomorphism condition. (B) A participant wearing a head-mounted display with a hand-tracking sensor pushing a controller with his non-dominant hand.

purpose of this study. To further verify its accuracy and robustness, we recorded the sensor-estimated hand sizes of ten individuals (i.e., five males and five females; 25.14 ± 6.59 (SD) years old) and measured the size of individuals' actual hands by a ruler prior to the experiment. As a measurement, we used the width of the palm across four bottom knuckles and the distance from the middle fingertip to the bottom knuckle. As for accuracy, the measured values by a ruler (palm width (cm): $M = 8.31, SD = 0.89$, middle finger length (cm): $M = 7.94, SD = 0.76$) and the estimated values by a sensor (palm width (cm): $M = 8.27, SD = 0.56$, middle finger length: $M = 8.09, SD = 0.64$) were significantly correlated (palm width: $r = 0.95, p < .001$, middle finger length: $r = 0.96, p < .001$), indicating a reasonable agreement. As for robustness, we calculated the standard deviations (SD) across 100 times of measurements by a sensor per individual and calculated the mean of the SD across individuals (palm width (cm): $M = 0.36$, middle finger length (cm): $M = 0.49$). Given that the actual one-time measured values by a ruler also have measurement errors, we consider that the sensor detects the hand size and sufficiently shows the veridical size of the virtual hand for each individual in the experiment. Note that in the experiment, we were interested in the relative values across conditions in the virtual setup rather than in the comparison between real and virtual environments.

4.2.3 Design

The experiment followed a $3 \times 2 \times 3 \times 2$ factorial design. The independent variables were avatar anthropomorphism (*high, medium, and low*), hand size (*veridical and enlarged*), cube size (*small, medium, and large*), and adjustment direction (*ascending and descending*). All variables were within-subject.

Conditions

Avatar anthropomorphism We used three types of hand appearance with different levels of anthropomorphism, as shown in Figure 4.1. The appearances were chosen based on the study by Argelaguet et al. [11] using a realistic male virtual hand, including a forearm, an iconic virtual hand representing a simplified robotic hand, and an abstract virtual hand formed as a sphere. We slightly modified its appearance based on our study context. First, we used a realistic female virtual hand for female participants because the study by Schwind et al. [35] revealed that women feel less presence and perceive more eeriness using virtual male hands. They also suggested providing male and female hands if human avatars are desired. Thus, we chose to use male virtual hands for male participants and female virtual hands for female participants. Second, we used a board instead of a sphere because we adopted a cube-carrying task that followed a realistic physical simulation as far as possible. Lastly, we decided to change the skin colors of the iconic and abstract hands to avoid any influence of color contrast on size perception.

As for the control scheme, the high- and medium-anthropomorphism hands used the same skeleton rig with the same number of degrees of freedom, but the low-anthropomorphism hand moved based only on the position and rotation of the participant's palm. In contrast, all hand models used the same collision-detection surfaces, which corresponded to the surfaces of the realistic hand. This implementation led to a somewhat unnatural situation for the low-anthropomorphism hand, i.e., the participants could carry cubes on transparent fingers. Nevertheless, we assured that all the virtual hands maintained the same functionality in spite of their different appearances so as to avoid any influence of the functionality on SoBO and object size estimation.

The three representations are summarized as follows:

Realistic hand (High anthropomorphism): realistic male and female virtual hands, including a forearm (Figure 4.1 A & B; Figure 4.3 B). 3D models were obtained from the Leap Motion Software Development Kit (SDK).

Iconic hand (Medium anthropomorphism): a non-human hand equipped with an ellipsoid representing bones and a torus representing the palm (Figure 4.1 C & D). 3D models were obtained from the Leap Motion SDK.

Abstract hand (Low anthropomorphism): a non-anthropomorphic board with the length and width equal to the participant's palm and with 1-cm thickness (Figure 4.1 E & F). The 3D model was created using Unity.

Hand Size In the *veridical* condition, the virtual hand was of the same size as the hand size of each participant (see subsection 4.2.2). In the *enlarged* condition, the virtual hand was larger than in the veridical condition by a factor of 1.25. The center point of scaling was the center of the palm; hence, the reaching ability and the spatial congruency between proprioception and vision did not change from the veridical hand. The rationale for the value of 1.25 is as follows: previous studies on body-based scaling used a quarter [25], half [25, 28, 174], or doubled [25] size of an artificial or virtual body. Nevertheless, we were interested in the effect of change in hand size on object size perception, which is a likely occurrence in common VR systems. According to our hand anthropometric data of the palm width (male: $M = 8.94$, $SD = 0.44$ and female: $M = 7.66$, $SD = 0.23$; see subsection 4.2.2), Jung et al.'s [144] data (male: M = 14.88, SD = 1.37 and female: M = 11.00, SD = 0.43), and Gordon et al.'s [244] data (male: M = 9.04, SD = 0.43 and female: M = 7.95, SD = 0.38), the male to female ratios roughly varied from 115% to 135%. Furthermore, men whose hand sizes were below or over 2 SD of the mean value, who accounted for 5% of the total, had approximately 20% smaller or larger size to the mean based on Jung et al.'s data [144]. In addition to these gender and individual differences, differences by race and age also existed. Therefore, we considered that the enlargement of the hand size by a factor of 1.25 is a likely situation.

Cube Size The sizes of the cubes that were carried by the participants were randomly selected as any of *small* (5 cm), *medium* (7.5 cm), or *large* (10 cm) for each trial.

Adjustment Direction The size-adjustable cube used by the participants to report their size estimations appeared as either 1 cm (*ascending* series) or 15 cm (*descending* series), which are typically used in the method of adjustment to eliminate the anchoring effects.

Measurements

Object Size Estimation As shown in Figure 4.2, each trial consisted of the cube-carrying task, followed by the cube size estimation task. In the cube-carrying task, the participants carried virtual cubes with the virtual hand. In the successive cube size estimation task, the participants could continuously enlarge or shrink the scale of the size-adjustable cube by pushing the controller's button, such that its perceived size corresponded to the size of the cube that they had carried only previously. For each trial, the ratio of the estimated cube size to the actual size of the carried cube was recorded. Our experimental protocol for the cube size estimation task was similar to that used by Jung et al. [144]. The difference was that the virtual hand was displayed while estimating the cube size in the previous work, while it was not in the present study. We did not show the virtual hand to avoid any possibility of the participants estimating the cube size by inference. We expect that the cube size may be directly estimated by comparing the viewed size of the virtual hand with the size of the cube.

Questionnaire The subjective evaluation of embodiment for a virtual hand was assessed through a questionnaire. Although we were interested in SoBO in particular, we measured the sense of embodiment [5], which consists of SoBO (i.e., one's self-attribution of a body), sense of agency (i.e., the feeling of control over actions and their consequences), and sense of self-location (i.e., one's spatial experience of being inside a body). The rationale for this is we consider that measuring the comprehensive effect of anthropomorphism on user perception is important for exploiting the insights for VR designers or developers. We used Gonzalez-Franco and Peck's embodiment questionnaire [145], but omitted items that were not applicable to our study context. As a result, the questionnaire consisted of nine items and three subsets of questions: SoBO (Ownership), agency and motor control (Agency), and body location (Location) (see Table 4.1). Each response was scored on a seven-point Likert scale (-3 = strongly disagree; 3 = strongly agree). The evaluation was performed for each avatar anthropomorphism, and the size of the virtual hand was not considered.

Hypotheses

Our hypotheses were:

H1 The object size is perceived to be smaller with the enlarged virtual hand than with the veridical virtual hand when the virtual hand is realistic.

H2 The less realistic the virtual hands, the weaker the SoBO.

H3 The less realistic the virtual hands, the less the impact of changes in hand size on the object size estimation.

Table 4.1: Questionnaire items to measure the sense of embodiment based on [145]. Items in italic are control questions. © 2019 IEEE.

Subscale	Question
Ownership	1) I felt as if the virtual hand was my hand. 2) *It felt as if the virtual hand I saw was someone else.* 3) *It seemed as if I might have more than one hand.*
Agency	4) It felt like I could control the virtual hand as if it was my own hand. 5) The movements of the virtual hand were caused by my movements. 6) I felt as if the movements of the virtual hand were influencing my own movements. 7) *I felt as if the virtual hand was moving by itself.*
Location	8) I felt as if my hand was located where I saw the virtual hand. 9) *I felt out of my body.*

H4 The participants with higher scores of SoBO tend to perceive the object size as smaller when the virtual hand is enlarged.

H1 is hypothesized based on the previous studies showing that object size perception is affected by the perceived size of the body [24, 25, 28, 174, 178, 238], although these did not explore the case of a change in body size as small as 1.25 times. **H2** is hypothesized based on a number of research showing that the reduction in anthropomorphism attenuates SoBO [11–14, 35, 245], although the presence of the uncanny valley effect is indicated [17]. **H3** is the main interest in this study, which is derived from **H1** and **H2**. **H4** is hypothesized based on Van der Hoort and Ehrsson's studies [24, 178], although they used visuotactile stimuli without VR, and aims to validate that SoBO is intermediate between the avatar anthropomorphism and the body-based scaling effect.

4.2.4 Procedures

Trial Flow

The experimental flow of each trial is described below. As explained in the 4.2.3 section, each trial consisted of a cube-carrying task, followed by a cube size estimation task. In the cube-carrying task, the participants carried cubes to the position of the target cylinder using their dominant virtual hand. The participants were instructed to carry the virtual cube as quickly as possible. The sizes of the carried cubes were any of *small*, *medium*, or *large* for each trial. The positions at which the cubes appeared and those of the cylinders were randomly chosen for each trial, such that they remained within the participants' reach. The cube-carrying task allowed sufficient time to remember the sizes of the cubes in a natural situation. Therefore, we did not measure the performance such as accuracy and the time taken for task completion. Nonetheless, we observed that the cube-carrying task in each trial took approximately 15 s. The cylinder, the cube, and the virtual hand disappeared when the participants successfully finished carrying the cube. Then, the cube size estimation task was performed, wherein the size-adjustable virtual cube with size of either 1 cm (*ascending* series) or 15 cm (*descending* series) appeared on the table for each trial. This appeared at a fixed position for all trials, but at a random orientation. The sizes of the cubes were adjusted, such that their sizes perceptually corresponded to the size of the cube carried by the participants immediately before. The participants could continuously enlarge and shrink this cube with a precision of 1 mm by pressing the up and down buttons on the controller held by their non-dominant hand. They could also rotate the orientation of the cube by pressing the left and right buttons of the controller, if needed. The estimated size of the cube can be considered to represent the perceived size of the carried cube. The virtual hands were not displayed during the cube size estimation task. Once the participants pressed the answer button, the screen turned black and shifted to the cube-carrying task of the next trial, although it was possible to freely adjust the enlargement/shrinkage until the OK button was pressed. We did not set a particular time limit, but the cube size estimation task in each trial took approximately 5 s.

Overall Flow

The overall flow of each experiment is described below. At the beginning, the participants read and signed the experiment consent form. After the explanation of the procedures, including instructions for using the controller, each participant was asked to wear the HMD and adjust the interpupillary distance of the lenses by moving a slider, such that they could clearly see the image. While they wore the HMD, they were unable to see their own real hands. Instead, they could see their virtual hand in the position where their real dominant hand was. The rest of the body, including a non-dominant hand, was invisible in the VE. Their non-dominant hands were holding the controllers placed on their laps during the experiment.

Six unique types of trials (three cube sizes $\times$ two adjustment directions) were successively performed for each hand representation. The successive six trials with the same hand representation were conducted in a random order for each of the six hand representations (three avatar anthropomorphisms $\times$ two hand sizes). These 36 unique trials constituted a block, and there were three blocks. The order of appearance of the hand representation was randomized in each block. A total of 108 trials per participant were conducted.

A question from the questionnaire and a slider with numbers from -3 to $+3$ were displayed in the VE after all the trials were completed. The questionnaire was shown both in English (original) and in Japanese (translated) at the same time. The participants could see their dominant virtual hand and freely interact with a virtual cube. They were instructed to assess their impressions of the observed virtual hand, whose appearance was at any of the three different levels of anthropomorphism and whose size was veridical to the participant's own hand. Once they answered the question regarding the observed virtual hand, the appearance of the hand changed to a different level of anthropomorphism, while the question remained the same. After they answered the same question in the questionnaire for all three types of virtual hands, the next question was shown, which was chosen from among the nine items in a randomized order. The participants were instructed to take off the HMD after the completion of the questionnaire. Finally, they filled up a demographic questionnaire. The whole experiment took approximately 1 h to complete.

4.3 Results

The data from two participants were excluded from the analysis because one male participant did not finish the experiment owing to fatigue or drowsiness, and one female participant consistently used the wood grain pattern as an absolute metric for size adjustment. Thus, we used a total of 22 data sets for the analysis that follows. ANOVA analyses were conducted when the normality assumption (Shapiro–Wilk's Normality test) was not violated ($p > .05$). When the sphericity assumption was violated (Mauchly's sphericity test), the degrees of freedom were corrected using the Greenhouse–Geisser correction. In addition, η_p^2 were provided for the quantitative comparison of the effect sizes. Finally, Tukey's post-hoc tests ($\alpha = .05$) were conducted to check the significance for the pairwise comparisons of the parametric data. When the normality assumption was violated or the measurement did not use continuous variables, a Friedman test was conducted followed by a post-hoc Wilcoxon signed rank test. For multiple post-hoc comparisons, the Holm correction was applied for non-parametric data. We report only the significant differences for ANOVAs and post-hoc tests ($p < .05$).

4.3.1 Object Size Estimation

We statistically tested the ratio of the estimated cube size to the actual size of the carried cubes to examine whether the perceived size of the cubes was influenced by the avatar representations. For data preprocessing, the data under/over 3 SD for each participant were excluded as outliers, resulting in data for 1 out of 108 trials being removed for eight participants. Next, the average value of three repetitions for each unique combination of conditions (36 combinations in total) was used in the analysis for each participant. Finally, four-way ANOVA analyses with repeated measures were conducted considering the within-group factors of avatar anthropomorphism (three levels: *high, medium, and low*), hand size (two levels: *veridical and enlarged*), cube size (three levels: *small, medium, and large*), and adjustment direction (two levels: *ascending and descending*).

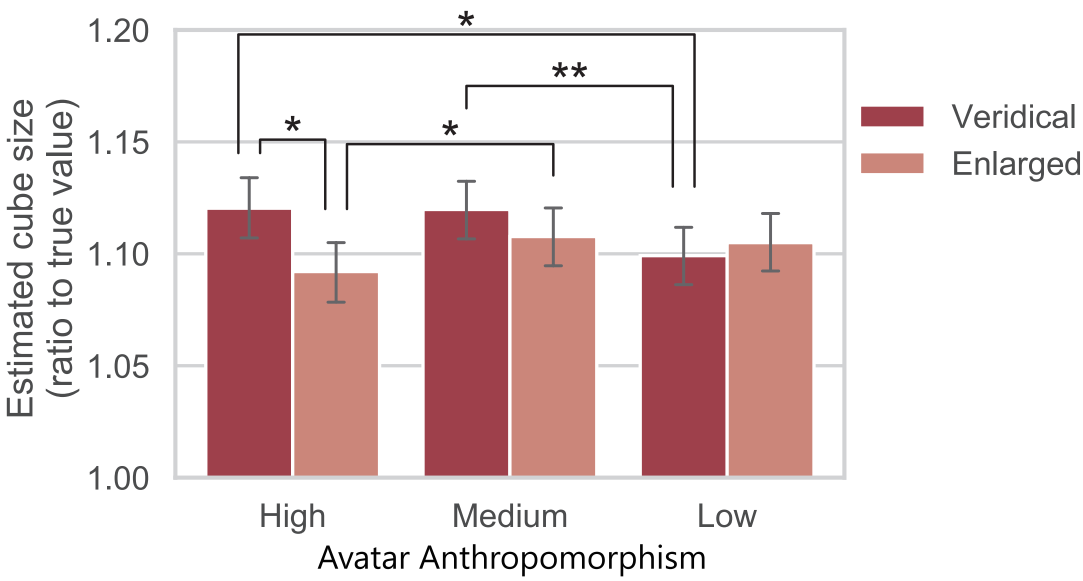

Fig. 4.4: Average estimated cube size as a ratio compared to the true size according to avatar anthropomorphism and hand size. Error bars indicate the SE. *: p<.05, **: p<.01. © 2019 IEEE.

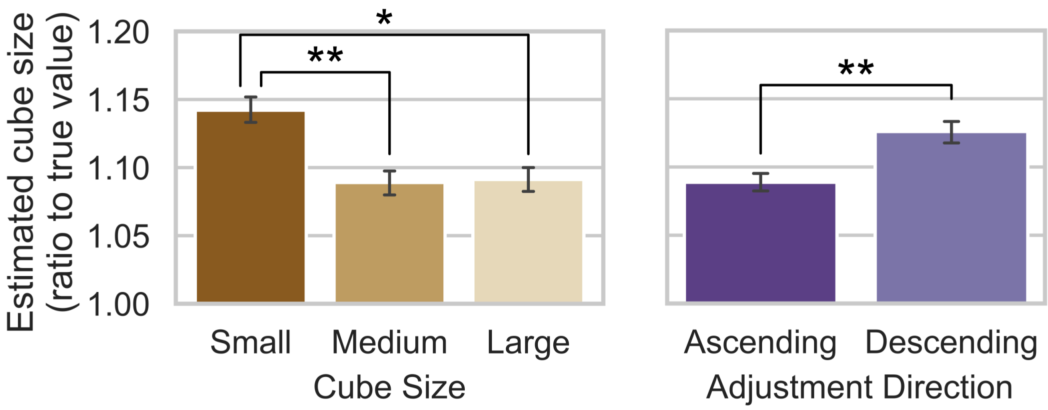

Fig. 4.5: Average estimated cube size as a ratio compared to the true size according to cube size (left) and adjustment direction (right). Error bars indicate the SE. *: p<.05, **: p<.01. © 2019 IEEE.

