Virtual embodiment for multiple agents

(複数エージェントのためのバーチャル身体化)

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Abstract（Doctor）

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Approx. 800 words

This thesis is inspired by the future vision of the Metaverse and Society 5.0, where cyberspace and physical space are expected to be merged seamlessly to improve our lives and also enhance capabilities of our bodies. We used Virtual Reality (VR) to investigate the Sense of Embodiment (SoE) for new types of bodies we may experience in the future Metaverse and Society 5.0 possibly through augmented virtual avatars in cyberspace or through advanced wearable robotic prostheses in the real world.

Current literature indicates that the SoE for real or virtual objects, apart from our own bodies, is typically induced through visual-tactile integration or visual-motor synchronization. However, there is a significant gap in knowledge on whether embodiment can be induced towards completely autonomous or partner-controlled limbs. To investigate this, in this thesis, we introduce a novel concept of virtual co-embodiment called the joint avatar, which is an avatar controlled by multiple individuals simultaneously. In the first experiment (chapter 4), the effects of goal and intention sharing on body ownership and agency were investigated using a joint avatar with left and right arms controlled by two different individuals in first-person view. The body ownership and agency towards the partner-controlled limb of the joint avatar were significantly higher when participants shared a common goal or could see the partner's target, compared to when the partner's target was invisible. However, participants consistently felt higher ownership and agency towards the arm they controlled. Skin conductance of participants also increased significantly when the controlled arm was threatened compared to the partner-controlled arm. The second experiment (chapter 5) examined how passive upper body movements influence body ownership and agency towards a partner-controlled arm, again using the same joint avatar. Behavioral measures included changes in body image and proprioceptive drifts. Results indicated that synchronized force feedback to the body matching the partner-controlled arm's movements significantly increased body ownership and agency. One behavioral test showed significant proprioceptive drift towards the partner-controlled arm with force feedback, indicating enhanced ownership of the partner-controlled arm in the presence of force feedback to the upper body.

The third experiment (chapter 6) explored how the speed of autonomous limb movements affects its embodiment and perception. A lower-arm prosthesis was pre-programmed to move in a minimum jerk trajectory to mimic human-like movements, and the study measured ownership, agency, usability, and robotic social attributes in a within-subject experiment. Moderate-speed movements (1 second motion time) were rated highest in ownership, agency, and usability, while the fastest (125 ms) and slowest (4 seconds) movements received lower ratings. Discomfort was lowest when embodiment and usability were highest, showing a negative correlation.

The fourth experiment (chapter 7) investigated the embodiment of biomechanically impossible arm movements using an unnatural avatar with reverse-bending arms. Participants performed reaching tasks with this avatar, with and without a 1-second delay between real and virtual movements. Results showed higher body ownership for synchronous conditions in both natural and unnatural avatars, with the natural avatar generally receiving higher ownership ratings. Agency was also higher for the natural avatar in synchronous conditions. No significant differences were observed in skin conductance responses across conditions.

In the fifth experiment (chapter 8), we examined empathic embarrassment towards humans and robots in virtual environments. Participants rated self-embarrassment and actor-embarrassment after observing human and robot avatars in embarrassing situations. Skin conductance was also measured. Results showed higher self-embarrassment and actor-embarrassment for the human avatar compared to the robot, especially in embarrassing conditions. Skin conductance responses were nearly significantly higher for the human avatar. A follow-up experiment assessed the plausibility of the stimuli, revealing that participants found the human avatar's situations more real than those of the robot avatar, particularly in embarrassing contexts.

This thesis experimentally proves that intention sharing (with a partner), passive upper-body movements synchronized with limb movements, and movement speed of partner-controlled limbs can affect the sense of embodiment. We also show that biomechanically impossible arm movements too can be embodied as long as temporal visuomotor synchrony is preserved.

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List of Abbreviations

AR Augmented Reality

EDA Electrodermal activity

GSR Galvanic Skin Response

HMD Head-mounted display

RoSAS Robotic Social Attributes Scale

SCR Skin conductance response

SoE Sense of Embodiment

SUS System Usability Scale

VR Virtual reality

Chapter 1

Introduction

1.1 Society 5.0 as a super smart society

Looking back on human history, we can categorize different ages into Societies (from 1.0 to 4.0). Society 1.0 was based on hunting and gathering. Society 2.0, the agricultural society emerged with the development of farming and the establishment of settled communities. Society 3.0, the industrial society began with the industrial revolution, characterized by mass production, and urbanization. Currently we live in Society 4.0, the information society, that arose in the late 20th century with the advent of computers and the internet, focusing on information and communication technologies that transformed economic and social life. As a part of the 5th Science and Technology Basic Plan in 2016, the government of Japan announced an initiative to realize a “Society 5.0”, a transformative and strategically critical next stage in the development of Japanese society that will involve merging the physical space and cyberspace by leveraging information and communication technology (ICT) to its fullest (Government of Japan 2016a, p. 13), thereby providing a common societal infrastructure for prosperity based on an advanced service platform (Iwano et al. 2017, p. 1). Society 5.0 is meant to be a “human-centric” society that will attend in detail to various needs of people, regardless of their region, age, gender, and language, by providing necessary items and services. The key to its realization is the fusion of cyber space and the real world (physical space) to generate quality data, and from there create new values and solutions to resolve challenges using technologies such as the Internet of things (IoT), digital twins, Artificial Intelligence (AI), XR (cross reality), and human-centered robotics. Japanese governmental agencies, universities, and businesses are actively collaborating in development and implementation of the Society 5.0 paradigm (Government of Japan 2016b; Harayama 2017; Prasetyo and Arman 2017; Shibata et al. 2017; Ding 2018; Ferreira and Serpa 2018; Fuji et al. 2018). For building such a human-centric futuristic society based on the fusion of cyber space with the real world, to truly benefit humans, it is also necessary to understand human psychology and perceptual attributes behind concepts such as Virtual Reality (VR), Augmented Reality (AR), avatars, embodiment, autonomous agents, metaverse, and empathy in cyberspace and real world for robots or AI characters as well as other humans.