As shown in Figure 4.4 and Figure 4.5, ANOVA revealed the significant main effects of hand size $[F(1,21)=8.32,\ p<.01,\ \eta_p^2=0.28]$, cube size $[F(1.26,26.53)=9.73,\ p<.01,\ \eta_p^2=0.32]$, and adjustment direction $[F(1,21)=8.32,\ p<.01,\ \eta_p^2=0.28]$.

ANOVA also showed a significant two-way interaction effect between hand size and avatar anthropomorphism [$F(1.74, 36.50) = 5.66$, $p < .01$, $\eta_p^2 = 0.21$]. An interaction effect existed between only the hand size and the avatar anthropomorphism; hence, the effects of the cube size and the adjustment direction can be interpreted individually. As we observed both the main effect of the hand size and an interaction effect between the hand size and the avatar anthropomorphism, we conducted Tukey's post-hoc tests for each anthropomorphism level and hand size (see Figure 4.4). When comparing the value for each anthropomorphism level, the sizes of the cubes were estimated as significantly smaller in the case of the enlarged hand size (M = 1.09, SE = 0.02) compared with the case of the veridical hand size (M = 1.13, SE = 0.02) only in the high-anthropomorphism condition ($p < .05$). This result supports [**H1**]: the object size is perceived to be smaller with the enlarged hand than with the veridical hand when the hand is realistic. In contrast, the cube sizes were estimated as significantly smaller with the low-anthropomorphism avatar (M = 1.10, SE = 0.02) compared with the medium- (M = 1.12, SE = 0.02; $p < .01$) and high-anthropomorphism avatars (M = 1.13, SE = 0.02; $p < .05$) for the veridical hand size condition and in the high-anthropomorphism avatar (M = 1.09, SE = 0.02) compared with the medium-anthropomorphism case (M = 1.11, SE = 0.02) for the enlarged hand size condition ($p < .05$). Next, as we observed the main effect of the cube size, we conducted Tukey's post-hoc tests. The result showed that the small cube size (M = 1.15, SE = 0.02) was perceived as larger than the true size when compared to the medium (M = 1.09, SE = 0.02; $p < .01$) and large cube sizes (M = 1.09, SE =0.02; $p < .05$) (see Figure 4.5, left). Note that cube sizes were estimated as larger than their true values for all conditions. The significant main effects of the adjustment direction ($p < .01$) showed that the cube size was perceived as smaller in ascending (M = 1.09, SE = 0.01) compared to the size in descending series (M = 1.13, SE = 0.02) (see Figure 4.5, right).

The results of the post-hoc analysis of four-way ANOVA indicated that hand enlargement influenced the estimated cube size only in the high-anthropomorphism condition. This indirectly supported [**H3**]: the less realistic the virtual hands, the less the impact of the changes in hand size on the object size estimation. To directly test [**H3**], we calculated the percentage ratio of the estimated cube size in the enlarged hand size condition normalized by the corresponding value in the veridical hand size condition for each degree of avatar anthropomorphism (see Figure 4.6). The values indicate the extent to which the cube size is perceived as smaller or larger for enlarged vs. veridical virtual hands for each level of avatar anthropomorphism. We conducted a one-way ANOVA analysis considering the within-group factors of avatar anthropomorphism to further examine whether the effect of hand enlargement on estimated cube size was different among the three levels of anthropomorphism. The ANOVA showed a significant effect for avatar anthropomorphism [$F(1.78, 37.29) = 5.72$, $p < .01$, $\eta_p^2 = 0.21$] and Tukey's post-hoc tests showed that the value was significantly smaller for high anthropomorphism than for low anthropomorphism ($p < .05$). This result supports [**H3**].

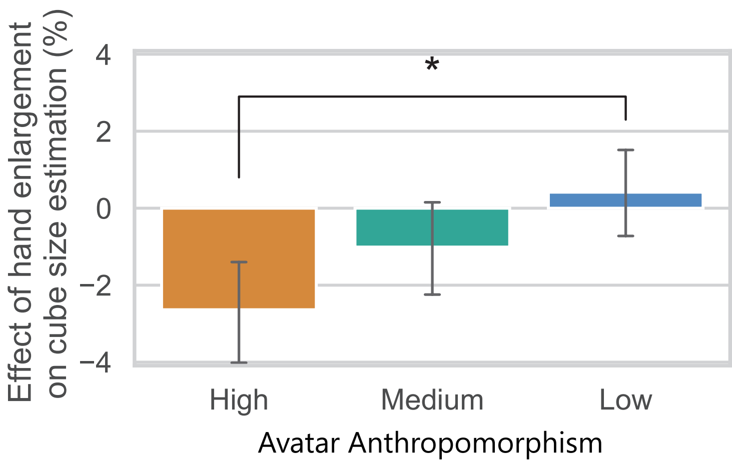

Fig. 4.6: Ratio of the average size estimation in the enlarged hand size condition normalized by the corresponding value in the veridical hand size condition according to avatar anthropomorphism (percentage deviation from 100 %). Error bars indicate SE. *: p<.05. © 2019 IEEE.

4.3.2 Questionnaire

To test [**H2**]: the less realistic the virtual hands, the weaker the SoBO; the subjective ratings of the questionnaire were analyzed. Agency, ownership, and location ratings were aggregated and averaged (answers for control items were inverted) to compute the scores for each avatar anthropomorphism per participant, as introduced in the original study containing the questionnaire [145]. We used different avatars for different genders in the high-anthropomorphism condition; hence, we examined the scores by considering the factor of gender as well as avatar anthropomorphism. We applied an aligned-rank transform (ART) to the data because of the non-parametric nature of the data. The ART procedure allows the use of ANOVA to analyze the interaction effects with the non-parametric data [246]. Two-way repeated-measure ANOVAs with the within-subject factor of avatar anthropomorphism (three levels: *high*, *medium*, and *low*) and between-subject factor of gender (two levels: *Male* and *Female*) were performed for each subscale. For all subscales, the ANOVA revealed a significant main effect only of avatar anthropomorphism [Ownership; $F(2,40) = 26.37$, $p < .001$, $\eta_p^2 = 0.57$, Agency; $F(2,40) = 39.92$, $p < .001$, $\eta_p^2 = 0.67$, Location; $F(2,40) = 40.68$, $p < .001$, $\eta_p^2 = 0.67$] (see Figure 4.7).

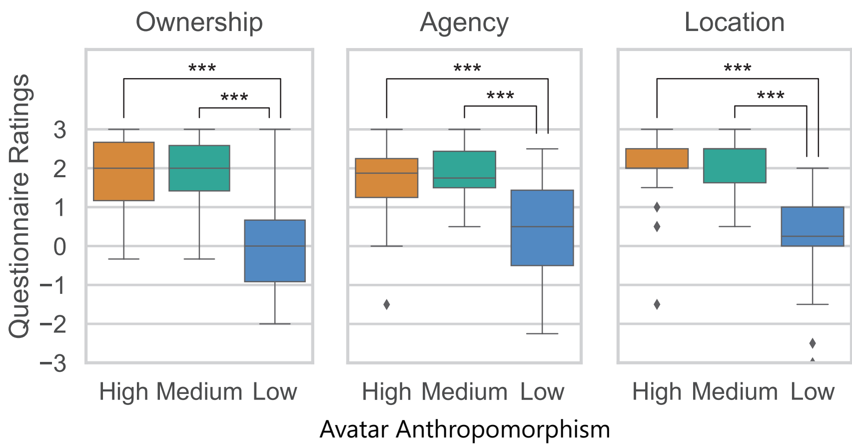

Fig. 4.7: Box plots of the perceived ownership (left), agency (center), and location (right) for each avatar anthropomorphism level obtained through the questionnaires (from − 3 to +3). ***: p<.001. © 2019 IEEE.

No interaction effects existed between gender and avatar anthropomorphism; thus, we conducted post-hoc pairwise comparisons using the Wilcoxon signed-rank test (Holm-corrected) considering the within-group factor of avatar anthropomorphism for each subscale. The results showed that in all the subscales, the scores were significantly lower in the low-anthropomorphism condition than in the medium- and high-anthropomorphism conditions (all p<.001). These results partially supported [**H2**] in the sense that low-anthropomorphism avatar elicited the lowest SoBO, although there was not significant difference in the strength of SoBO between high- and medium- anthropomorphism avatars.

4.3.3 Correlation Analysis

To test [**H4**]: the participants with higher scores of SoBO tend to perceive the object size as smaller under the influence of hand enlargement. We examined whether the score of SoBO positively correlates with the degree to which hand enlargement influences the underestimation of the object size. A polyserial correlation analysis, which is used for the data between a quantitative and an ordinal variable, was conducted between the effect of hand enlargement on estimated cube size (see Figure 4.6) and the scores of SoBO (see Figure 4.7) among participants for each anthropomorphism level. As shown in Figure 4.8, marginally significant weak correlations were found for high- and medium-anthropomorphism conditions: (High: $\rho = -0.37, p = .07$, Medium: $\rho = 0.39, p = .05$). In contrast, no significant correlation was found for low anthropomorphism ($\rho = -0.16, p = .45$). These results did not fully support [**H4**] in the sense that a negative correlation was found for the high-anthropomorphism avatar, as expected (i.e., a positive correlation with the tendency of underestimation), but the opposite was found for medium-anthropomorphism avatar.

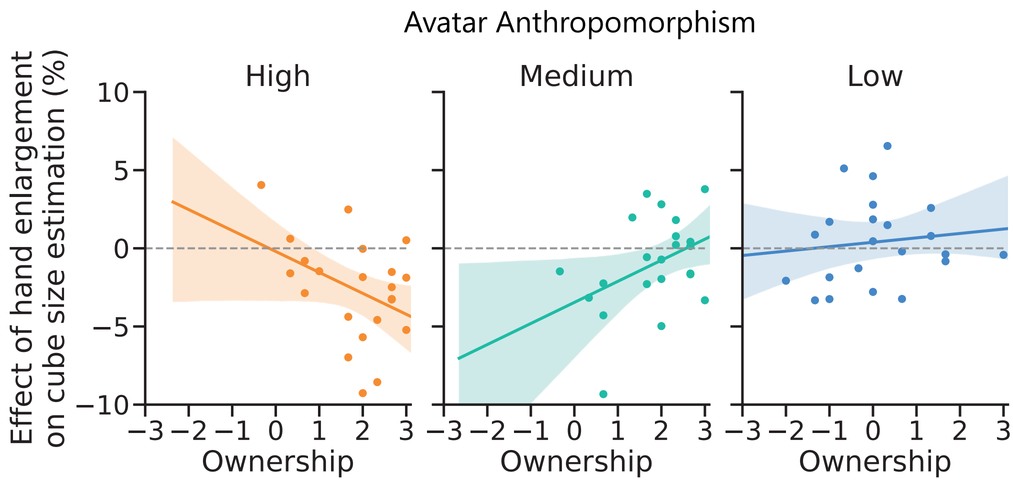

Fig. 4.8: Scatter plots with linear regression lines between the effect of hand enlargement on the estimated cube size and the SoBO scores for each anthropomorphism level. Translucent bands indicate 95% CIs. 10,000 bootstrap samples were used to estimate each 95% CI. © 2019 IEEE.

4.4 Discussion

4.4.1 Main Results

The main objective of this study was to examine how avatar anthropomorphism affects perceived object sizes as the size of the virtual hand changes. We found four main results from the experiment. First, the object size was perceived as smaller when the virtual hand size was enlarged only in the case of a highly realistic virtual hand (see Figure 4.4), which confirmed [**H1**]. Second, the data from the questionnaire (see Figure 4.7) showed that the low-anthropomorphism virtual hand produced significantly lower scores of ownership, agency, and location compared with the high- and medium-anthropomorphism virtual hands. It partially confirmed [**H2**], considering that the medium-anthropomorphism avatar did not elicit weaker sense of embodiment than the high-anthropomorphism avatar. Third, the degree of influence of body size on the object size perception was lower in the low-level anthropomorphism conditions compared with the highly realistic avatar, which confirmed [**H3**] (see Figure 4.6). Lastly, a participant's score for SoBO had a weak trend of positive correlation with his/her tendency to perceive the object size as smaller when the virtual hand was enlarged for the high-anthropomorphism avatar and negative correlation for the medium-anthropomorphism avatar. The trend is consistent with our hypothesis [**H4**] for the high-anthropomorphism condition. However, the opposite trend was found for the medium-anthropomorphism condition. This result did not fully support [**H4**], even though the support for [**H2**] and [**H3**] indicated that the avatar with low anthropomorphism provided the weakest SoBO and influence of hand enlargement on size perception. In summary, these findings support the conclusion that avatar anthropomorphism influences the extent to which the size of a virtual object is perceived based on the size of the virtual hand. Our study provides evidence that self-avatar appearance affects how we perceive not only a virtual body but also virtual spaces. Hence, the effects of the virtual hand appearance on *perception* must be considered to design better virtual experiences that provide precise space perception, even though an avatar can be rendered with any appearance in terms of its *action*.

Our findings indicate that the more realistic the avatar, the more susceptible one's size perception becomes to the difference in the avatar size. At the same time, it also provides a stronger sense of embodiment, including SoBO. This trade-off provides a new insight in the field of 3DUI: we should consider the avatar appearance in scale-sensitive VR applications. Current VR applications often display generic avatars of a certain size, regardless of the user's actual body size, especially when users hold controllers. In such cases, the user recognizes virtual spaces through avatars whose sizes differ from the actual size of the user's body. Consequently, the user's perception of object size is potentially affected. Therefore, in the case of scale-sensitive VR applications, our results indicate the following: if the size of a virtual hand is generic to all users, then it is desirable that the avatar appearance be non-anthropomorphic (e.g., cursors and controllers), which reduces or even eliminates the influence of the avatar size on object size perception, even though it provides a weaker SoBO. In contrast, if the application needs to achieve a strong SoBO and consistent scale perception among users, then it is better for the virtual hand to be realistic and have a personalized size for users.

Our results showed that when the size of the realistic virtual hand was enlarged to 125% of its actual size, the object size was perceived as smaller by approximately 2.64% compared to the size perceived with the veridical virtual hand. In addition, the ANOVA showed that the effect was regardless of the cube size and hysteresis direction. Several previous studies [28, 144, 174] also confirmed that object sizes are perceived as different when realistic avatar sizes are changed in VEs. However, the size of a full-body avatar was nearly halved in the study by Banakou et al. [28], and the size of the virtual hand was doubled or halved in the study by Linkenauger et al. [174]. In contrast to their studies, our study provides evidence for the first time that even a change of 125% compared to one's own hand size, which sometimes happens when the virtual hand is generic, can influence the object size perception in VEs, even when the only change is in the virtual hand size. Jung et al. [144] compared the accuracy of size perception with a personalized video-based hand against a generic virtual hand. This is a likely occurrence in common VR systems. Nevertheless, the cue that contributed to the size estimation is still unclear in their study because several differences existed between the personalized and generic hands other than the appearance, such as the rendering technique (3DCG vs. chroma key composition) and size. Furthermore, the personalized hand size may have contributed to estimating the object size when compared to a generic hand whose size is unrelated to the participant's own hand size because size estimation is performed while observing the hand next to an object, possibly leading to size estimation by inference. In contrast, our results showed that the mere difference in anthropomorphism modulated the effect of hand size on the object size estimation even without a direct comparison with the hand. Therefore, we provided the evidence that the size of the implicit body representation, altered through the illusion of SoBO, affects object size perception rather than the viewed size of the virtual hands.

Even though the level of anthropomorphism influenced both the strength of embodiment and the effect of hand enlargement on size perception, the correlation analysis among the participants only showed a marginal significance between them for the high-anthropomorphism condition. Figure 4.8 indicates two weak trends: that stronger SoBO for a realistic avatar results in a greater effect of hand enlargement on object size underestimation and vice versa for the medium-anthropomorphism avatar. As for the high-anthropomorphism condition, the SoBO was almost constantly high because of the interactive immersive VR's powerful potential for embodying a virtual realistic avatar, compared to the previous studies [24, 178] that showed the correlation but used visuotactile stimuli. This might cause a ceiling effect and attenuate the correlation among the participants. If a future study finds a clear correlation between the strength of SoBO and the magnitude of the influence of body size on the object size perception, this link could offer an alternative measurement of SoBO in VR. The opposite trend of the medium-anthropomorphism avatar can be interpreted in reference to the study by Banakou et al. [28], which showed that the embodiment of a child avatar resulted in a greater underestimation of the object size than that of an adult avatar scaled to the same height as the child. They attributed their results to the fact that the cognitive mechanism triggered past experiences associated with being younger. They also explained that if the body type was not one that had been coded in memory through past experience, the participants might be influenced by socially and culturally derived expectations of how it would feel to have a specific body type [28]. In our case, it is considered that our expectation of an "iconic avatar-like" perception, which might be rather mechanic, delivered the opposite effect compared with the realistic avatar, as one feels stronger ownership over the iconic avatar. The influence of the semantic aspects of avatars on perception is an interesting subject for future research. The possibilities of a ceiling effect and a semantic effect can also explain the result that despite the strong sense of embodiment with both high- and medium-anthropomorphism avatars, the effect of hand enlargement on cube size underestimation tended to be weaker with the medium-anthropomorphism avatar than with the high-anthropomorphism avatar, although the difference was not significant.