1.2 Virtual reality

Virtual Reality (VR) is a computer-generated artificial environment that can typically be experienced by wearing a head mounted display (HMD) to feel immersed and located in a different world and operate in similar ways to interacting with our physical surroundings (Slater & Sanchez-Vives, 2016). With the help of specialized multisensory equipment such as immersion helmets, VR headsets and omnidirectional treadmills, this experience can be further amplified through the modalities of vision, sound, touch, movement and the natural interaction with virtual objects (Pellas et al., 2021; Pellas et al., 2020). VR allows users to "embody" various types of virtual avatars and interact with other VR users and virtual characters using non-verbal communication such as body language, and movements in addition to verbal communication over voice chat. With significant advancement in consumer VR headsets and huge tech companies (Meta, and Apple for example) paying increased attention to improving cross reality and cyberspace lately, our future societies can be expected to use VR, and AR seamlessly for various purposes beyond entertainment. Among various applications of VR such as entertainment, education, rehabilitation and skill training, VR is currently becoming more and more popular in psychological research as well, from social to cognitive and even clinical research. VR provides psychological researchers the opportunity to study human cognition and behavior in more controllable and safe environments compared to other traditional psychological methods and also evoke more genuine responses from participants due to its high level of immersion.

1.3 Metaverse

The Metaverse represents a post-reality realm, offering a continuous and enduring multiuser space that blends physical reality with digital virtuality (Mystakidis, 2022). It relies on the integration of technologies that facilitate multisensory engagement with virtual settings, digital entities, and other users, such as VR and AR. Essentially, the Metaverse is a network of interconnected, social, and immersive environments on persistent multiuser platforms. It allows for seamless, real-time embodied user communication and dynamic interactions with digital artifacts. Initially, it consisted of a web of virtual worlds and avatars could teleport between them. The current version of the Metaverse includes social, immersive VR platforms that are compatible with large-scale multiplayer online games, open game worlds, and AR collaborative spaces (Mystakidis, 2022). With the improvement of the metaverse, XR sports, games, collaborations, remote work, family reunions, and meeting friends etc. are highly likely to shift gradually into cyberspace.

1.4 Human-centered robotics

Research on robotics has extended from its primary focus on industrial applications to fields such as medicine, healthcare, search and rescue, assisting disabled people in daily life etc., increasingly being focused on developing intelligent robots that can co-exist with humans. The New Robotics has to embrace a broad interdisciplinary approach, ranging from traditional mathematical issues of robotics to novel issues in psychology, neuroscience, and ethics (Schaal, 2007). An essential aspect of this evolution is understanding and integrating robotic social attributes, which are measured using the Robotic Social Attributes Scale (RoSAS). RoSAS evaluates how humans perceive robots in terms of warmth, competence, and discomfort, crucial for designing robots that can effectively and comfortably interact with humans in various social contexts. Additionally, advancements in smart robotic prosthetic limbs emphasize creating a strong sense of embodiment, allowing users to feel as though prosthetic body parts are natural extensions of their bodies. This sense of embodiment is critical for improving the functionality and acceptance of robotic prosthetics in daily life.

1.5 Motivation

This dissertation is driven by the vision of the future metaverse and Society 5.0, where physical and cyberspace seamlessly merge to improve our lives. The use of virtual reality (VR) to explore the sense of embodiment in new types of bodies, whether through avatars in cyberspace or advanced wearable robotics and prosthetics in the real world, forms the core inspiration for this work. In addition to embodiment, this work was motivated to further investigate the emotional empathy we experience with virtual agents in cyberspace, and robotic social attributes for autonomous robotic arms in the virtual space, aiming to enhance our understanding of human interaction in these evolving environments.

Chapter 2

Literature review

2.1 Sense of embodiment

The concept of sense of embodiment is phenomenologically complex and the term embodiment has been defined differently in various contexts. From a philosophical perspective, embodiment is considered to be how a person defines and experiences himself/herself (Blanke & Metzinger, 2009; Metzinger, 2007). On the other hand, embodiment science in virtual reality (VR) research studies the effects of self-avatars on its users (Spanlang et al., 2014). Embodied avatars are defined to be avatars that are co-located with the user's body and seen from a first-person perspective within an immersive virtual environment (Kilteni et al., 2012). Here we are interested in sense of embodiment, as defined in cognitive neuroscience, in which embodiment is known to be related to how the brain expresses the body and is defined to consist of three subcomponents (Kilteni et al., 2012): the 'sense of self-location', the 'sense of agency' and the 'sense of ownership'. Sense of self-location is known as the ability to perceive the location of one's body parts (Blanke & Metzinger, 2009; Lenggenhager et al., 2009), sense of agency is the sense of having control of motion (Blanke & Metzinger, 2009; Haggard, 2005), and sense of ownership refers to one's self-attribution of the body (Gallagher, 2000).