Although our main results showed that the cube size was perceived as smaller for the enlarged realistic virtual hand compared to the veridical hand, the cube sizes tended to be overestimated compared with the actual virtual cube size under any conditions, as shown in Figure 4.4 and Figure 4.5. This tendency has also been shown in a previous study [247]. The overestimation bias does not affect our findings because it can be considered a fixed tendency throughout the experiment and we were only interested in the relative values among the conditions. However, it might be useful to investigate the reason for the overestimation bias.

One possible explanation is that the change in the viewing angle relative to the cube caused an overestimation (i.e., the cubes were on the table when estimating their sizes and above the table when carried). Another explanation is that overestimation occurred because of the absence of the virtual hand display when estimating the cube size. Indeed, egocentric distance perception, which is inseparable from size perception, has been shown to be shrunk by approximately 7% when the avatar is not displayed in VEs [182]. Assuming that the cube was perceived as closer when estimating the cube size, it is expected to be overestimated because closer objects would be larger in terms of their retinal sizes. This view also explains the result that the cube sizes were estimated as significantly smaller with the low-anthropomorphism avatar compared with the medium- and high-anthropomorphism avatars for the veridical hand size condition; the abstract hand had less impact on shrinkage in distance perception, resulting in smaller overestimation of the cube size. If this is the case, a change in the avatar appearance immediately affects the perceived scale of the VE. One participant mentioned that he noticed the size of the table continually changing during the experiment, supporting this view. Note that in fact the size of the table was constant throughout the experiment. It implies that the designers of VR applications are recommended to avoid switching the display of the avatar and changing its size when consistent-scale perception is required.

4.4.2 Limitations and Future Work

This study focused on the unexplored relationship between avatar anthropomorphism and body-based scaling, i.e., the effect of hand size on object size perception, evidencing that avatar anthropomorphism affects the way we perceive the size of virtual objects in near space. Nevertheless, we believe that a number of parameters still encourage further research.

First, it is necessary to investigate whether the effect can also be verified with larger and further objects that one cannot interact with. We adopted herein a cube as an object that could be operated by hand based on previous research [144, 174]. However, for VR applications involving architectural scenarios, the scale of the whole external environment is more important than the size of a particular object. For example, when users view a large building virtually, they would like to know the scale of the space as a whole. Thus, an interesting subject for future study is whether the perceived object size could be influenced by body size, regardless of the object's type, size, and distance. Studies have shown that the whole-body illusory ownership of a Barbie doll changes size perception, even at large distances [25, 178], and that the eye height affects the distance perception of the dimensions of the overall environment [182]; this is expected at distant spaces as well, but future verification is needed.

Second, the relative impact of avatar anthropomorphism and size compared to other cues would require exploration. The VE used in this study was a simplified room, not a realistic one. However, object size perception depends on various cues from our surrounding environment, such as depth cues, familiar object sizes, shadows, and viewing angles. A recent study showed that changing a user's eye height alone cannot override robust familiar size cues in a richly detailed VE filled with objects [248] despite a number of previous reports of the effect of an eye height in simple environments [179–182]. Thus, it is also important to know whether the effect can also be verified in a highly detailed VE filled with many objects capable of providing rich size cues. In addition, the specification of dominant factors for the determination of perceived body size would be required (e.g., what happens when eye height and visual hand size are conflicting).

Lastly, the influence of different types of distortion in body representation other than simple enlargement would be an interesting topic to explore. For example, it will contribute to further characterization of the relationship among them to measure the perceived object size as a function of the avatar size, including the case of shrinkage, according to the avatar representations. Otherwise, it will be useful to consider other cases of distortion of body representation rather than enlargement, which is sometimes caused by a common 3DUI technique, such as the Go–Go interaction [249]. This perhaps causes a phenomenon similar to the remapping of space by active tool use: space previously mapped as far can be remapped as near in the brain [175, 177, 230]. It is also interesting to explore the effect of a tracking device (e.g., controllers vs gestures) and its accuracy. The difference in tracking form influences the degree to which a user's own movement reflects an avatar's movement; thus, it might affect agency and SoBO.

4.5 Conclusion

It is necessary to explore what happens to size perception when we embody the different avatars so that the VEs are perceived as precisely as the real environment, especially in scale-sensitive VR applications (e.g., 3D modeling, architecture design, and telemedical practices). This study investigated the unexplored relationship between avatar anthropomorphism and body-based scaling, i.e., the effect of hand size on object size perception. Our results showed that perceived object sizes are underestimated only when a realistic virtual hand is used in the case where the virtual hand is enlarged (instead of using a veridical hand size). Our findings indicate that the more realistic the avatar is, the stronger is the sense of embodiment including SoBO, which fosters scaling the size of objects using the size of body representation as a fundamental metric. This provides evidence that self-avatar appearances affect how we perceive not only a virtual body but also virtual spaces.

Chapter 5

Effect on Behavior

In this chapter[1], we investigated whether the anthropomorphism of self-avatars influenced not only the users' perception but also their behavior in VEs. By focusing on how realistically users behave in VEs, we addressed the issue of preventing users from walking through virtual boundaries (e.g., walls) in room-scale VEs for safety and design limitations. Sensory feedback from wall collisions is shown to be effective, but it may disrupt the immersion. We assumed that a greater sense of presence and SoBO would discourage users from walking through walls, as "respond as if real" in VEs is an operational definition of the concept of presence. Therefore, we investigated whether the realistic, full-body self-avatar could discourage users from walking through the wall in VEs. By conducting a two-factor between-subjects experiment that controls the anthropomorphism (realistic or abstract) and visibility (full-body or hand-only) of self-avatars, we analyzed the participants' behaviors and the moment they first penetrated the wall in game-like VEs that instigated participants to penetrate the walls. The results revealed that the realistic full-body self-avatar was the most effective in discouraging the participants from penetrating the walls. Furthermore, the participants with lower presence tended to walk through the walls sooner. The results suggest that by simply changing the visibility and the level of anthropomorphism, a VE designer can implicitly encourage users to behave realistically (e.g., avoiding the wall) or unrealistically (e.g., passing through the wall) depending on the situation.

[1] The content in this chapter will be published as Nami Ogawa, Takuji Narumi, Hideaki Kuzuoka, and Michitaka Hirose (2020). Do You Feel Like Passing Through Walls?: Effect of Self-Avatar Appearance on Facilitating Realistic Behavior in Virtual Environments. *In Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (CHI '20)*. ACM. (to appear) https://doi.org/10.1145/3313831.3376562 (© Owner/Authors 2020)

5.1 Introduction

Fig. 5.1: A user walking through a virtual wall in the virtual (left) and real environments (right).

Proliferation of low-cost VR devices and tracking systems has encouraged the development of room-scale applications that allow users to walk around in a VE. Compared with other locomotion modalities (e.g., teleportation and controllers), physical walking ensures natural and highly flexible movements [135]. However, the associated high degree of freedom also leads to issues when the users' movements need to be restricted within a certain area or to follow certain paths. A prominent example is the problem of users walking through virtual boundaries, often represented by virtual walls, with which VR designers intend to confine the users within the boundaries (Figure 5.1). Conventional video games that typically use controllers simply restrict a virtual camera from passing through the walls. However, in room-scale VEs wherein users can freely walk around, the same strategy may cause a problem because the asynchronous movements of a user and a virtual camera can cause motion-sickness. In addition, when the virtual walls represent the physical boundaries of the safety area, passing through these walls may lead to dangers such as hitting a real wall. Consequently, it is necessary for room-scale VR applications to control the user's locomotion.

To address this problem, Boldt et al. [31] showed that a combination of auditory, visual, and vibrotactile feedback for head-wall and hand-wall collisions was effective in refraining players from walking through virtual walls without degrading the game experience. However, as this method can interfere with the other vibration or sound feedback that might be provided, especially during gaming, other methods that can discourage the users from passing through walls are required.

In this regard, our idea is to induce realistic user behavior, that is, facilitating the users to instinctively avoid colliding with the wall. It is known that the users behave more realistically when they feel a higher sense of presence, the sense of "being there", in a VE [126,141] (see Subsection 2.3.3 for details). Therefore, we can assume that a greater sense of presence would discourage users from walking through the virtual walls without providing them vibration or sound feedback. In addition, considering the strong relationship between SoBO and presence, we can assume that the higher the visual fidelity of a self-avatar (i.e., the closer the appearance is to our own body), the stronger the sense of presence as well as SoBO, facilitating the user's more realistic behavior in a VE (see Subsection 2.4.4 for details). Indeed, one of the important factors that affect the sense of presence is the presentation of a self-avatar in VEs [141], and the SoBO is considered to be analogous to a form of presence called self-presence, i.e., the effect of embodiment on mental models of the self [143]. Moreover, recent studies have showed that the appearance of self-avatars, e.g., anthropomorphism (human-like – object-like) [11,12,35,232] and visibility (full body – partial body) [114,250], influences the presence and the sense of embodiment. Considering these studies on presence and SoBO, we can assume that the higher the visual fidelity of a self-avatar (i.e., the closer the appearance is to our own body), the stronger the sense of presence as well as SoBO, facilitating the user's more realistic behavior in a VE.

In addition, developments in VR technology have facilitated the tracking of the motion of a user's multiple body parts and reflecting of these tracked motions on a full-body avatar in real time. However, the combination of hand-held controllers with partial avatar provision (e.g., hand and/or controller models) is common in current VR applications. Nevertheless, even though it is becoming more common to provide at least a partial avatar in VR applications today, the comparison of partial self-avatar with full-body self-avatar has not been studied extensively. Although there are no studies that have compared hand-only and full-body self-avatar representations, to the best of our knowledge, the visibility of arms, which regulates the connectivity of hands with a torso, has been considered one of the important factors for evoking SoBO [114, 250, 251]. However, while the effect of the presentation of a self-avatar (vs. without self-avatar) and the visual fidelity of avatars of others on presence has been well investigated, especially in communication research [18, 49, 141], few studies have focused on how visual fidelity of self-avatars influences presence, showing only the inconclusive evidence [34, 35, 82, 144]. These backgrounds have motivated us to focus on the visibility of self-avatar in addition to the anthropomorphism, which consist of visual fidelity of self-avatar appearance.

Therefore, we investigate how the anthropomorphism and visibility of a self-avatar affect whether or not the users walk through the virtual walls in VEs with room-scale mapping. We hypothesized that the participants who used full-body and realistic self-avatars are more likely to behave in a VE as they would in a real environment (RE). Thus, they are less likely to walk through walls than the participants who used unrealistic or partial self-avatars. Then, we conducted a between-subjects experiment in which the participants (N = 92) embodied one of the four self-avatars, Controller, Human Hand, Robot, and Full-body Human (Figure 5.2), which are combinations of anthropomorphism factors (realistic or abstract) and visibility factors (full-body or hand-only). Using a simple game-like VE that instigates the participants to walk through walls by giving them increasing incentives as they transit from room to room, we analyzed the tendency of the participants to walk through the walls. Additionally, we measured the presence physiologically (i.e., SCR) and subjectively (i.e., questionnaire). The behavioral data showed that the use of the Full-body Human avatar (i.e., full-body realistic avatar) discouraged the participants from walking through the walls. Furthermore, the participants with a lower sense of presence tended to take less time to walk through the walls, despite no significant differences in the subjective ratings of presence and SCR in avatar conditions.

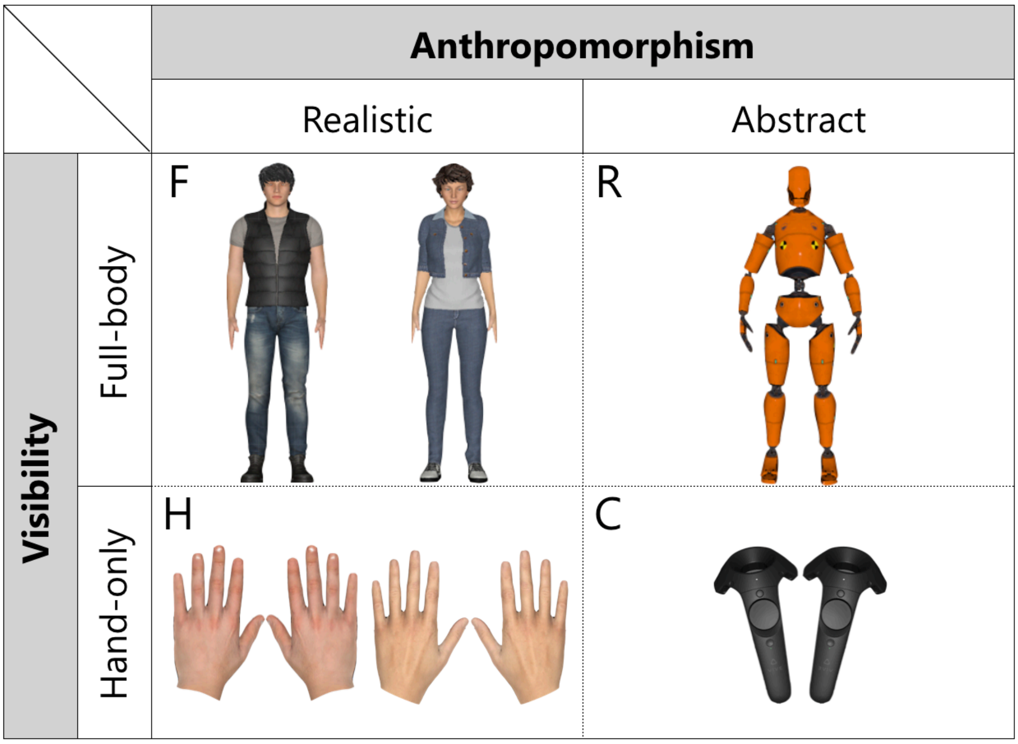

Fig. 5.2: Four types of avatars were used in the experiment (F: Full-body Human, H: Human Hand, R: Robot, and C: Controller). For realistic avatars (F and H), gender-matching avatars were used (left: male, right: female).

Through this study, we provide quantitative evidence of the fact that a combination of high visibility and high anthropomorphism in avatars can induce realistic user behavior (i.e., avoiding the walls) in a VE, presumably owing to a higher sense of presence. We expect our results to also contribute to wider VR applications that require realistic user responses in VEs such as training, simulators, and psychotherapies.

5.2 Sensory feedback of virtual walls

Common feedback techniques used in current consumer VR games for avoiding collisions with virtual walls have been extensively reviewed by Boldt et al. [31]. According to them, *"most state of the art VR games either (1) stop the game progress and limit rewards or otherwise punish the player using game mechanics when crossing walls, (2) are designed in a way so the players cannot get close to the walls at all, or (3) simply avoid walls completely within the play area."* Altogether, these techniques strictly limit the game design and require additional strategies to alleviate the problem.

Although it is uncommon in consumer VR games, providing haptic feedback can be effective in physically preventing users from crossing the wall. For example, a considerable number of studies have been conducted to develop force feedback devices such as wire-based force systems (e.g., SPIDAR-W [252]), pseudo-force feedback actuators (e.g., Traxion [253]), and exoskeletons (e.g., Dexmo [254]). In addition, Lopes et al. [255] used electrical muscle stimulation, which created a counter force that pulled the user's arm backwards. In contrast, passive haptics utilize physical objects to provide haptic feedback from virtual objects. Specifically, hand retargeting techniques, wherein the movements of a virtual hand are mapped to guide the user's actual hand toward physical haptic props for providing passive haptics for multiple virtual objects [29, 195], can be effectively used to prevent a virtual hand from interpenetrating virtual objects [196, 214]. However, these haptic feedback techniques can only be implemented for hand penetration and do not address the problems with the head, which determines the viewpoint in immersive VR, passing through the walls.

Even though there has been an attempt to provide passive haptics such as walls without redirecting viewpoints, it requires several volunteers to carry physical props in real time [256]. In addition, hand retargeting techniques cannot simply be adopted for heads. Generally, although redirected walking techniques have shown that humans can tolerate a small amount of rotational shift in the viewpoint [216], mapping a virtual viewpoint that is different from the actual head movement could induce severe motion sickness.

Although existing studies have focused primarily on haptic feedback systems in general, Boldt et al. [31] specifically investigated the effect of sensory feedback on preventing users from walking through walls. They proposed a combination of visual, auditory, and vibrotactile feedback for both hand–wall collisions (vibrating controllers and presenting a knocking sound) and head–wall collisions (blackened vision and dampened surrounding sound), which is non-intrusive and requires no special equipment. They verified that users receiving the feedback were less likely to walk through walls than users who did not receive the feedback. Contrary to all aforementioned approaches, which provide sensory feedback from wall collisions, our approach aims to prompt realistic user behavior, that is, avoiding collision with the walls, by inducing a higher sense of presence without any feedback or instruction.

5.3 Experiment

A between-subjects experiment was performed to investigate whether the anthropomorphism (realistic or abstract) and visibility (full-body or hand-only) of self-avatars discourage the participants from walking through the walls. The participants were instigated to walk through the virtual walls in a VE with room-scale mapping, while embodied with any of four types of self-avatars. We analyzed the participants' behavior using motion-tracking data with two main indices: whether (i.e., the number of participants) and when (i.e., duration) they walked through the walls. Additionally, we analyzed their physiological reaction to the virtual threats using SCR as an indicator of the sense of presence and SoBO, as well as the subjective scores of presence and SoBO using a questionnaire.

5.3.1 Participants

We conducted the experiment with 92 participants (64 males and 28 females, 30.48 ± 9.29 (SD) years old), recruited from the public through social media. Only a summarized aim of the experiment (i.e., to evaluate user experiences in room-scale VR) was announced when recruiting the participants. These naive participants were assigned to any avatar condition to ensure that each group had the maximum similar distribution of gender and prior experience with VR. Thirty participants had no previous experience with VR, forty-four had few previous experiences, eight occasionally used VR, eight often used VR, and two used VR daily. They signed an approved statement of consent, and they were compensated with an Amazon gift card amounting to approximately $5. The experiment was approved by the local ethical committee and conducted at a room at the university.

5.3.2 Apparatus

The experimental apparatus included an HMD (Vive Pro, HTC), three position trackers (Vive Tracker, HTC), a pair of controllers (Vive Controller, HTC), a wearable SCR sensor (Shimmer3 GSR+ unit, Shimmer), and a Windows-based backpack computer (VR One 6RE-002JP, MSI) (Figure 5.3A). Two trackers were attached to the top of the shoes and a tracker was attached to the belt on the waist. The HMD, trackers, and controllers were tracked using HTC's Lighthouse system. The controllers were only used to track the positions of the users' hands. To display the VEs, we used a backpack computer (with an Intel i7-6820HK, 32 GB RAM, and NVIDIA GTX1070) to ensure that the participants could freely walk around without bothered by the cables. The experimental program was developed using Unity 3D and ran at a frame rate of 100 Hz on average.

5.3.3 Avatar Appearance

We used four types of avatar appearances with different levels of anthropomorphism and visibility, as shown in Figure 5.2. We used **Full-body Human:** realistic full-body 3D models obtained from Morph 3D, **Robot:** a robotic humanoid avatar created by CGBoat, **Human Hand:** the hand parts of the avatars used in the Full-body Human condition, and **Controller:** a controller model that was obtained from HTC. For the realistic avatars, we used male and female gender-matching avatars. For the full-body avatars, the full-body animation was calculated via inverse kinematics using the VRIK package. The avatar's height was set to the participants'

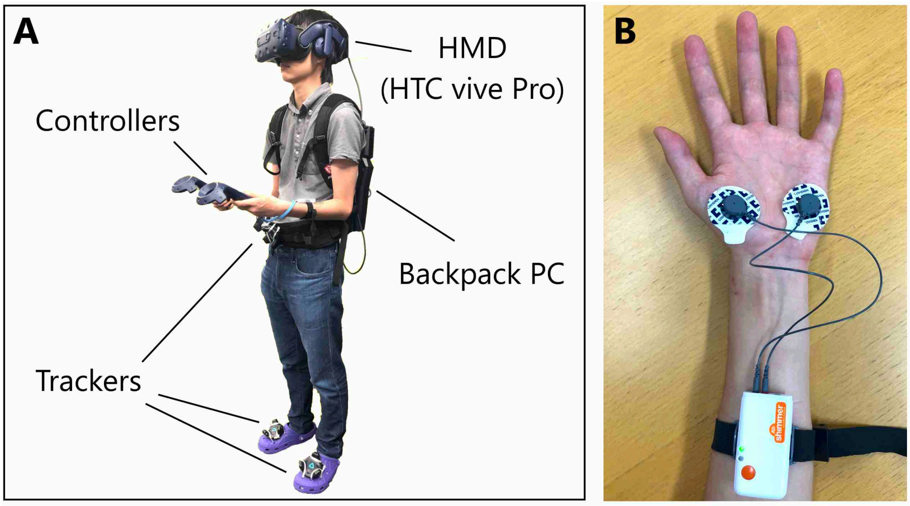

Fig. 5.3: (A) A participant equipped with experimental apparatus. (B) A wearable sensor used to estimate participants' SCR to threatening stimuli.

height. In addition, at the beginning of the experiment, the participants looked at a virtual mirror in the scene so that they would see a reflection of their virtual body. This procedure is often used to enhance SoBO, particularly when using full-body avatars [257, 258].

5.3.4 Skin Conductance Response (SCR)

SCR is commonly used to measure SoBO, but also used to quantify the sense of presence [133] (see Subsection 2.3.3 and 2.4.1 for details). We provided the participants with virtual threatening stimuli and measured their physiological response to the stimuli using SCR. In this study, we considered that SCR reflects SoBO and presence because the greater ownership of the virtual body and presence in the VE, including virtual threats, would contribute towards a realistic reaction to the threat. As illustrated in Figure 5.3B, the participants were equipped with a wearable SCR sensor on their left wrist. Two electrodes were attached to the palm of the participants' left hand using Kendall Arbo H135 (COVIDIEN). The galvanic skin response (GSR; the variation of the electrical conductance of the skin) signals were recorded and analyzed using Tobii Pro Lab (Tobii Technology K.K.). The raw data was registered at a sample rate of 125 Hz in real time. The software removed them by applying a median filter with a time window of 500 ms, followed by a mean filter with a time window of 1000 ms. We used the event-related SCR, defined as the amplitude of the peak in GSR that occurred 1–5 s after the onset of the threatening stimuli, as an index of SCR analysis. It can be calculated as the difference between the peak and the preceding minimum values of GSR of the identified response.

5.3.5 Experimental Scene

We followed the experimental setup of Boldt's study [31] but slightly modified the design to ensure that it could be implemented to the context of our study. There were four virtual rooms (4×4 m) that provided the participants with different levels of incentives to walk through the walls. In each room, the participants were asked to move from the starting point to the goal where the teleporter to the next room was located. They were tasked with pushing all buttons in the correct order and go to the teleporter. As stated in Boldt's study [31], most users rarely attempt to walk through walls in brief play sessions unless there is a clear incentive. Therefore, we designed virtual rooms to quickly instigate the participants to walk through the walls as the following; (1) The inner walls were made of 5-cm-thick chain link fence instead of solid walls so that the participants could easily see the buttons over the wall. (2) No feedback was provided on head- and hand-collision with walls, and hands or controllers could penetrate the walls. However, visual and auditory feedbacks were given when the button was pressed or the teleporter was activated. To avoid any influence of the ease in pushing buttons, the collision-detection areas of the avatar models, which were used to determine whether the button was pressed, were the same for all avatars. (3) A time limit was set for each room. The participants saw a timer counting down from 150 s. In room 3, the time was exceptionally set for 180 s. If the time was up, the teleporter was activated spontaneously. The room layouts are illustrated in Figure 5.4. They were designed to provide the participants with gradually increasing incentives to walk through the walls. The participants were asked to move from the starting point (S) to the goal (G) where the teleporter was located in each room. Room 4 also played a role of providing the participants with threatening stimuli to measure the SCR.

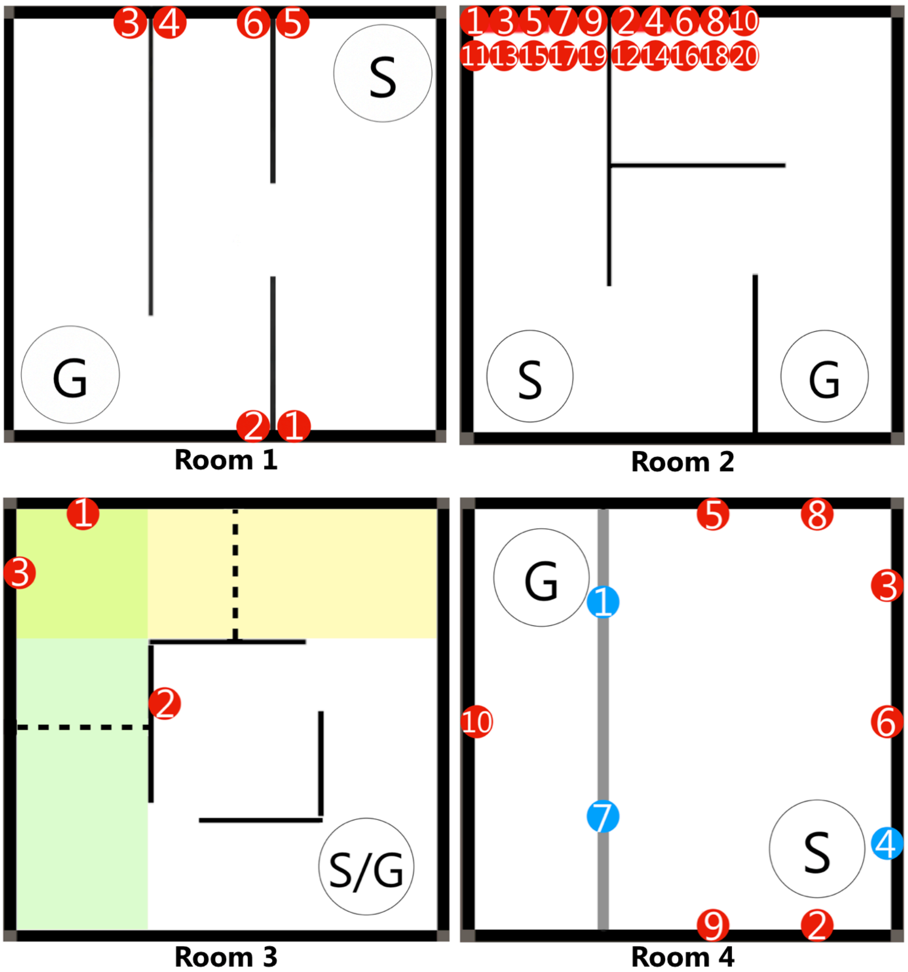

Fig. 5.4: Room layouts. S and G represent the start and goal, respectively. The buttons are numbered and must be pushed sequentially to activate the teleporter at the goal in each room. The dashed lines in room 3 represent the sliding doors that closed when the participants entered the yellow- and green-colored areas. The gray line in room 4 represents the wall through which electric lightning was passed when the participants got closer to it. On pushing the blue buttons in room 4, the participants were presented with threatening stimuli.

Fig. 5.5: Characteristics of room 1 and 2. (Room 1) The participants could easily push the button on the other side of the wall if they penetrated their hand. However, they also had the option to pass their hand under the wall and walk around. (Room 2) The participants had to walk back and forth several times but could take a shortcut if they walked through the wall.

Room 1

Room 1 was designed to instigate the participants to penetrate their hand into the wall (Figure 5.5). Three pairs of two successive buttons were placed next to each other across the wall. Hence, if the participants penetrated their hand, they could easily push the paired buttons without walking around. Alternatively, the participants could walk around the walls or insert their hand through the aperture in the wall to push the button nearby. Thus, the incentive to penetrate the body was thus kept little to avoid too many participants penetrating in the first room and moderately control the incentives of penetration throughout the entire experiment.

Room 2

Room 2 provided an incentive to the participants to walk through the wall to solve a repetitive and time-consuming task faster (Figure 5.5). A total of twenty buttons were used. As odds and evens were separately located across the wall, the participants must walk back and forth between two locations that were spatially close but separated by the wall. The time-limit was set so that they could successfully complete in time when they walked fast. However, if they walked through the wall, they could easily push the buttons from the other side of the wall without walking around it. The buttons right next to the wall (2, 9, 12, and 19) could be pushed without head-wall collision if they inserted their arm.

Room 3

Room 3 was impossible to complete without walking through a wall. It had three buttons. Buttons 1 and 3 were located at the area surrounded by the two sliding walls, which closed when the participants got closer; thus, the buttons could be pushed only if the participants walked through the walls (Figure 5.6). We expected remarkable differences in the time until the participants first walked through the wall rather than whether or not they did so; this is because it would become obvious that they had no choice than walking through the wall to push the buttons immediately after they tried several other possible solutions. Hence, the time-limit was set to 180 s, which is 30 s longer than in the other rooms; this was done to allow sufficient variation in time to reflect the participants' reluctance to walk through the walls.

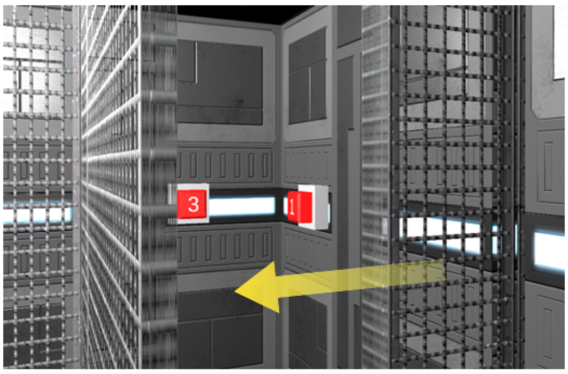

Fig. 5.6: Characteristics of room 3. The buttons could only be pushed if the participants walked through the sliding door, which closed when they approached.

Room 4

Room 4 was also impossible to complete without walking through the wall and it was more obvious than room 3. Nevertheless, the main purpose of room 4 was to provide the participants with threatening stimuli to measure SCR. There were a total of ten buttons and a wall across the room. Buttons 1 and 7 were located on the wall and if a participant's hand got closer to the wall, electric lightning visually and auditorily passed through the wall (Figure 5.7A). In addition, when button 4 was pushed, a number of needles popped out from the wall (Figure 5.7B). Furthermore, they had to walk through the wall, which electrically lit up when they got closer, to push button 10, which was located on the other side of the wall. We expected greater SCR if they felt greater SoBO over an avatar or greater presence in the VE. Additionally, we expected the participants who felt greater SoBO or presence to hesitate before walking through the lightning wall.

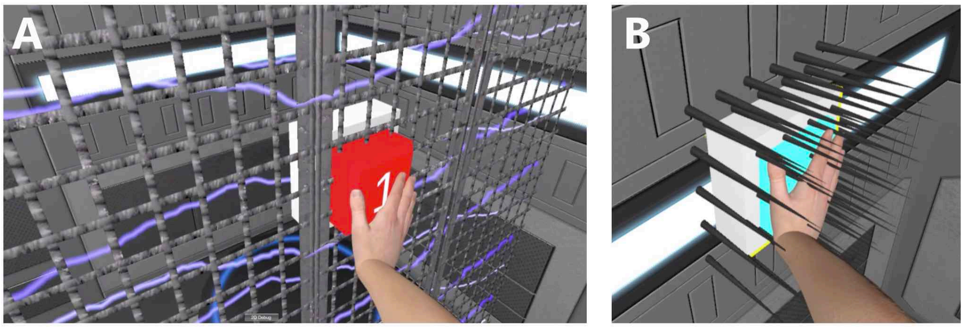

Fig. 5.7: Characteristics of room 4. (A) Electric lightning was passed throughout the wall when the participants approached it (i.e., when button 1 or button 7 was pushed and when they walked through the wall to push button 10). (B) A bunch of needles popped out when button 4 was pushed.

5.3.6 Questionnaire

The subjective evaluation of presence and SoBO for virtual avatars was assessed through a questionnaire (see Table 5.1). For the presence, we used the Slater–Usoh–Steed questionnaire [127]. For SoBO, we used Gonzalez–Franco and Peck's

Table 5.1: Questionnaire items. For body ownership and response to threat, we used the avatar embodiment questionnaire [145]. For presence, we used the Slater–Usoh–Steed questionnaire [127]. Items in italics represent control questions.

Subscale		Question
Ownership	O1	I felt as if the virtual body[1] was my body[2].
	O2	*It felt as if the virtual body[1] I saw was someone else.*
	O3	*It seemed as if I might have more than one body[2].*
	O4	I felt as if the virtual body[1] I saw when looking in the mirror was my own body[2].
	O5	*I felt as if the virtual body[1] I saw when looking at myself in the mirror was another person[3].*
Response	R1	I felt that my own body could be affected by the electricity.
	R2	When the current flowed, I felt the instinct to the electricity.
	R3	I had the feeling that I might be harmed by the electric shock.
Presence	P1	Please rate your sense of being in the virtual environment, on a scale of 1 to 7, where 7 represents your normal experience of being in a place.
	P2	To what extent were there times during the experience when the virtual environment was the reality for you?
	P3	When you think back to the experience, do you think of the virtual environment more as images that you saw or more as somewhere that you visited?
	P4	During the time of the experience, which was the strongest on the whole, your sense of being in the virtual environment or of being elsewhere?
	P5	Consider your memory of being in the virtual environment. How similar in terms of the structure of the memory is this to the structure of the memory of other places you have been today? By 'structure of the memory' consider things like the extent to which you have a visual memory of the virtual environment, whether that memory is in colour, the extent to which the memory seems vivid or realistic, its size, location in your imagination, the extent to which it is panoramic in your imagination, and other such structural elements.
	P6	During the time of your experience, did you often think to yourself that you were actually in the virtual environment?

VR-specific avatar embodiment questionnaire [145]. We omitted items that were not applicable to our study, such as the question regarding tactile sensation, from the avatar embodiment questionnaire. Consequently, the questionnaire of SoBO consisted of five items. We used the word "body" for full-body groups but replaced them with "hand" for hand-only groups where it was appropriate. Additionally, among the six subsets that constitute the avatar embodiment questionnaire, we used the questions about 'Response to external stimuli' as well as 'Body ownership', as several experiments have shown correlations between the questionnaires and the physiological and behavioral responses for bodily threats [16, 259]. Hence, we considered that this scale reflects the aspects of SoBO and presence, as in the case of SCR. All questionnaire items were supplemented by a local tongue translation. Each response was scored on a seven-point Likert scale (-3 = strongly disagree and $+3$ = strongly agree). In addition, we asked the participants to rate their VR- and video-game-experiences on a scale of 1 to 5 to test if these characteristics influenced their behaviors.

5.3.7 Procedure

Upon entering the room, the participants were asked to read and sign an experiment consent form. Then, the experimenter set the SCR sensor on the participants' left hand. Next, the participants put on the belt and the shoes with trackers. After wearing the backpack computer and the HMD, the participants were given controllers and instructed not to grip the controller strongly because muscular activity could make noise on measuring the SCR. The participants were initially in the room without any walls. They were instructed not to go outside the exterior walls for their safety. After confirming that they could clearly see the virtual view and body, the virtual mirror appeared in front of them. They were asked to look at the mirror while freely moving their bodies for 30s. They were then asked to walk around

[1] "body" was replaced with "hand" and "controller" in Human Hand and Controller condition, respectively.