2.1.1 Sense of body ownership

All our lives, we have been experiencing ourselves being immersed inside a body that can be moved as we intend, to interact with our surroundings. Various sensations we continuously receive through vision, touch and proprioception during such interactions allow us to distinguish what is "ours" among the objects we perceive. The term 'body ownership' has been given to this self-attribution of the body (Gallagher, 2000) that presumably depends on the afferent sensations arising within the body itself (Tsakiris et al., 2007). Our sense of body ownership also depends on the coherence of the current sensory input with the pre-existing cognitive representations of the body (Tsakiris & Haggard, 2005) making it difficult for us to feel embodied in new objects or bodies apart from our own.

2.1.2 Sense of self-agency

In adult life, people normally know what they are doing. This experience of controlling one's own actions and, through them, controlling the course of events in the outside world is called sense of self-agency (Blanke & Metzinger, 2009; Haggard, 2005; Haggard 2017). Therefore, Therefore, the matching of action and the outcome of one's actions is crucial for feeling a sense of agency. Previous studies have shown that the special displacement or temporal delay between action and outcome attenuates sense of agency (Farrer et al., 2008; Franck et al., 2001; Haggard & Chambon, 2012). Along with the sense of body ownership, and sense of self-location, sense of agency is also a dimension of sense of embodiment.

2.2 Virtual embodiment

In recent years, the development of VR and AR devices has allowed more users to engage in activities such as socializing, gaming, participating in meetings, working, teaching, skill learning etc. virtually. Tracking and reflecting body movements into virtual avatars in real time has made embodying avatars possible with an enhanced sense of embodiment where users can experience and take full control over avatars in first person view to perform various tasks in virtual environments, inducing sense of body ownership and sense of agency towards their virtual avatars. A variety of both VR and real-life studies have investigated the subcomponents of sense of embodiment and have shown that, given the right sensory and/or motor stimulations, humans can elicit embodiment of virtual and physical objects other than their own bodies (Gonzalez-Franco et al., 2010; Aymerich-Franch & Ganesh, 2016). For example, previous studies have shown that humans elicit illusory body ownership to a child or a small doll (Banakou & Slater, 2014; Tajadura-Jiménez et al., 2014; Van Der Hoort et al., 2011), slimmer and wider mannequin bodies (Preston & Ehrsson, 2014), bodies in a different skin color (Peck et al., 2013), a longer arm (Kilteni et al, 2012), animal bodies (Krekhov et al., 2019), and even towards robots (Nishio et al., 2012; Aymerich-Franch et al., 2017; Aymerich-Franch et al., 2015). Furthermore, embodiment can also be elicited when different body parts are re-associated (Kondo et al., 2020) or even when the body is fully or partially invisible (Guterstam et al., 2015; Kondo et al., 2020; Kondo et al., 2018). For inducing sense of embodiment for virtual avatars in VR, visual-tactile integration or visual-motor synchrony are known to be important.

2.2.1 Visual-tactile integration

Manipulating visual, tactile, proprioceptive, and motor sensations in specific ways can trick our minds into believing external or virtual objects to be parts of us. One classic body ownership illusion found in literature is the rubber hand illusion (RHI) (Botvinick, & Cohen, 1998; Rorden et al., 1999; Farne et al., 2000), where participants reported a feeling of owning a rubber hand after observing it being stroked with a paint brush while the hidden real hand was also synchronously stroked. Immediately after experiencing the RHI, with their eyes closed, participants typically tend to point at a position drifted away from their own hand and towards the rubber hand when asked to point at their real hand, showing a proprioceptive drift (Botvinick & Cohen, 1998; Costantini & Haggard, 2007; Tsakiris & Haggard, 2005, Tosi et al., 2023). Some studies also report an increase in skin conductance levels when the rubber hand is threatened during the experience of the illusion (Armel & Ramachandran, 2003; Tsuji et al., 2013; Honma et al., 2009). However, when the stroking on the real hand is asynchronous/incongruent with that on the rubber hand, the illusion is known to occur to a much lesser extent (Armel & Ramachandran, 2003) meaning that the illusion is mainly caused by the multisensory integration of what is seen (the visual input of the rubber hand being stroked) and what is felt (the synchronous tactile sensation on the real hand).

2.2.2 Visual-motor synchronicity

In addition to such visual-tactile correlations, synchronous visual-proprioceptive (passive as well as active movements) and visuomotor (active movements) correlations are also known to induce illusions of owning surrogate body parts (Dummer et al., 2009; Tsakiris et al., 2006; Walsh et al., 2011; Kalckert & Ehrsson, 2012; Kalckert & Ehrsson, 2014; Kondo et al., 2020b). When it comes to synchronous visuomotor stimulations, immersive Virtual Reality (VR) with real-time body tracking has been used to investigate further into the underlying mechanisms of illusory body ownership (Petkova & Ehrsson, 2008; Slater et al., 2010; Gonzalez-Franco et al., 2010; Sachez-Vives et al., 2010; Weijs et al., 2021, Inoue & Kitazaki, 2021). Some studies even suggest that synchronous visuomotor stimulations induce stronger body ownership illusions compared to synchronous visual-tactile stimulations (Kokkinara & Slater, 2014), highlighting the importance of visuomotor synchrony for embodiment.

2.2.3 Role of haptic feedback

Many previous studies on sense of embodiment have highlighted haptic feedback in synchrony with visual feedback as a promising mode of induction of sense of ownership (Botvinick & Cohen, 1998; Kokkinara & Slater, 2014; Tsakiris & Haggard, 2005). With the development of VR and robotic devices, studies have shown the benefits and usage of haptic devices in virtual reality with regards to presence (García-Valle et al., 2017; Kreimeier & Götzelmann, 2019), performance (Götzelmann, 2019), and learning (Lemole et al., 2007). Recently some studies have shown that different types of haptic feedback such as force, and vibro-tactile feedback can affect embodiment differently

(Krogmeier et al., 2019; Richard et al., 2021).

2.2.4 Embodiment of robotic limbs

But almost all previous embodiment studies have considered scenarios where a real limb is replaced by an artificial limb (like a rubber hand). In these scenarios, tactile feedback (Botvinick & Cohen, 1998, Tsakiris & Haggard, 2005) or proprioceptive feedback (Dummer et al., 2009; Walsh et al., 2011; Pinardi et al., 2020) corresponding to visible touch or movement (Walsh et al., 2011; Pinardi et al., 2020) of the artificial limb, can be provided on the real limb it replaces. However, such scenarios are not possible with 'Independent additional limbs' (Umezawa et al., 2021), like in the case of robotics prosthetics or robotics supernumerary limbs, as there is no replacement limb in these scenarios to provide a movement or tactile feedback on. Previous studies by Kalckert & Ehrsson (Kalckert & Ehrsson, 2014, Kalckert and Ehrsson, 2012) have shown that passive synchronous movement of a participant's finger along with the corresponding finger of a rubber hand (while the participant observes only the rubber hand) induces an equally strong sense of ownership towards the rubber hand compared to the traditional rubber hand illusion which involves visuo-tactile stimulation with a paint brush.

2.3 Virtual co-embodiment

The idea of two individuals co-embodying one avatar in first-person view is an emerging new concept that has been proposed in a few recent studies. Hagiwara et al. (2020) conducted an experiment where two participants were embodied within a concurrent shared avatar that moved with the weighted average of limb orientations of the two participants in VR and showed that the movements of the shared avatar were straighter, and less jerky compared to the movements of the individual participants and the solo body avatar during a reaching task (Hagiwara et al., 2020). Fribourg et al. (2020) introduced the concept of virtual co-embodiment (again with an avatar with weighted average movements of two individuals in VR) and showed that the participants were good at estimating their real levels of control but significantly overestimated their sense of agency when they could anticipate the motion of the avatar (Fribourg et al., 2020). A few studies have also studied effects of collaborative training using virtual co-embodiment on motor skill training (Kodama et al., 2023; Katsumata et al., 2023). These previous studies on virtual co-embodiment have studied avatars of which the movements were determined by averaging the movements of the two participants in real time (occasionally in different ratios of control). In this dissertation, we will define a new type of virtual co-embodiment where control over different body parts of the co-embodied avatar is given to different users.

2.3.1 Vicarious agency

We usually feel a sense of agency for our actions and not for the actions of others. Sense of agency is the experience of controlling one's own actions and, through them, controlling the course of events in the outside world (Blanke & Metzinger, 2009; Haggard, 2005; Haggard 2017). However, when the action is clearly occurring to another person’s body, apparent mental causation might still prompt some experience of agency. Wegner et al. (2004) did a study where, participants watched themselves in a mirror while another person behind them hidden from the view extended hands forward on each side where participants’ hands would normally appear, (similar to Ninin-baori in Japanese comedy) and performed a series of movements with the hands. When participants could hear instructions previewing each movement, they reported an enhanced feeling of controlling the hands. Hearing instructions for the movements also enhanced skin conductance responses when a rubber band was snapped on the other's wrist after the movements. Such vicarious agency was not felt when the instructions followed the movements, and participants' own covet movement mimicry was not essential to the influence of previews on reported control (Wegner et al., 2004). In such cases there is neither visual-motor synchrony nor visual-tactile integration or any haptic feedback and yet participants report some level vicarious agency towards another’s arm highlighting the importance of knowing the intentions behind arm movements on sense of agency. When it comes to amputated individuals using autonomous prosthetic limbs, to feel a sense of embodiment towards the prosthesis, inducing vicarious agency becomes crucial.

2.3.2 Joint action and we-mode

Joint action refers to the coordinated and interdependent behaviour of two or more individuals who work together to achieve a common goal. This type of action involves shared intentionality, mutual responsiveness, and the establishment of a common goal, allowing participants to align their actions and intentions to effectively collaborate. Joint action is characterized by the participants' ability to predict and adapt to each other's behaviours, ensuring a smooth cooperation (Sebanz et al., 2006). During virtual co-embodiment of avatars, participants can engage in joint action to collaboratively accomplish various goals in “we-mode”. We-mode is a theoretical framework that describes how individuals engage in collective intentionality, where the group’s perspective takes precedence over individual perspectives (Tuomela, 2007; Gallotti & Frith, 2013). The work by Hagiwara et al., showing that the jerk minimizes towards the co-embodied avatar over the individual avatars could be an indication that virtual co-embodiment facilitates we-mode (Hagiwara et al., 2020). Understanding joint action and we-mode is crucial for designing systems and environments that support effective collaboration. In cognitive science and artificial intelligence, these concepts may inform the development of interactive systems and robots that can seamlessly integrate with human partners. In social psychology, they shed light on the mechanisms underlying group behaviour, and corporation and possible even empathy towards other members in a group.