[2] "body" was replaced with "hand" in Human Hand condition and Controller condition.

[3] "another person" was replaced with "another person's" in Human Hand condition and Controller condition.

the room while looking down at their lower bodies. These processes were aimed to ensure the participants' embodiment of their avatar. Next, they were instructed on how to push the buttons, use the teleporters, their tasks, and that there were four rooms with a certain time limit. They were told that if they mistakenly pushed the button with incorrect number, they had to start over from the first one. They were also instructed to head for the teleporter if they exceeded the time-limit. Nevertheless, they were not informed about the walls, nor they saw the walls before entering room 1. Before entering room 1, they were told that they could not ask any questions during the experiment. When they went to the activated teleporter in each room, they were automatically transported to the next room and the timer started to count-down. If some participants did not walk through any wall even after 30 s had passed beyond the time limit of the last room, the experimenter told them to walk through the wall and complete the task. This procedure was introduced to ensure the SCR against the lightning wall could be measured for all the participants including those who did not walk through the wall in time, and the value of 30 s was determined through the preliminary experiment. In the actual experiment, only one participant was instructed to do so. After removing all the apparatus, the participants answered the questionnaire regarding SoBO, response to threat, presence, and demographics through a web form. Finally, the experimenter conducted a semi-structured interview with the participants on why they decided to walk through the wall and how they felt during the VR experience. After the interview, the experimenter debriefed the true purpose and hypotheses of the experiment when asked by the participant.

5.3.8 Hypotheses

Our hypotheses were as follows:

H1 The more realistic and visible the self-avatars, the more participants tend to refrain from passing through the walls.

H2 The more realistic and visible the self-avatars, the longer the participants take before passing through the walls.

H3 The more realistic and visible the self-avatars, the stronger the SoBO and presence.

H4 The participants with a higher sense of presence tend to refrain from passing through the walls.

5.4 Results

5.4.1 Behavioral Data

For the behavioral analysis, we followed the analysis method used in Boldt et al.'s study [31] but revised it according to our study design. For the behavioral data, we analyzed the number of participants who walked through the walls ([**H1**]) and the time until they first walked through ([**H2**]) for each room based on the head tracking data. As ANOVA is known to be robust to normality assumption, we conducted ANOVA for continuous data even when the data were not normally distributed. Two-way factorial ANOVA was used considering the between-group factors of anthropomorphism (two levels: *realistic* and *abstract*) and visibility (two levels: *full-body* and *hand-only*). Controller, Human Hand, Robot, and Full-body Human conditions are denoted by C, H, R, and F, respectively, for readability. For the distribution of the participants' behavior in each room, we provided the stacked bar chart with percentages in Figure 5.8, 5.10, and 5.11. See Table 5.2 for the combinations of raw numbers and percentage.

Room 1

In room 3, we did not expect the participants to walk through the walls except to insert their hands. Nevertheless, a few participants (C: 1, H: 2, R: 1, F: 0) walked

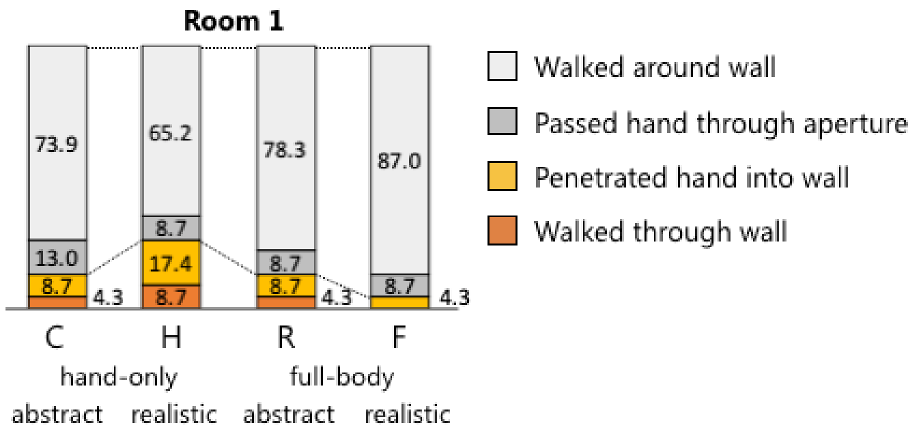

Fig. 5.8: Distribution of participants' behavior in room 1 according to avatar anthropomorphism and visibility. C, H, R, and F represent Controller, Human Hand, Robot, and Full-body Human, respectively. The shown numbers are the percentage out of 23 participants for each condition.

through. The participants' other typical behavior to push the nearby button obstructed by the wall was classified as follows: to penetrate their hand into the wall (C: 2, H: 4, R: 2, F: 1), to pass their hand through the aperture in the wall (C: 3, H: 2, R: 2, F: 2), and to make a detour (C: 17, H: 15, R: 18, F: 20) (Figure 5.8) Although we counted the passing-hand and detour groups separately, we were interested in the ratio of the participants who penetrated their hands into the wall, including those who walked through the walls. To test if the ratio was influenced by each between-group factor (anthropomorphism and visibility) and their interaction, we used a binary logistic regression. The likelihood ratio test showed that no variables significantly explained the ratio (anthropomorphism: $\chi^2(1) = 0.09$, $p = .76$, visibility: $\chi^2(1) = 2.29$, $p = .13$, interaction: $\chi^2(1) = 2.31$, $p = .13$). Hence, contrary to **[H1]**, the number of participants who penetrated their hand into the wall was not statistically different depending on their avatars.

Table 5.2: Distribution of participants' behavior in each room according to avatar anthropomorphism and visibility. The numbers and the percentage out of 23 participants for each condition are shown.

Room 1

	Controller	Human Hand	Robot	Full-body Human
Walked around wall	17 (73.9%)	15 (65.2%)	18 (78.3%)	20 (87.0%)
Passed hand through aperture	3 (13.0%)	2 (8.7%)	2 (8.7%)	2 (8.7%)
Penetrated hand into wall	2 (8.7%)	4 (17.4%)	2 (8.7%)	1 (4.3%)
Walked through wall	1 (4.3%)	2 (8.7%)	1 (4.3%)	0 (0%)

Room 2

	Controller	Human Hand	Robot	Full-body Human
Walked around wall	11 (47.8%)	7 (30.4%)	9 (39.1%)	16 (69.6%)
Penetrated hand into wall	5 (21.7%)	3 (13.0%)	6 (26.1%)	2 (8.7%)
Walked through wall	7 (30.4%)	13 (56.5%)	8 (34.8%)	5 (21.7%)

Room 3

	Controller	Human Hand	Robot	Full-body Human
Penetrated hand into wall	2 (8.7%)	1 (4.3%)	2 (8.7%)	6 (26.1%)
Walked through wall	21 (91.3%)	22 (95.7%)	21 (91.3%)	17 (73.9%)

Room 4

	Controller	Human Hand	Robot	Full-body Human
Walked through wall	23 (100%)	23 (100%)	23 (100%)	23 (100%)

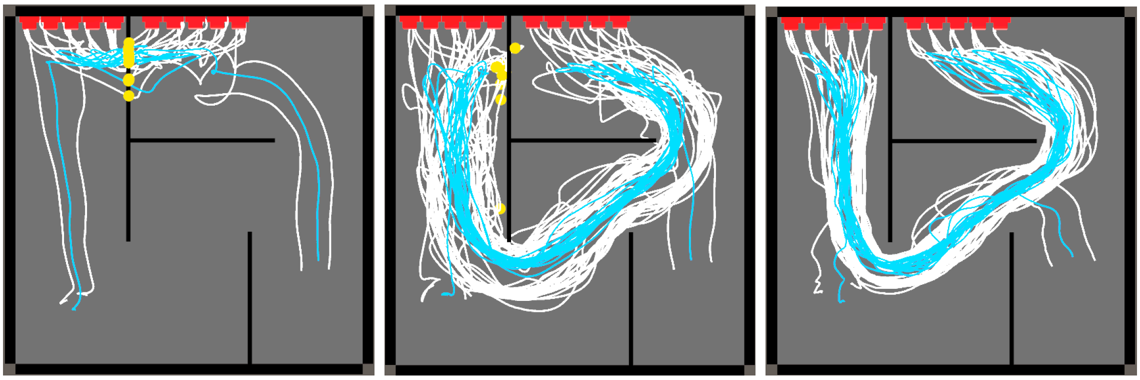

Fig. 5.9: Representative trajectories for typical behavior patterns in room 2. (left) A participant who walked through the wall. (center) A participant who penetrated his/her hand into the wall but never walked through the wall. (right) A participant who did not contact the wall at all. The trajectories of head and hands are colored in white and blue, respectively. Yellow dots represent collisions of head or hands with walls.

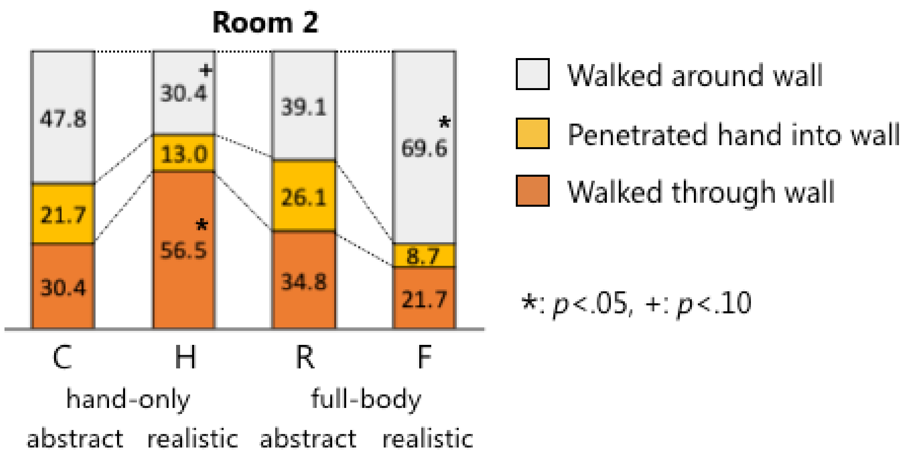

Fig. 5.10: Distribution of participants' behavior in room 2 according to avatar anthropomorphism and visibility. C, H, R, and F represent Controller, Human Hand, Robot, and Full-body Human, respectively. The shown numbers are the percentage out of 23 participants for each condition.

Room 2

In room 2, some participants (C: 7, H: 13, R: 8, F: 5) walked through the walls to take a shortcut as expected (Figure 5.9 left and Figure 5.10). Nonetheless, several participants (C: 5, H: 3, R: 6, F: 2) penetrated their hands into the wall (Figure 5.9 center and Figure 5.10). Although only a few participants (C: 1, H: 0, R: 1, F: 1) did so to touch the button, most of them typically withdrew their hand soon after penetration on the wall away from the buttons. According to the semi-structured interviews, 11 out of 16 participants intentionally did that to check if they could or were allowed to put their hand beyond the wall, and they determined that they were allowed to pass through the wall because no feedback (e.g., visual or haptic) or penalty (e.g., alert screen or audio) occurred. This "confirmation behavior" was also often observed in the participants who eventually walked through the wall (C: 4, H: 3, R: 3, F: 2). Conversely, the remaining participants who walked through the wall (C: 3, H: 10, R: 5, F: 3) walked through the wall straight without any confirmation behavior. Eventually, the remaining participants (C: 11, H: 7, R: 9, F: 16) walked the long way around the wall without contacting the wall to the end (Figure 5.9 right and Figure 5.10).

To test if the distributions of the three types of participant behavior were influenced by avatars, we conducted the likelihood ratio test of the ordered logistic regression model. The result revealed that the interaction effect was significant ($\chi^2(1) = 6.06$, $p < .05$). A post-hoc adjusted residual analysis of a Chi-squared test showed that the number of participants who walked through the wall in the H condition and the number of participants who did not contact the wall in the F condition were significantly larger than the corresponding expected values ($residual = 2.38$, $p < .05$; $residual = 2.53$, $p < .05$). Each expected value was calculated under the null hypothesis that the self-avatars and behaviors were independent. Additionally, the number of participants who did not contact the wall in the H condition demonstrated a trend of being smaller than the expected value ($residual = -1.81$, $p = .07$). These results supported **[H1]**.

Fig. 5.11: Distribution of participants' behavior in room 3 according to avatar anthropomorphism and visibility. C, H, R, and F represent Controller, Human Hand, Robot, and Full-body Human, respectively. The shown numbers are the percentage out of 23 participants for each condition.

Room 3

In room 3, most participants walked through the wall (C: 21, H: 22, R: 21, F: 17; Figure 5.11). The likelihood ratio test of the binary logistic regression model showed that no variables significantly explained the ratio of the participants who walked through the wall against who did not so (anthropomorphism: $\chi^2(1) = 0.97$, $p = .33$, visibility: $\chi^2(1) = 2.69$, $p = .10$, interaction: $\chi^2(1) = 1.91$, $p = .17$). Although we expected that the ratio to be different depending on avatar groups ([**H1**]), the result was not surprising considering that room 3 could not be solved obviously without entering the walls.

However, it was typical that they had been looking for the gimmick to open the door before they entered the wall, although a part of the participants (C: 11, H: 13, R: 11, F: 6) walked through the wall straight without hesitation. Hence, even though the binary counting indicated a ceiling effect and did not support [**H1**], the time until the participants first walked through the wall in the room largely varied. Thus, we next analyzed the time data among the participants who walked through the wall to test [**H2**]. The time data were not normally distributed. Two-

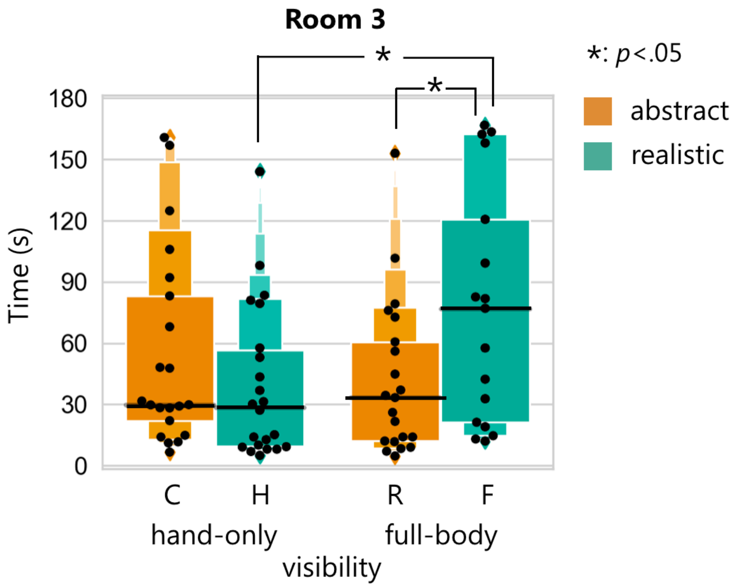

Fig. 5.12: Letter-value box plot[1] with data points of the time until the participants first walked through the wall in room 3 according to avatar anthropomorphism and visibility. C, H, R, and F represent Controller, Human Hand, Robot, and Full-body Human, respectively.

way factorial ANOVA was conducted (Figure 5.12). The result showed a significant interaction effect ($F(1, 77) = 6.44$, $p < .05$, $\eta_p^2 = 0.08$). Finally, Tukey's post-hoc tests ($\alpha = .05$) were conducted for pairwise comparisons. The result demonstrated that the time in the F condition was longer than that in the H and R conditions (H: $t(77) = 2.64$, $p < .05$, R: $t(77) = 2.44$, $p < .05$). Although we did not find any significant difference in the ratio, the ratio data and time analysis exhibited a similar tendency that the participants under the F condition hesitated in walking through the wall. Note that the time analysis did not include the data from the participants who did not walk through the wall. These results supported **[H2]**.

[1]By plotting more quantiles than in a conventional box plot, a letter-value box plot provides additional information about the shape of the distribution, particularly in the tails [260].

Room 4

In room 4, all participants walked through the wall in the end. However, a few of them (C: 1, H: 1, R: 0, F: 2) passed after the time was up. Only one participant, under the F condition, was instructed by the experimenter to walk through the wall in accordance with the rule as she did not walk through even though 30s had passed after the time-limit. Some participants seemed to hesitate to walk through the lightning wall, including the participants who had already walked through the walls before room 4. Figure 5.13 is the visualization of the average velocity of head movement over time in the temporal proximity of the wall penetration for each avatar type. The velocity was calculated at each frame and then averaged among each time window of 0.1s for each participant. By setting the moment of the wall penetration to time 0, the time series data of velocities were averaged among the participants. For those (N=15) who passed through the walls more than once, we averaged the velocities regarding all the wall penetrations for each participant. Although we did not conduct any statistical test on the velocity data, several interesting characteristics can be observed from Figure 5.13. First, the participants tended to speed up while penetrating the wall irrespective of avatar types. Second, the participants in the F condition seemed to move more slowly than others before penetrating the wall, indicating that they might have hesitated to penetrate it than the others. Qualitative observations of the behavior also indicate that some participants stepped back before walking through the wall, whereas a few participants, especially those who had not walked through the wall before, took time to search for the gimmick, similar to room 3.

These characteristic behaviors remarkably appeared in the time until the participants walked through the lightning wall after they pushed button 9. Thus, the time can be considered to reflect the amount of psychological resistance to walk through the lightning wall. It can also be considered to reflect presence in the sense that the resistance is a realistic response to a threat. Moreover, time data were not normally distributed. Two-way factorial ANOVA showed a significant interac-

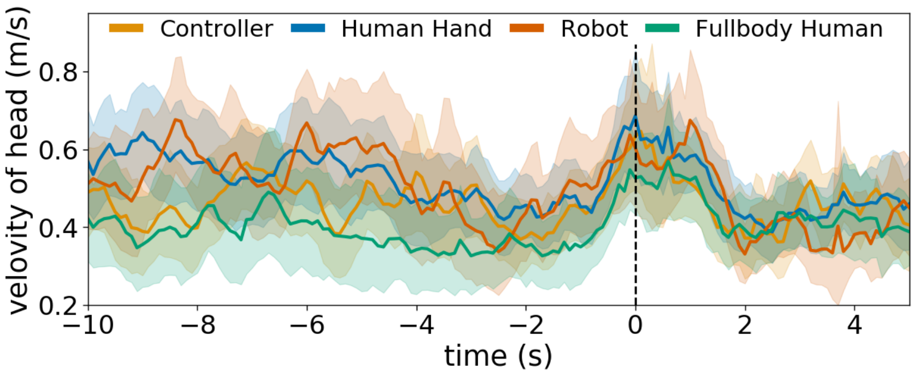

Fig. 5.13: Line plot of the velocity of head movement over time in the temporal proximity of wall penetration in room 4 for each avatar type. Time 0 indicates the moment the participants penetrated the wall. Translucent bands indicate 95% CIs, estimated by 1,000 bootstraps.

tion effect ($F(1,88) = 9.88$, $p < .01$, $\eta_p^2 = 0.10$) (Figure 5.14). Tukey's post-hoc tests ($\alpha = .05$) showed that the time in the F condition was longer than that in the H and R conditions (H: $t(88) = 2.88$, $p < .01$, R: $t(88) = 2.53$, $p < .05$). In addition, the time in the C condition showed a trend to be longer than that in the H condition ($t(88) = 1.92$, $p = .06$). These results indirectly supported [**H3**].

Cross-rooms results

To determine whether the participants' behavior throughout the experiment was influenced by self-avatars, we calculated the total time spent by each participant before they first walked through the wall, from the start time of the experiment. The time data were normally distributed except for the H condition. Two-way factorial ANOVA showed a significant interaction effect ($F(1,88) = 6.09$, $p < .05$, $\eta_p^2 = 0.06$) (Figure 5.15). Tukey's post-hoc tests ($\alpha = .05$) revealed that the time under the F condition was longer than the time under the H and R conditions (H: $t(88) = 3.41$, $p < .001$, R: $t(88) = 2.60$, $p < .05$). These results supported [**H2**].

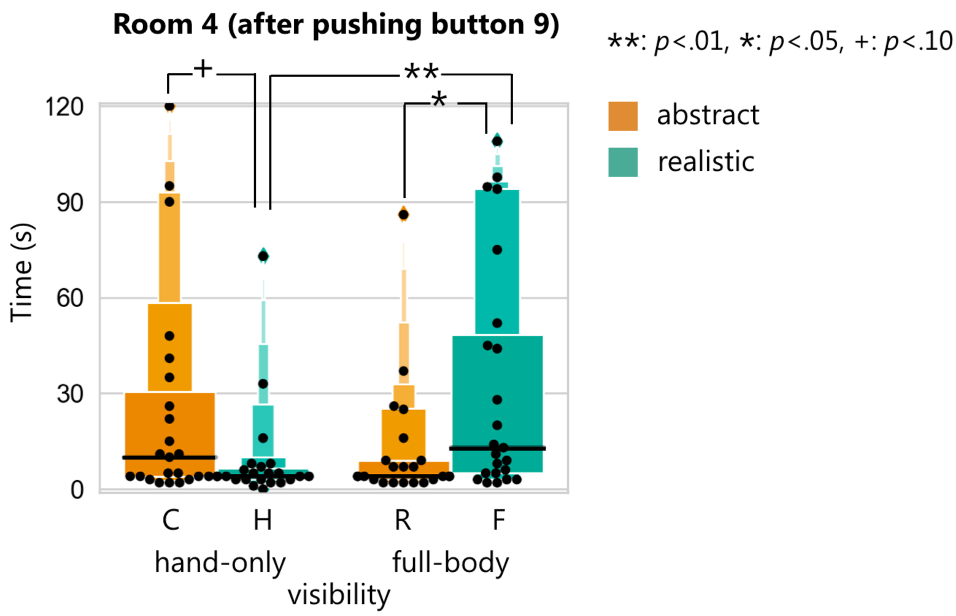

Fig. 5.14: Letter-value box plot with data points of the time until the participants first walked through the wall in room 4 according to avatar anthropomorphism and visibility. C, H, R, and F represent Controller, Human Hand, Robot, and Full-body Human, respectively.

5.4.2 Physiological Data: Skin Conductance Response

As a physiological measurement of presence and SoBO, SCRs for the four threatening stimuli in room 4 were analyzed to test [**H3**]. The data for some participants (C: 4, H: 1, R: 4, F: 2) were not recorded due to technical issues. Hence, the following analysis was conducted excluding those data. In addition, if no peak in GSR was detected 1 to 5s after the threat, the SCR was calculated as 0. The data was normalized using the Log of SCR magnitude + 1 and standardized by Z-scores using mean and standard deviation of GSR metrics 0 to 5s before each threat due to the GSR signal characteristics in accordance with [261]. Among the SCRs of the four threats, the threat of walking through the lightning wall affected the whole-body whereas the others worked for hand. Therefore, we analyzed these separately. We calculated the mean SCRs among the first three threats (button 1, 4, and 7) as **hand-threat** and the SCRs of the last threat (walking through the lightning wall)

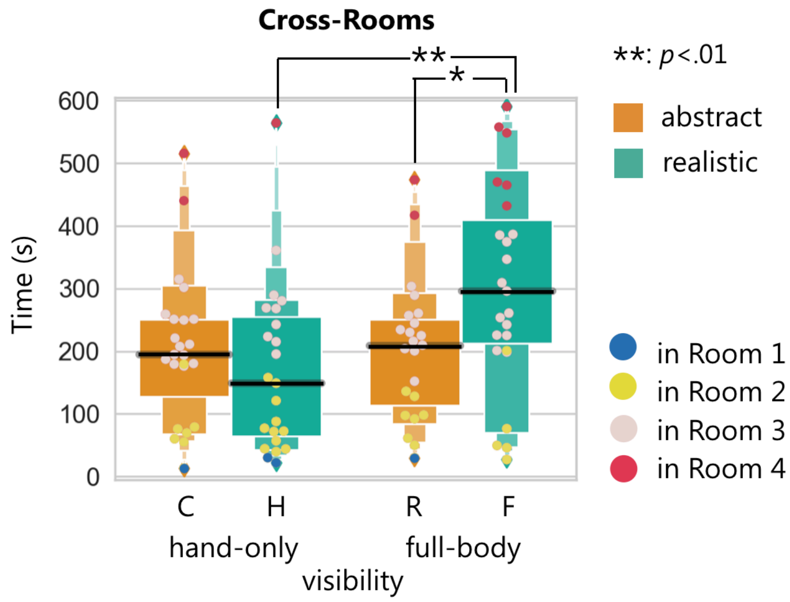

Fig. 5.15: Letter-value box plot with data points of the time until the participants first walked through the wall across rooms according to avatar anthropomorphism and visibility. C, H, R, and F represent Controller, Human Hand, Robot, and Full-body Human, respectively. In the cross-room results, the data points are colored according to the rooms where the participants first walked through the wall.

as **full-body-threat** (Figure 5.16). For the supplementary time series graph of mean GSRs for each threat, see Figure 5.17.

For hand-threat, two-way ANOVA showed no significant effects (anthropomorphism: $F(1,77) = 0.20$, $p = .66$, $\eta_p^2 < 0.003$, visibility: $F(1,77) = 1.63$, $p = .21$, $\eta_p^2 = 0.02$, interaction: $F(1,77) = 0.73$, $p = .40$, $\eta_p^2 = 0.009$). For full-body-threat, two-way ANOVA only showed a trend of main effect of visibility ($F(1,77) = 3.27$, $p = .08$, $\eta_p^2 = 0.04$); the SCR for full-body-threat under the full-body condition tended to be greater than that under the hand-only condition. These results did not support [**H3**].

5.4.3 Subjective Data: Questionnaire

To further test **[H3]**, the subjective ratings of the questionnaire were analyzed. For each scale (Ownership, Response, Presence), we first checked internal consistency. Because some items of Presence (P4 and P6) were negatively correlated with other items, we excluded these items. Consequently, Cronbach's αs were $\alpha = 0.69$ (Ownership), $\alpha = 0.8$ (Response), and $\alpha = 0.56$ (Presence). The answers for each item were aggregated and averaged (answers for control items were inverted) to compute the scores for each scale per participant. Because Likert scale is considered to be an ordinal scale, an aligned-rank transform, which allowed the use of ANOVA to analyze the interaction effects with the non-parametric data [246], was first applied and then two-way ANOVA was conducted (Figure 5.18). For Ownership, the ANOVA revealed a significant main effect of anthropomorphism ($F(1, 88) = 8.63$, $p < .01$, $\eta_p^2 = 0.09$). Contrary to **[H3]**, the score of Ownership with abstract avatars was significantly higher than that with realistic avatars. For Response and Presence,

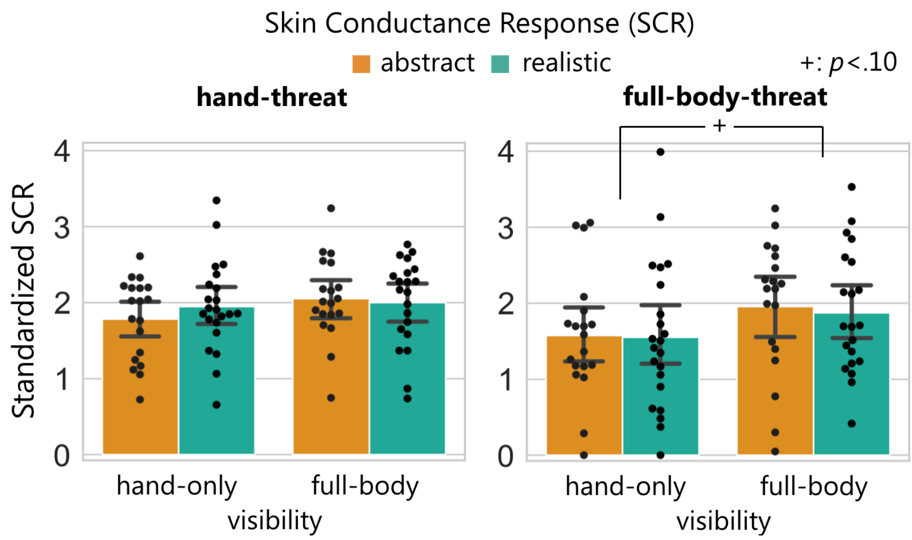

Fig. 5.16: Bar plots with data points of SCR for the hand-threats and full-body-threat in room 4 according to avatar anthropomorphism and visibility. The SCR for hand-threats is the mean SCR for the three hand-threats. Error Bars indicate 95% CIs, estimated by 1,000 bootstraps.

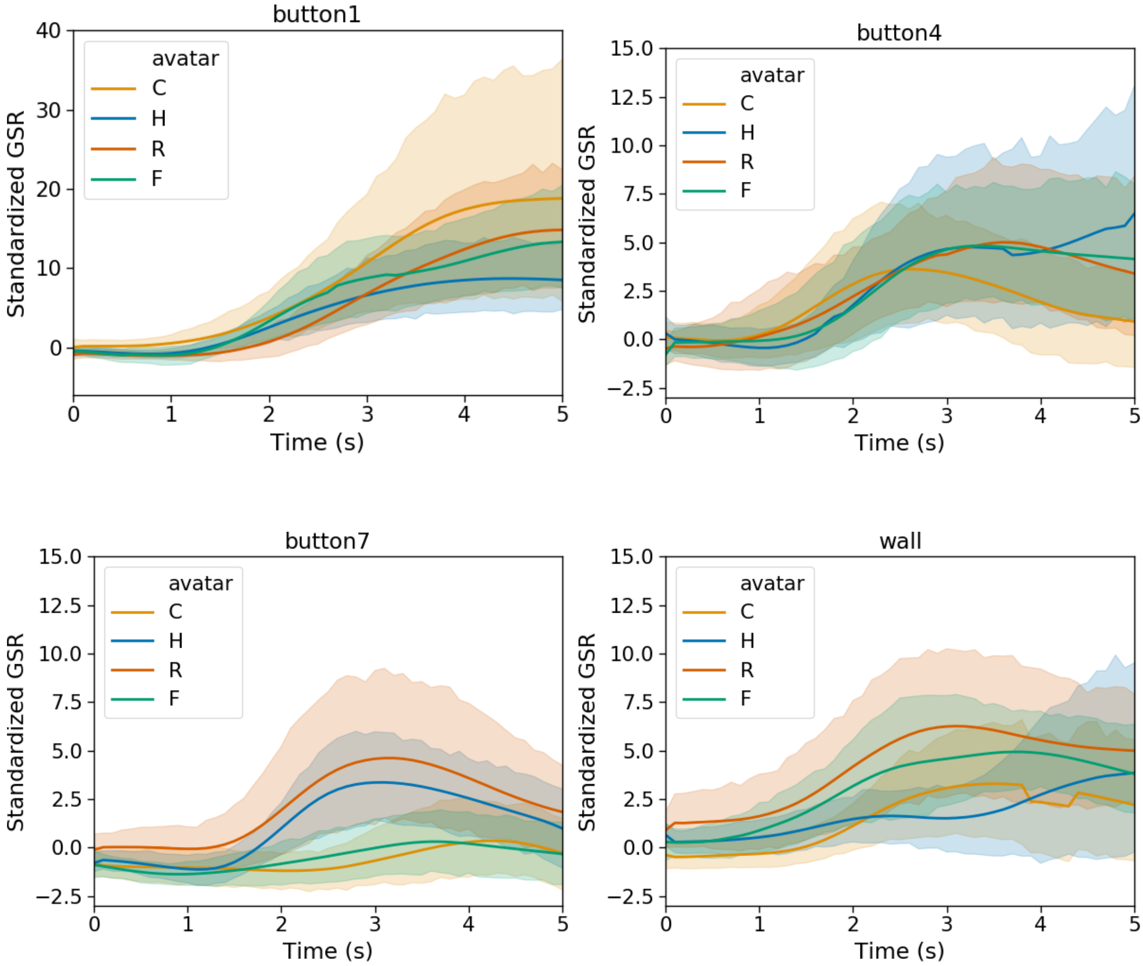

Fig. 5.17: Line plots of time series data of mean standardized GSRs for each threat in room 4 according to avatar types. C, H, R, and F represent Controller, Human Hand, Robot, and Full-body Human, respectively. Time 0 indicates the moment the participants were presented with the threat. The raw data was registered at a sample rate of 125 Hz in real time. The software applied a median filter with a time window of 500 ms, followed by a mean filter with a time window of 1000 ms. Thereafter, the GSRs were averaged among each time window of 0.1s for each participant to plot the graph. Translucent bands indicate 95% CIs, estimated by 1,000 bootstraps.

no significant differences were observed. These results did not support [**H3**].

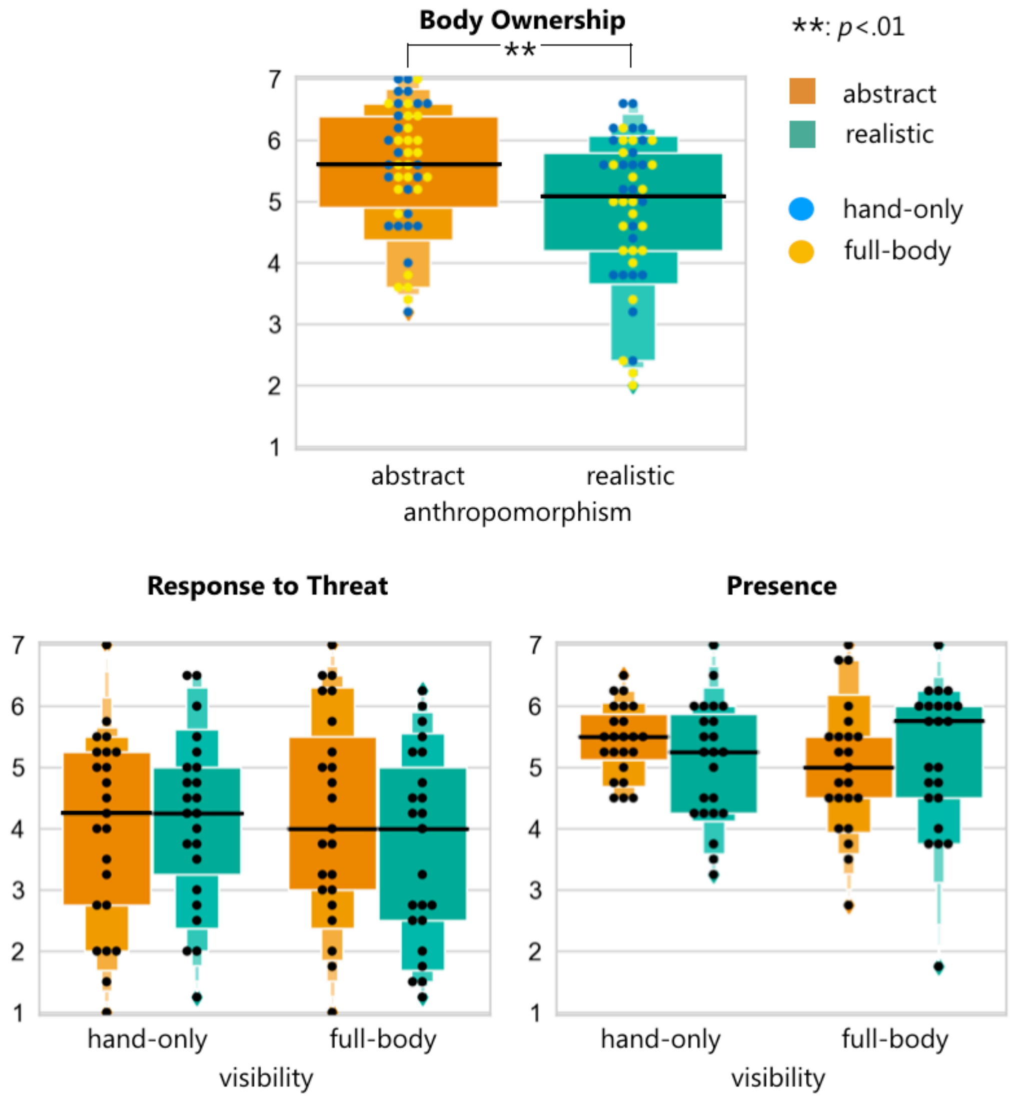

Fig. 5.18: Letter-value box plots with data points of the subjective ratings (from −3 to +3) of Body ownership (left), Response to threat (center), and Presence (right) obtained through the questionnaires according to avatar anthropomorphism and visibility.