2.4 Empathy for human and non-human agents

Empathy is a factor that is long considered to be a mediator or a contributor to positive human interactions, altruistic behavior and sympathy (Eisenberg & Miller, 1987). The term "empathy" has been used as a label for a number of psychological processes and related consequences over the past century (Davis et al., 1994). One of the most common definitions of empathy is "feeling a vicarious emotion that is congruent with but not necessarily identical to the emotion of another" (Batson et al., 1991). Empathy is distinguishable since it is felt on behalf of another person, whereas other emotions are generally felt on one's own behalf (Batson et al., 1997). Even though it is also possible to respond with empathic joy when another is experiencing positive states (Smith et al., 1989), empathy is often interpreted as an emotion felt by witnessing another's suffering (Davis et al., 1994l; Hoffman, 2001; Krebs, 1975), pain (Jackson et al., 2005; Lamm et al., 2007; Cheng et al., 2007; Gu & Han, 2007), anger caused by injustice (Hoffman, 2001; Montada 1989; Vitaglione, 2003), or even embarrassment (Stocks et al., 2011). The majority of studies on empathy mentioned above are focused on how people empathize with other humans. However, recently with the increasing use of robots and virtual platforms in different sectors of our lives, chances of interacting with robots, AI, and non-human agents have increased considerably and can be expected to keep increasing. Therefore, it is necessary to build good relationships with robots as well in addition to humans (Rosenthal-von der Putten et al., 2013; Suzuki et al., 2015; Broadbent, 2017; Wiese et al., 2017; Hortensius et al., 2018; Henschel et al., 2020). However, are we capable of empathizing with non-human agents such as robots and virtual characters during interactions or while observing them interact with others? Humans socially interact and communicate with computers and virtual characters (Nass et al., 1997; Hoffmann et al., 2009; Von der Putten et al., 2010). The media equation phenomenon contributes to such communication with computers and robots (Reeves & Nass, 1996; Bartneck & Hu, 2008).

2.4.1 Empathy for pain

Previous studies have provided physiological evidence of humans' ability to empathize with pain experienced by robots (Pütten et al., 2014; Suzuki et al., 2015). Pütten, et al. (2014) found a similar activation in the limbic system of participants during the observation of violent human-robot interactions as well as violent human-human interactions, but the neural activation was higher while observing the human-human interactions than the human-robot interactions (Pütten et al., 2014). Suzuki et al. (2015) measured electroencephalography of participants while watching humans and robots in painful situations (such as the hand being cut by a knife) and showed that while participants empathized with humanoid robots in late top-down processing in a similar manner to empathizing with humans, the beginning of the top-down process of empathy was weaker for robots compared to humans (Suzuki et al., 2015). In another study that measured how people empathize with robots experiencing mistreatment by humans, participants reported a higher level of empathy with more human-looking robots and less with mechanical looking robots (Riek et al., 2009). These studies suggest that during painful scenarios or mistreatment, people do show a tendency of showing empathy for robots as well even though it is lower compared to the level of empathy felt with other humans. Since these previous studies on empathy for robots are focused on mistreatment or pain, in this dissertation we focused on another emotion, "empathic embarrassment" felt with robots compared to humans.

2.4.2 Empathy for embarrassment

Embarrassment is an essential emotion of humans in society (Edelmaan, 1987; Miller & Tangney, 1994), but one of the least studied emotions when it comes to previous studies on empathy. Embarrassment is a member of the family of "self-conscious" emotions that are evoked by self-reflection and self-evaluation (Tangney, 1999). This emotion is evoked by a wide range of apparently dissimilar situations such as being introduced to an unfamiliar audience, arriving at a social occasion under-dressed, making mistakes in front of an audience, and so on. It indeed is an unpleasant experience and causes an emotional response that has important personal and social consequences, for those observing as well as for the victim experiencing the embarrassing situation himself or herself (Stocks et al., 2011). Although we tend to consider embarrassment as an unpleasant emotion, previous studies have highlighted some social benefits of embarrassment. Child developmental studies show that embarrassment is related to social development of self (Buss et al., 1979) and self-recognition (Lewis et al., 1989), suggesting that embarrassment is a higher-order cognitive ability. Eller et al. (2011) showed that people are more likely to be embarrassed in front of members of their own social group compared to outside social groups suggesting that embarrassment is tied to intergroup relations of people and that expressing embarrassed emotions tend to repair social relations and elicit for forgiveness (Eller et al., 2011). Furthermore, a study by Feinberg et al. (2012) has shown that individuals who tend to express more outward signs of embarrassment also showed a tendency to be more prosocial and generous (Feinberg et al., 2012). Individuals who revealed signs embarrassment were also perceived to be more trustworthy by others and the observers were willing to give resources and express a desire to affiliate with them more (Feinberg et al., 2012). These studies highlight the close relationship between embarrassment and empathy.

Chapter 3

Research purpose

To realize a human-centered Society 5.0, which merges the real world and cyberspace, it is necessary to extend human capabilities (augment humans) and enhance interactions between people (Augmented human-human interactions), while also expanding interactions between humans and non-human agents including robots (Augmented human-robot interactions). Furthermore, it is important to understand empathy, psychological responses and behavior of humans in a society where humans and robots coexist (Fig. 1). This doctoral thesis particularly focuses on the SoE and empathy experienced by humans during such futuristic interactions.

According to the currently available literature, SoE for real or virtual objects other than our own bodies is typically induced through visual-tactile integration (RHI for example) or using visual-motor synchronization (self-controlled virtual avatars or robots). However, there is a lack of know-how on how sense of embodiment can be induced towards autonomous or partner-controlled limbs. The purpose of this research is to introduce a new type of virtual co-embodiment called the joint avatar and with it study the sense of embodiment towards completely partner-controlled arms and autonomous robotic prostheses. The novel joint avatar introduced in this dissertation is an avatar controlled by two individuals at the same time where left-side limbs are controlled by one while the right-side limbs are controlled by another. We investigated the effect of intention sharing, partner's goal visibility, force feedback to the body, on the SoE towards the partner-controlled arms of the joint avatar. We also aimed to investigate how the movement speed of an autonomous prosthetic limb affects its sense of embodiment, usability and robotic social attributes such as competence, warmth and discomfort (without using the joint avatar). While prosthetic limbs and virtual avatars in VR investigated by previous studies are mostly restricted to human-like movements, we further investigated whether avatars with biomechanically impossible (for humans) movements too can be embodied in VR. Finally, we investigated how empathy is felt for non-human agents in virtual environments. The purpose of that study was to understand how we empathize towards robots in comparison to other humans in cyberspace. Fig. 1, and Fig. 2 summarize the types of human-augmentation investigated in this dissertation. Overall, we aim to provide experimental evidence on factors affecting embodiment of partner-controlled, autonomous and biomechanically unnatural arms as well as empathy towards humans and robots in cyberspace.