5.4.4 Correlation Analysis

To test **[H4]** and to specify if any of the variables from the questionnaire and SCR data were related to the participants' behaviors, we conducted multiple regression analyses. We used the time that each participant took before they first walked through the wall across rooms (Figure 5.15) as an index to represent the tendency of behaviors throughout the experiment. We also used the VR- and video-game-experiences (both 1–5) as predictors. As a result, only the subjective score of presence was found to be a marginally significant predictor ($p = .06$). To further test the strength of the relationship between presence and behavior indices, polyserial correlation analyses, which are used for the data between a quantitative and an ordinal variable, were conducted. The results revealed a significant weak correlation ($\rho = 0.23, p < .05$). Specifically, the participants who took a shorter time before walking through the wall tended to have lower sense of presence, supporting [**H4**].

5.5 Discussion

The main findings are as follows:

1) The results consistently showed that participants who had the full-body human avatar tended to refrain from walking through the walls, as evident from the ratio in room 2 ($p < .05$ for detour), time in room 3 ($p < .05$ against H and R), and time across rooms ($p < .01$ against H and $p < .05$ against R), which supported [**H1**] and [**H2**]. In addition, participants with the Human Hand avatar showed tendencies to walk through the walls, with fewer indices, as seen from the ratio in room 2 ($p < .05$ for walking through and $p = .07$ for detour) and time in room 4 ($p = .06$ against C).

2) The SCR for full-body-threat (i.e., walking through the lightning wall) in the full-body conditions (R or F) showed a trend of being greater than that in the hand-only conditions (C or H) ($p = .08$). For the hand-threat (i.e., touch the threatening stimuli), there were no significant differences among the avatar conditions. In addition, the subjective ratings of ownership of the participants embodied with abstract avatars (C or R) were significantly higher than that of those with realistic avatars (H or F) ($p < .01$). In contrast, the ratings of presence and response to threat were not significantly different among the avatar conditions. These results did not support [**H3**].

3) The participants with a lower sense of presence tended to take less time before walking through the walls ($p < .05$), which supported **[H4]**. Their behavioral tendency was explained only by presence instead of other indices (ownership, response, SCR, VR-experience, and video-game-experience).

Overall, the results showed that the embodiment of high-visibility and high-anthropomorphism self-avatars could discourage participants from walking through the walls, presumably because of a higher sense of presence. More generally, we demonstrated that a higher visual fidelity of self-avatars can facilitate realistic user behavior in the VE. The major difference between our results and those of previous studies is that most of them found no significant effect of the presentation [139], anthropomorphism [190], or visibility [60] of self-avatars on the game performance [60], affordance judgment [139, 262], and behavior [139]. The only exceptional study, by Lin et al. [140], showed that the presentation of self-avatars had an effect on affordance judgment and the corresponding behavior. However, they did not investigate either the anthropomorphism factor or the visibility factor. Moreover, it is also interesting to note that when the participants were asked in the post-experiment interview about why they hesitated or decided to pass through the wall, none of them mentioned their avatars. This shows that the participants' actions were affected by their avatar designs, even though they were not conscious of this fact. Our finding is important because our results suggest that simply by changing the visibility and the level of anthropomorphism, a VE designer can implicitly navigate users to behave realistically (i.e., avoiding the wall) or unrealistically (i.e., passing through the wall) depending on the situation.

The main concern of our study, i.e., the hypothesis that self-avatars of higher fidelity would discourage the users from walking through the virtual walls without any explicit feedback, was supported by the experiment. Nevertheless, there are some unexpected results that need further discussions. First, unlike behavioral data, we did not observe any significant differences between the subjective scores of presence and SCR among self-avatar groups. This raises the concern that the self-avatar affected the behavior irrespective of the level of sense of presence. However, the result of the correlation analysis indicates that the change in behavior could be explained by the sense of presence. In addition, the SCR data was noisy and not much reliable because of the practical constraints that it was recorded during the participants' active movements. Hence, we consider that in our study the behavioral data could reflect the presence more apparently than the questionnaire and the physiological data. Nevertheless, these contradictory results may imply that there might be other factors than presence that affect the relation between self-avatar appearance and users' behaviors in VEs. For example, the semantic aspects of self-avatars, e.g., skin color [40] and attractiveness [41], have also been shown to affect users' attitude and behavior through stereotype or memory, which is automatically associated with avatars (i.e., Proteus effect). Although in this study we focused on visual fidelity of self-avatars, the semantics of each distinctive avatar could also influence the behavior. Therefore, further research is necessary to clarify the mechanism.

Second, contrary to expectation, the results of the questionnaire indicated that the abstract self-avatars evoked stronger SoBO compared with the realistic self-avatars. One possible reason can be the uncanny valley effect [66]. Previous studies [17, 34] have revealed that robotic and cartoon-like full-body avatars elicit a slightly stronger SoBO than realistic human avatars. However, in the case of hand-only avatars, a number of studies have shown that realistic human virtual hands induced greater SoBO compared with various virtual objects (e.g., sphere, board, block, and arrow) [11, 12, 14, 232]. One noticeable difference between existing studies and our study is that, even though the existing studies showed arbitrary virtual objects to represent participants' hands, we showed virtual controllers with high visual realism that moved in nearly complete correspondence with the physical controller. In addition, Human Hand avatars were displayed as having open palms, even though the participants closed their fists to hold the controllers. Hence, compared with Human Hand avatars, it is possible that Controller avatars produced higher visuomotor and visuo-proprioceptive synchrony, which is a critical factor for inducing SoBO [10]. It was also remarkable that visibility did not affect SoBO. To the best of our knowledge, this is the first study that compares full-body and hand-only avatars with regard to SoBO and presence. Interestingly, the SCR results revealed a marginally significant difference in visibility for the full-body threat. Hence, it still remains unclear if the hand-only avatars elicited an equivalent level of the full-body ownership illusion, compared with full-body avatars.

Similarly, with some indices, participants with the Human Hand avatar were likely to walk through the walls, although participants with the Controller avatar did not show such a tendency. This may be also because the participants perceived higher SoBO when they saw the Controller avatar rather than the Human Hand avatar. However, we need to conduct further studies with various avatar designs to clarify the actual reason.

Considering our results that the effect of self-avatar appearance on behavior is presumably mediated by the sense of presence, improving presence by using other factors may also contribute to preventing users from passing through the walls, such as passive haptics [263], visual realism of VEs [54], and avatar personalization [82]. In addition, combining other approaches to prevent penetration, such as multisensory feedback from wall collisions, would further improve the effectiveness. Combinations and comparisons with these parameters and approaches constitute prospects for future studies. Moreover, the results also indicate that high-fidelity self-avatars can potentially improve a wide variety of VR applications where realistic user responses are required in VEs, e.g., to seriously engage users in evacuation drills, and to the intensity of exposure therapy for PTSD depending on stages. Nevertheless, generalisability of the results for practical applications is subject to certain limitations because the scope of this study is limited to the issue of users' walk-through-wall behaviors. For instance, the effect of self-avatar visibility may not be applicable to behaviors unrelated to the body penetration.

5.6 Conclusion

To test our hypothesis that self-avatars with high visual fidelity would induce users to refrain from passing through virtual walls, we investigated whether the anthropomorphism and visibility of self-avatars could influence participants' behavior with respect to walls in room-scale VEs. The results of the experiment showed that the use of a full-body realistic avatar discouraged participants from walking through the walls, presumably because of a higher sense of presence.

Chapter 6

General Discussion

This chapter revisits the contributions of the thesis by summarizing the findings stated in Chapter 3, 4, and 5 and discusses the limitations of the studies and some promising areas for future research in the VR field.

6.1 Summary

The goal of the thesis was to explore the hitherto unknown effect of self-avatar anthropomorphism on user experiences, that is, how users perceive and behave in VEs. The key idea is to incorporate the empirical and theoretical evidence that the BOI not only induces the subjective SoBO but also promotes an artificial or virtual body to be incorporated into one's self-body representation that is then functionally used to perceive and behave in the environment. Along with this idea and considering that the anthropomorphism of the avatars is one of the important factors to modulate the BOIs' strength, it can be hypothesized that the use of human-like self-avatars fosters the users to experience the virtual world based on the virtual body representation rather than the physical body representation. Therefore, the thesis specifically explored the effect of self-avatar anthropomorphism on the following three aspects: processing of sensory information from one's own body (*visuo-proprioceptive integration*; Chapter 3), processing of environmental information (*object size perception*; Chapter 4), and the way one responds to this information (*behavior*; Chapter 5). Altogether, the anthropomorphism of the self-avatars did influence these aspects, corroborating the hypothesis. The thesis also proposed a novel perspective that the self-avatars are key to solving challenges, which have (as of yet) hardly been discussed from the aspect of avatar appearances, faced by VR applications: 1. the spatial limit in the exploit of visual dominance over proprioception in the hand interaction techniques in VR (Chapter 3), 2. distortion in spatial perception in VEs (Chapter 4), and 3. that users behave in VEs differently from how they would in an equivalent RE (Chapter 5).

These findings enable a novel approach of manipulating the self-avatar appearances to navigate user experiences in VR, and they provide evidence-based guidelines for selecting appropriate self-avatar representation that takes into consideration the wide range of its psychological effects on user experiences. In fact, in contrast to the existing findings that realistic avatars are the best for inducing strong BOIs, despite their generally high computational cost, the findings provided in the thesis do not imply that the realistic avatars always produce the best perceptual effect when considering a wide range of users' experiences in VEs; rather, they suggest that avatars of appropriate levels of anthropomorphism should be used depending on the situation and purpose by taking their perceptual effects into consideration. For instance, the study in Chapter 3 indicates that abstract avatars are acceptable when the displacement of a virtual hand from the actual hand is small while realistic avatars decrease the detection thresholds of the displacement and are therefore acceptable at greater displacements. In addition, the study in Chapter 4 suggests the following in the case of scale-sensitive VR applications: if the size of a virtual hand is generic to all users, then it is desirable that the avatar appearance be non-anthropomorphic, which reduces or even eliminates the influence of avatar size on object size perception, even though it provides a weaker SoBO. In contrast, if the application needs to achieve a strong SoBO and consistent scale perception among users, then it is better for the virtual hand to be realistic and have size personalized for each user. Furthermore, the study in Chapter 5 implies that abstract avatars can be used to implicitly encourage users to behave unrealistically, which may be useful in VR applications where interaction techniques specific to VEs are introduced. In contrast, high-fidelity self-avatars can potentially improve practical VR applications where realistic user responses in the VEs are required (e.g., to seriously engage users in evacuation drills and to adjust the intensity of exposure therapy for

Post Traumatic Stress Disorder (PTSD) depending on the stages).

6.2 Limitations and Future Research

Although the thesis successfully offers valuable insight into the effect of the self-avatar anthropomorphism on user experiences in VEs, there remains a number of aspects beyond the main scope of the thesis as stated in Section 1.4; hence, several potential limitations need to be noted. The methodological limitations of the study should also be discussed in regards to the generality of the findings. Finally, bringing together the findings alongside the acknowledgement of the limitations provides fruitful insights into future research direction.

6.2.1 Underlying Mechanism

Although limited and specific appearances of self-avatars were compared in each study, the expected common mechanism that the more human-like the self-avatar, the more one's self-body representation, that implicitly functions in perceiving and behaving in the world, is likely to be altered, implies that a different avatar appearance may also affect the functions as long as the strength of the BOI is affected. This is especially in contrast to the Proteus effect; as it is the effect of semantic aspects of self-avatars through stereotype or memory associated with the avatars, it is highly likely to depend on the user's past experience and racial or cultural differences. In addition, there are myriad combinations between specific avatars and specific stereotypes or memory that they hardly systematized. In contrast, the anthropomorphism is considered to generally influence human perception and behavior as it depends on the general and not self-specific properties of the human body, even though the experiments in the thesis were conducted for participants of a limited race and culture (i.e., those who live in Japan). Yet, the common underlying mechanism needs careful consideration; it remains unclear how far these findings hold true for different avatar appearances without empirical evidence.

Approaches for Revealing Mechanism

A further investigation from several different aspects may be necessary in future studies to specify the mechanism. First, the exploration of what is "anthropomorphic" for the appearance of self-avatars would be an interesting subject for future research. As mentioned in Subsection 1.4.2, the thesis categorized the levels of anthropomorphism into abstract (e.g., object), iconic (e.g., humanoid but non-human), and realistic (e.g., human) based on the existing literature (e.g., [12–14, 35]). Although they have already been shown to produce different levels of perceived realism [12], the evaluation of perceived human-likeness as well as the SoBO in our studies would have been effective in validating the classification. In addition, the effect of different appearances within the same category on the perceived anthropomorphism is unknown (e.g., zombie hand vs robot hand). For future studies, it seems promising to investigate what constitutes perceived anthropomorphism and how humans judge human-likeness from purely visual perspectives without the multisensory induction BOI.

Moreover, it will be necessary, in the future, to specify the effect of visual anthropomorphic levels on the BOI. Even though the principle of the BOI is that "the closer the avatar appearances are to our own body, the stronger the SoBO," the strength of the SoBO is also influenced by gender [35] and does not necessarily correspond to perceived levels of anthropomorphism [12]. Hence, it would be useful to develop a data set of avatar appearances that can robustly control the subjective strength of BOIs as well as the reliable evaluation standard. In order to achieve this, a method would be required to effectively collect a large amount of data, such as installing VR applications in a museum.

Finally, the detailed relationship between avatar anthropomorphism (or the strength of the BOI) and perceptual and behavioral influences and if the relationship varies according to the subject matter (e.g., perceptual or behavioral influence) remain unknown. In the thesis, only the study in Chapter 4 adopted three levels of avatar anthropomorphism, suggesting that the avatar with the medium level of anthropomorphism produced a medium impact of avatar size on object size perception, even though the degree of impact was not significantly different from those of realistic and abstract avatars. Hence, the mechanism should be elucidated by investigating the relationship using multiple types of self-avatars to cover a range of variations in anthropomorphism.

Objective Measurements vs Subjective Sense of Body Ownership

Throughout the experiments, the strength of the SoBO was measured using a questionnaire. The questionnaire results in Chapter 4 showed that the high-anthropomorphism avatar elicits the stronger SoBO than the low-anthropomorphism avatar, in line with a considerable number of studies that have shown the effect of the anthropomorphism on the SoBO (e.g., [11–16] ; see Subsection 2.2.2 for details). However, contrary to the prevailing view, the questionnaire results of different studies indicated that realistic avatar appearances did not significantly increase the SoBO (Chapter 3) or even decreased the SoBO (Chapter 5) compared with abstract avatars. In addition, in Chapter 4, participants' subjective scores for the SoBO had a weak positive correlation with their tendency to perceive the object size as smaller when the virtual hand was enlarged for the high-anthropomorphism avatar but they had a negative correlation for the medium-anthropomorphism avatar; this result did not fully support [H4]: *The participants with higher scores of the SoBO tend to perceive the object's size as smaller when the virtual hand is enlarged.* Furthermore, similar trends were also observed in a previous study; Schwind et al. [13] investigated an effect of avatar anthropomorphism on visuo-haptic integration and found that massive violations of the human-likeness of a virtual hand (i.e., robot, invisible, or cartoon hand) could affect tactile experiences. However, in their results, the relationship between them was not monotonic, and the changes in the sensitivity of the integration did not correlate with the degree of the SoBO. Altogether, the subjective evidence regarding SoBO does not clearly show that the strength of the BOI mediated the effects of the self-avatar anthropomorphism on the perceptual and behavioral consequences. Nonetheless, the unexpected results of the questionnaire and the SCR in Chapter 5 can be explained by the peculiarity of the Controller avatar in the experimental settings and the uncanny valley effect [66], which is often observed with full-body avatars as discussed in Chapter 5.

The possible explanations for these unexpected results from the questionnaire may be as follows: 1. the questionnaires did not validly and reliably measure the SoBO, 2. the avatar anthropomorphism influenced one's perception and behavior irrespective of the BOI, 3. the effect of the avatar anthropomorphism on the BOI worked differently on the subjective feelings of the SoBO and the change in self-body representation.