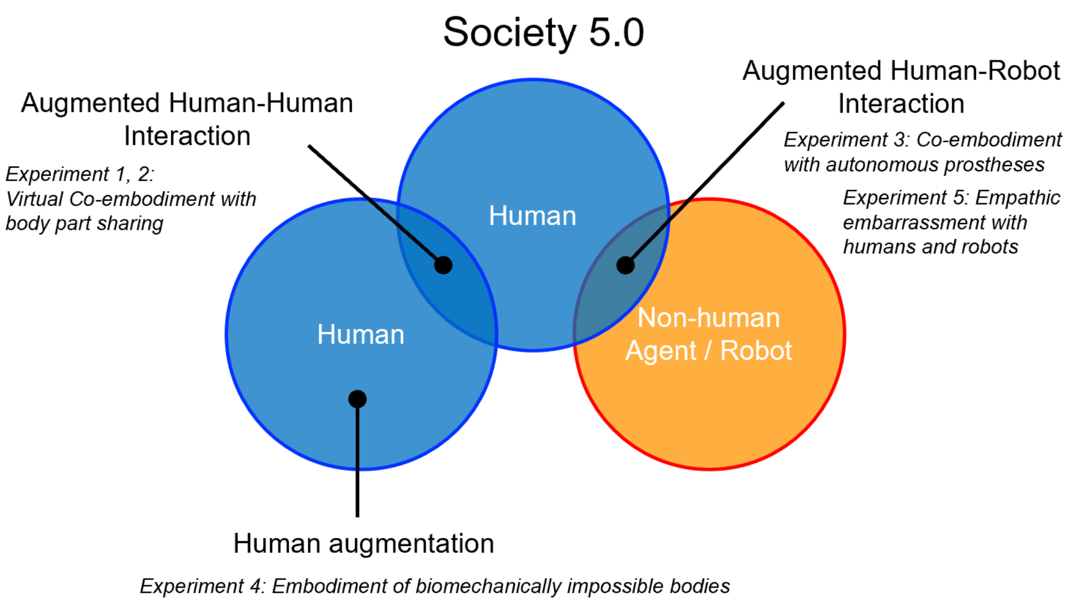

Figure 1: Areas investigated in this dissertation

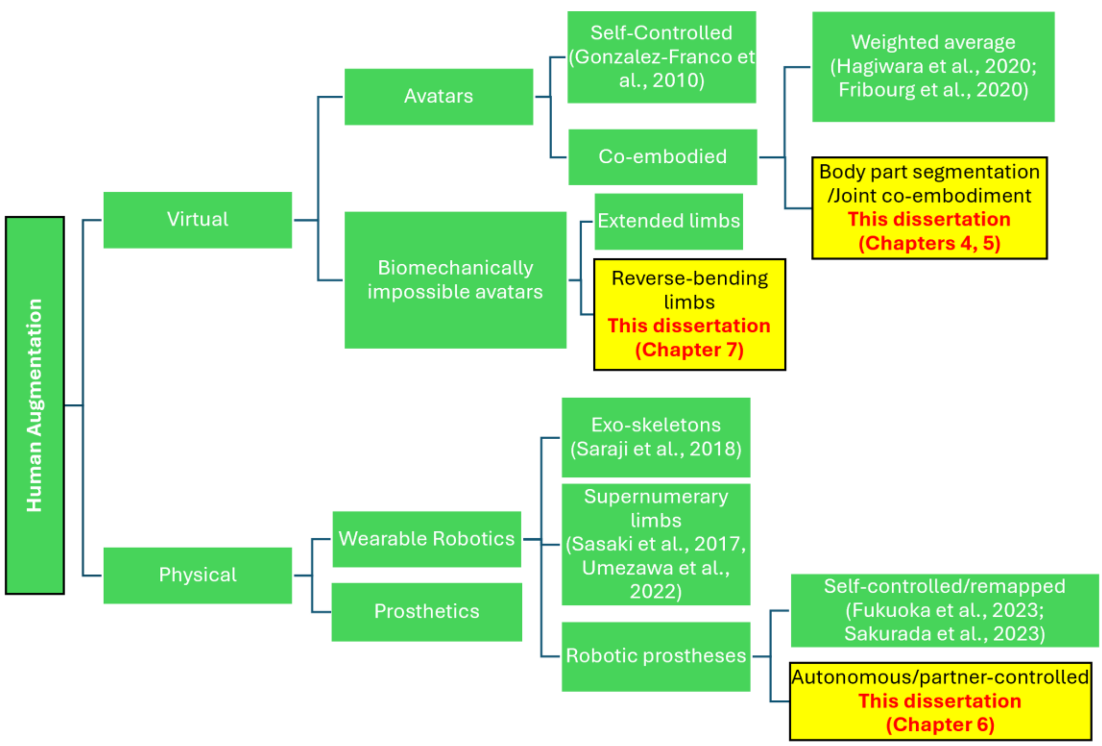

Figure 2: Types of human augmentation introduced in this dissertation

Chapter 4

Virtual co-embodiment enhanced by sharing intentions

4.1 Introduction

A single user embodying one humanoid avatar to control all of its limbs as he or she would control his or her own body in real world is the most conventional way of avatar embodiment (Kilteni et al., 2012; Gonzalez-Franco et al., 2010). In this study, we explore a new side of the concept of virtual co-embodiment where two or more users embody one avatar to collaboratively perform joint tasks. Co-embodiment can be achieved in several ways such as reflecting average movements (or movements in different ratios of control) of multiple users to one avatar or a robot (Hagiwara et al., 2020; Fribourg et al., 2020; Kodama et al., 2023; Katsumata et al., 2023), or allowing multiple users to control different sections of one avatar limb or a robotic arm (Hagiwara et al., 2021). In this study, we utilized a virtual avatar of which left and right limbs could be controlled by two different individuals at the same time while both of them were immersed in the first-person view of the virtual avatar. Fig. 3A shows the shared body avatar from precious studies which is controlled by two individuals, and their movements are averaged and reflected in the shared avatar (Hagiwara et al., 2020; Fribourg et al., 2020). Fig. 3B shows our novel joint body avatar of which the body parts such as the left and right half bodies are controlled by two different individuals.

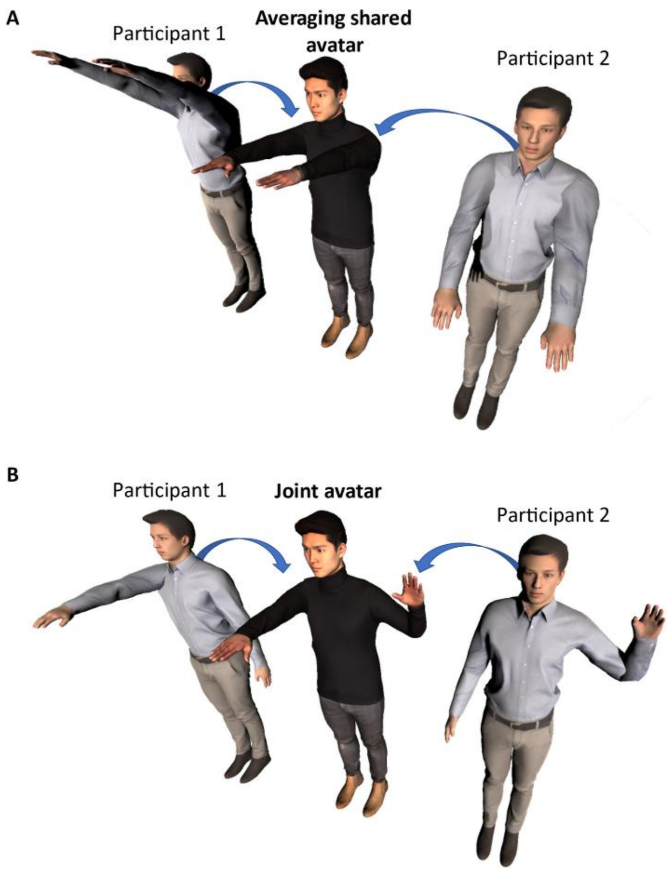

Figure 3: Two types of virtual co-embodiment

A previous study with a special setting similar to "Ninin Baori" in a real environment (Participants viewed themselves in a mirror while another person behind them put hands forward as if they were the participants' hands) on experiencing control over the movements of others suggests that when participants could hear instructions previewing movement of limbs controlled by another, they reported an enhanced feeling of controlling the hands that belonged to another person (Wegner et al., 2004). In this study, we used a new paradigm to further explore the effect of knowing the intentions behind arm movements on sense of embodiment towards an arm controlled by a partner during virtual co-embodiment.