In fact, the use of the questionnaires for the BOI in VR appear to have limitations. For example, the ceiling effect, which may be induced by highly precise visuomotor synchrony in conjunction with the 1PP enabled by VR, was often observed in the questionnaire results. In addition, subjective and objective measures of the SoBO were shown to not always correspond [157–161]. Hence, the development of reliable and valid measurements of the strength of the BOI in VR is one of the major challenges for future studies, although several scholars have already tackled the challenge (e.g., [145, 264]). From this perspective, further research should also include the effective control condition that would be expected to produce the rather weak SoBO. For example, by comparing the conditions where participants control a self-avatar in a VE and where they watch a recorded 1PP video, the effect of SoBO can be clearly measured.

Considering that the studies provide converging objective evidence corroborating the hypothesis that the anthropomorphism of self-avatars influence perception and behavior such that they rely more on virtual body representation rather than physical body representation, the second explanation (i.e., the avatar anthropomorphism influenced one's perception and behavior irrespective of the BOI) is hard to support. Indeed, the study of the Chapter 4 indicated that the avatar with low anthropomorphism provided both the weakest SoBO and the weakest influence of hand enlargement on size perception. In addition, the results in Chapter 3 that both measurements of the threshold of the remapped movement and the proprioceptive drift indicated similar findings, the latter of which is considered to be an objective measurement of BOI (although the relationship between the SoBO and proprioceptive drift is a matter of debate [157–161]), suggest that the BOI mediates the effect of avatar appearance on the visuo-proprioceptive integration and the perceived threshold of the movement remapping.

Rather, the third explanation (i.e., the avatar anthropomorphism on the BOI worked differently on the subjective feelings of the SoBO and the change in self-body representation) appears to be more reasonable. For this aspect, further investigation on self-body representations would be needed (see Subsection 6.2.3). In addition, there might be a different mechanism for the effect on perception and behavior; the result of the correlation analysis in Chapter 5 indicates that the change in behavior would be explained by the sense of presence, rather than the SoBO. Furthermore, although it is hard to consider that the BOIs never mediate the effect of avatar appearance on the users' perception and behavior in VEs, it is possible that the strength of the BOI, modulated by the avatar anthropomorphism, is not the only factor that mediates the effects. The following subsection discusses this possibility.

6.2.2 Effect of Semantic Aspects of Self-avatars

It should be carefully considered that the higher-order cognitive influence of the semantic aspects of avatars (i.e., Proteus effect) may be inevitable. For example, a recent study indicated that a robot-like avatar tends to produce a certain feeling of security when one is facing a dangerous situation [36]. In fact, the results of the correlation analysis in Chapter 4 that the stronger SoBO for a medium-anthropomorphism avatar tended to result in a smaller effect of hand enlargement on object size underestimation can be interpreted in reference to the Proteus effect; it is likely that our expectation of an "iconic avatar-like" perception, which might be rather mechanic, delivered the opposite effect compared with the realistic avatar. In addition, the result in Chapter 5 that the participants with the Human Hand avatar were likely to walk through the walls according to some indices can be a result of cognitive aspects; we speculate that this is partly because Human Hand avatars produced feelings of invisibility. In fact, a third person view of virtual hands and feet that moved synchronously with participants' movements are shown to induce ownership of the invisible body [265]. Furthermore, the experience of having an invisible body reduces the social anxiety response to standing in front of an audience [266]. In our case, seeing the virtual hands through the mirror could induce ownership of an invisible body, and the participants might behave as if their bodies were transparent.

6.2.3 Sense of Agency and Body Schema

The thesis did not directly deal with behavioral realism (i.e., movement) of self-avatars, which are related to the concepts of SoA rather than SoBO. Hence, the controllability or functionality of avatars, which derive from the morphological characteristics of the avatars, was kept the same as much as possible among self-avatars of different levels of anthropomorphism to exclude the influence on SoA for simplicity. This is because of the complex effect of avatar anthropomorphism in the case of the BOI induced by visuo-motor correspondence; the morphological characteristics of avatars, which change as the anthropomorphism changes, also constitute their controllability, whereas the morphological aspects of anthropomorphism only relate to the top-down expectations in the case of the BOI induced by visuotactile stimuli (e.g., RHI) because the artificial body cannot be controlled by a participant. However, this is not a natural assumption for practical use, because the anthropomorphism of self-avatars generally affects both visual and behavioral (functional) aspects. Indeed, it led to a somewhat unnatural situation for the low-anthropomorphism avatar especially in Chapter 4 (e.g., the participants could carry cubes on transparent fingers) because abstract avatars generally have a reduced freedom of movement compared with human avatars.

The Cyborg dilemma theory [143] emphasizes the potential influence of the morphology as follows: " *Choose technological embodiment to amplify the body, but* *beware that your body schema and identity may adapt to this cyborg form.*" In fact, the morphological inconsistencies of avatars from the user can influence both body schema and body image (see 1.1 for definitions), which are the two distinct types of body representations, and a modulation of the body image and body schema underlie the SoBO and SoA, respectively [22]. While the body image is often characterized as a cognitive appraisal, perception, or evaluation of one's own appearance and body shape and the related or resulting affect, the body schema, in contrast, is a plastic, non-conscious neural map of the spatial relations among the body parts and the body's motor capacities, and is constantly updated due to incoming sensory input [22].

In this regard, it would be an interesting perspective of self-body representations that while BOI enables incorporating artificial/virtual bodies into body image, which is used for perception, tool use enables incorporation of objects into body schema, which is used for action [22], although much evidence has suggested that RHI can induce changes in both types of body representations [20, 21]. Considering that tool use alters the perception of the environment by bringing objects perceived as farther away closer and into the action space [175] and that modifications of peripersonal space (i.e., a functional representation of reach space) usually co-occur with body schema changes [267], the change in body schema can also affect perceptual spatial representations. In addition, using a mechanical grabber that physically extends the arm has been shown to alter the kinematics of subsequent free-hand grasping movements [176]. Participants also reported that after tool use, localized touches delivered on the elbow and middle fingertip of their arm felt as if they were farther apart. These findings indicate that the body schema acts as the somatosensory representation of intrinsic properties of the body morphology and that the morphological aspects of self-avatar can also affect perception and actions by updating the body schema.

6.2.4 Effect of Realism of Self-avatars

While realism or fidelity of avatars consists of several components, the thesis focused on anthropomorphism as it is well established that the human-resemblance of artificial/virtual bodies influence the strength of BOIs (see Subsection 1.4.2). Nevertheless, recent evidence suggests that other components (e.g., photorealism (i.e., realism in rendering styles) and truthfulness (i.e., similarity of the appearance between the user and their avatar)) also affect the BOI; personalization of an avatar for a user [82] and photorealistic rendering of a virtual hand [12] improved the SoBO. Hence, it would be promising to explore the effect of avatar visual fidelity components other than anthropomorphism, which would enable closer appearance of self-avatars to users, not just a non-self-specific human appearance.

In virtual character research, McDonnell et al. [64] investigated the effect of photorealism (realistic or stylized rendering style) on perceived realism and other feelings (i.e., appealing, familiar, and friendly) of the facial animation of virtual humans in a video. On the whole, their results were in line with the Uncanny Valley theory. However, negative reactions occurred mainly for characters that used human texture maps that were not rendered with realistic eye and skin shades. In addition, they found that cartoon characters were considered highly appealing and were rated as more pleasant than characters with human appearance when large motion artifacts were present. More recently, Zibrek et al. [39] investigated the effect of photorealism on users' perception, particularly for interactive, emotional scenarios in VR. Their results revealed that a photorealistic character changed the emotional responses of participants, increasing the feeling of being present in an actual space, and were considered more visually appealing as compared to the stylized versions. Even though these studies cannot directly apply to the studies of self-avatars, such interactive effects between visual and behavioral realism and between the components of realism would be important aspects to incorporate. It would also be interesting to incorporate the dimensions of perception used in these studies, such as pleasant, trustworthy, friendly, familiar, and appealing [64] or the perceived realism, appeal, eeriness, and familiarity [65] into the studies of self-avatars. From this perspective, Schwind et al. [35] studied the presence, likability, attractiveness, naturalness, and eeriness of the virtual hands of various kinds of anthropomorphism and photorealism, and found that the responses highly varied between participants. As their sample size was $N = 16$ and the sample sizes in the virtual character studies are usually larger (e.g., $N = 797$ [39]), further extensive research is necessary to investigate how such perceptual dimensions of self-avatar appearances relate to the BOI.

On the other hand, current advances in capturing individualized human bodies by photogrammetry methods have enabled a high-degree of truthfulness in generating 3D models of humans such as a scanned full body including the individual's clothes (e.g., [34,82,268]). Waltemate et al. [82] found that personalized avatars significantly increased the SoBO and presence compared to photorealistic but generic virtual avatars are equal in terms of the degree of graphical quality [34, 82]. Alternatively, the impact of a personalized hand using video feedback on subjective feelings (e.g., the SoBO, presence, and user acceptance), performance, and object size estimation has also been investigated [144, 245]. Even though equipping personalized avatars is still a labor-intensive and time-consuming process and current VR applications often adopt generic avatar appearances, personalization will become increasingly common as the technology develops. Hence, investigation of the impact of personalized self-avatars on BOIs and their perceptual and behavioral consequences are recommended in future studies.

6.2.5 Long-term Influences in Various Contexts

Finally, the more extensive and longer-term influences of BOIs on both positive and negative aspects need to be investigated before VR technologies are widely spread into society in the future. In the thesis, the long-term adaptation or after-effects and the types of a media were beyond scope; each experiment took approximately 0.5-1 hour per participant and used CG avatars with HMDs. However, it may happen that one will be under the BOI over a virtual body that is different from one's own perpetual body for a long duration. In addition, the influence could last not only within the VE but also in the real world after the BOIs. Furthermore, virtual bodies are not limited to CG rendered by HMDs; they also include physical substitutional bodies (e.g., a robot and another person) in the context of tele-presence. Therefore, investigation and experimentation into the generalizability of the perceptual and behavioral influence of BOIs into a wide range of contexts, including social interactions, is recommended.

Chapter 7

Conclusion

The thesis explored the effect of self-avatar anthropomorphism on the following three aspects: processing of sensory information from one's own body (*visuo-proprioceptive integration*; Chapter 3), processing of environmental information (*object size perception*; Chapter 4), and the way one responds to this information (*behavior*; Chapter 5). Altogether, the anthropomorphism of the self-avatars did influence these aspects, corroborating the hypothesis that the use of human-like self-avatars fosters the users to experience the virtual world based on the virtual body representation rather than the physical body representation. The thesis also proposed a novel perspective that the self-avatars are key to solving challenges, which have (as of yet) hardly been discussed from the aspect of avatar appearances, faced by VR applications: 1. the spatial limit in the exploit of visual dominance over proprioception in the hand interaction techniques in VR (Chapter 3), 2. distortion in spatial perception in VEs (Chapter 4), and 3. that users behave in VEs differently from how they would in an equivalent RE (Chapter 5). These findings enable a novel approach of manipulating the self-avatar appearances to navigate user experiences in VR, and they provide evidence-based guidelines for selecting appropriate self-avatar representation that takes into consideration the wide range of its psychological effects on user experiences.

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Achievements

Original Papers

[1] **Nami Ogawa**, Takuji Narumi, Michitaka Hirose: Effect of Avatar Appearance on Detection Thresholds for Remapped Hand Movements. IEEE Transactions on Visualization and Computer Graphics, vol.xx, no.xx, pp.xx–xx. 2020. (to appear) [* Chapter 3 is based on this publication]

[2] Rebecca Fribourg*, **Nami Ogawa***, Ludovic Hoyet, Ferran Argelaguet, Takuji Narumi, Michitaka Hirose and Anatole Lecuyer: Virtual Co-Embodiment: Evaluation of the Sense of Agency while Sharing the Control of a Virtual Body among Two Individuals. IEEE Transactions on Visualization and Computer Graphics (under revision) (*: equally contributed)

[3] Daisuke Mine, **Nami Ogawa**, Takuji Narumi, and Kazuhiko Yokosawa: The relationship between the body and the environment in the virtual world: The interpupillary distance affects the body size perception. PLOS ONE (under revision)

[4] **小川奈美**，鳴海拓志，伴祐樹，櫻井翔，谷川智洋，廣瀬通孝．えくす手: バーチャルな拡張身体を用いたピアノとのインタラクション．日本バーチャルリアリティ学会論文誌, vol.23, no.3, pp.91–101. 2018.

[5] 茂山丈太郎，**小川奈美**，鳴海拓志，谷川智洋，廣瀬通孝．アバタの関節角補正による疑似抵抗感提示．日本バーチャルリアリティ学会論文誌, vol.22, no.3, pp.369–378. 2017.

International Conferences (Peer-reviewed)

[1] **Nami Ogawa**, Takuji Narumi, Hideaki Kuzuoka, Michitaka Hirose: Do You Feel Like Passing Through Walls?: Effect of Self-Avatar Appearance on Facilitating Realistic Behavior in Virtual Environments, In Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (CHI '20), pp.xx–xx, 2020. (to appear) [* Chapter 5 is based on this publication]

[2] Ryota Ito, **Nami Ogawa**, Takuji Narumi, and Michitaka Hirose: Do We Have to Look at the Mirror All the Time? Effect of Partial Visuomotor Feedback

on Body Ownership of a Virtual Human Tail, In Proceedings of the 16th ACM Symposium on Applied Perception (SAP '19), pp.8:1–8:9, 2019.

[3] **Nami Ogawa**, Takuji Narumi, Michitaka Hirose: Virtual Hand Realism Affects Object Size Perception in Body-Based Scaling, In Proceedings of 2019 IEEE Conference on Virtual Reality and 3D User Interfaces (IEEE VR'19), pp.519–528, 2019.

[4] **Nami Ogawa**, Takuji Narumi, Michitaka Hirose: Factors and Influences of Body Ownership over Virtual Hands, International Conference on Human Interface and the Management of Information, pp.589–597, 2017 (invited)

[5] **Nami Ogawa**, Takuji Narumi and Michitaka Hirose: Distortion in perceived size and body-based scaling in virtual environments, In Proceedings of the 8th International Conference on Augmented Human (AH'17), pp.35:1–35:5, 2017.

[6] Shoichi Tagami, Shigeo Yoshida, **Nami Ogawa**, Takuji Narumi, Tomohiro Tanikawa, and Michitaka Hirose: Routine++: Implementing Pre-Performance Routine in a Short Time with an Artificial Success Simulator, In Proceedings of the 8th International Conference on Augmented Human (AH'17), pp.18:1–18.9, 2017.

[7] Sho Sakurai, Yuki Ban, **Nami Ogawa**, Takuji Narumi, Tomohiro Tanikawa, Michitaka Hirose: Diminished Agency: Attenuating a Sense of Agency for Problem Finding on Personal Physical Performance, International Conference on Human Interface and the Management of Information, pp.487–493, 2016. (invited)

[8] **Nami Ogawa**, Yuki Ban, Sho Sakurai, Takuji Narumi, Tomohiro Tanikawa and Michitaka Hirose: Metamorphosis Hand: Interactive Experience of Embodying Virtually Transformed Hands, Virtual Reality International Conference (VRIC'16), 2016. (invited)

Demonstrations (Peer-reviewed)

[1] Keigo Matsumoto*, **Nami Ogawa***, Hiroyuki Inou, Shizuo Kaji, Yutaka Ishii, Michitaka Hirose: Polyvision: 4D space manipulation through multiple projection, SIGGRAPH Asia '19 Emerging Technologies, Brisbane, Australia, Nov. 2019. (*: equally contributed)

[2] **Nami Ogawa**, Jotaro Shigeyama, Takuji Narumi, Michitaka Hirose: Swinging 3D Lamps: A Projection Technique to Create 3D Illusions on a Static 2D Image, SIGGRAPH Asia '17 Emerging Technologies, Bangkok, Thailand, Nov. 2017.

[3] Jotaro Shigeyama, **Nami Ogawa**, Takuji Narumi, Tomohiro Tanikawa, and Michitaka Hirose: Presenting pseudo-haptic feedback in immersive VR environment by modifying avatar's joint angle, IEEE World Haptics Conference 2017, Munich, Germany, Jun. 2017.

[4] **Nami Ogawa**, Yuki Ban, Sho Sakurai, Takuji Narumi, Tomohiro Tanikawa, and Michitaka Hirose: Metamorphosis Hand: Interactive Experience of Embodying Virtually Transformed Hands, Laval Virtual ReVolution 2016, Laval, France, Mar. 2016.

[5] **Nami Ogawa**, Yuki Ban, Sho Sakurai, Takuji Narumi, Tomohiro Tanikawa and Michitaka Hirose: Metamorphosis Hand: Dynamically Transforming Hands, The 7th International Conference on Augmented Human (AH2016), Geneva, Switzerland, Feb. 2016.

Poster Presentations (Peer-reviewed)

[1] Daisuke Mine, **Nami Ogawa**, Takuji Narumi, and Kazuhiko Yokosawa:Wider IPD Makes People Perceive Their Body to be not so Large when Large Hands are Presented, International Conference on Artificial Reality and Telexistence Eurographics Symposium on Virtual Environments (ICAT-EGVE '19 Posters), 2019.

[2] **Nami Ogawa**, Takuji Narumi, Michitaka Hirose: Object Size Perception in Immersive Virtual Reality: Avatar Realism Affects the Way We Perceive, In proceedings of 2018 IEEE Conference on Virtual Reality and 3D User Interfaces (IEEE VR'18), pp.647–648, 2018.

[3] **Nami Ogawa**, Takuji Narumi, Michitaka Hirose: Swinging 3D Lamps: A Projection Technique to Convert a Static 2D Picture to 3D using Wiggle Stereoscopy, ACM SIGGRAPH ' 17 Posters, pp.29:1–29:2, 2017.

国内会議口頭発表（査読なし）

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