Although averaging movements may have its benefits for some tasks for normal VR users, allowing a partner to completely control the virtual avatar's limb corresponding to a person's missing or immovable limb would be more applicable in the case of disabled VR users such as hemiplegic patients and amputees. Such aid by partners would allow amputees to weaken disabilities and perform complicated tasks in one avatar where each participant can focus on one detailed sub task. Hagiwara et al. (2021) developed a robotic arm application where two users can control different sections (ie., elbow and wrist) of a robot arm to perform complicated tasks with more accuracy where the users can divide work and focus on one detailed sub task to collaboratively increase task performance of the overall task (Hagiwara et al., 2021). Inspired by such studies, we have developed a new type of co-embodiment avatar called a “joint avatar”, in which the left half of the avatar is controlled by one user and the right half of the avatar is controlled by another (Fig. 3B). However, allowing another person to fully control a limb of a virtual avatar in which an individual is immersed in first person perspective may cause a severe lack of “sense of embodiment” towards that limb, which may lead to an uncomfortable experience associated with the feeling of being partly possessed by someone else. Therefore, addressing this lack of sense of embodiment towards limbs controlled by others is necessary for a pleasant virtual co-embodiment.

In this study, using the joint avatar, we investigated whether sense of embodiment towards a limb fully controlled by a partner would change depending on the nature of the task itself performed in the co-embodied/joint avatar. The task performed in the joint avatar can be considered as a 'joint action'. Sebanz et al. (2006) defined joint action as any form of social interaction whereby two or more individuals “coordinate” their actions in space and time to bring about a change in the environment (Sebanz et al., 2006). For example, two people carrying a table together would require both of them to coordinate their actions in a temporally and spatially precise manner to successfully execute the task. Some coordination mechanisms depend on sensorimotor information shared between co-actors, thereby making joint attention, prediction, non-verbal communication, or the sharing of emotional states possible (Vesper et al., 2017). Previous studies related to joint attention have suggested that the ability to direct one’s attention to where an interaction partner is attending provides a basic mechanism for sharing representations of objects and events (Frischen & Tipper, 2004; Tollefson, 2005) which may possibly encourage the ‘we’ intention or the ‘we-mode’ (Gallotti & Frith, 2013) believed by some philosophers to be what joint action mostly depends on (Tollefsen, 2005). Here, we thought of the possibility of enhancing embodiment towards a co-embodied avatar by encouraging we-mode through sensory (visual) information manipulation during joint action, to eventually investigate on the relationship between embodiment and joint attention (or the sensory information responsible for joint attention).

Therefore, we hypothesized there to be an increase in embodiment if the individual and the partner shared one common intention/goal compared to having their own separate intentions before observing the partner’s action during the task (H1). Furthermore, we hypothesized that in the case of having two different targets, the embodiment would be higher when the partner’s target is visible compared to when it is invisible (H2).

H1

Embodiment towards the limb controlled by a partner is higher when the goal is common to the partner.

H2

Embodiment towards the limb controlled by a partner is higher when the partner's goal is visible.

To test these hypotheses, we conducted an experiment using the joint avatar. Participant dyads performed three types of reaching tasks involving and not involving joint action (Fig. 4).

Multiple previous studies regarding ownership illusions towards rubber hands (Armel & Ramachandran, 2003; Ehrsson et al., 2008; Tsuji et al., 2013) have shown that the increase in skin conductance level in response to threatening stimuli is higher towards objects with ownership illusions. For example, skin conductance when a strong blow with a hammer was given to a fake hand after tactile stimulation that induces an ownership illusion towards the rubber hand, the participants have shown a higher increase in skin conductance compared to when the fake hand was hammered before the tactile stimulation (Tsuji et al., 2013). Thus, the skin conductance response (SCR) to a threatening stimulus is considered a physiological measure of illusory body ownership. In line with this, we adapted a method to assess ownership illusions for the two virtual hands in our study by virtually stabbing the hands of the joint avatar at the end of each session and recording the levels of skin conductance of the participants in response. The participants were instructed to reach the targets and keep the hand touching the target until it erases before returning their hands back to the original position. In the last target reach at the end of each session, we displayed a stimulus of a knife stabbing one of the hands of the joint avatar to measure startle responses using the skin conductance response (Fig. 5). We hypothesized that the change in skin conductance would be higher when the controlled arm is stabbed with the virtual knife compared to when the non-controlled arm is stabbed (H3). We also hypothesized there to be a difference in skin conductance levels towards the non-controlled arm between the three goal conditions (H4).

H3

SCR is higher when the controlled arm is threatened than when the non-controlled arm is threatened.

H4

SCR when the partner-controlled arm is threatened is higher while sharing the same goal with the partner compared to having separate goals and in the case of having separate goals, SCR when the partner-controlled arm is threatened is higher when the partner's goal is visible compared to when it is invisible.

Participants answered a questionnaire regarding senses of body ownership and agency at the end of each session.

4.2 Experiment 1: Methods

Participants

Twenty university students as ten dyads (All males, mean age 22.3, SD 2.4, 19 right-handed) participated in the experiment as dyads. The sample size was determined by a power analysis with repeated measures ANOVA (6 within factors: 2 × 3 conditions), an effect size (f) of 0.25 (medium), an alpha of 0.05, and power of 0.80 using G*Power 3.1. The calculated sample size was 19, then we determined the sample size as 20 for making dyads. All participants were unaware of the hypothesis of the experiments and had normal or corrected-to-normal eyesight. They provided informed consent before the experiment. The methods of the experiment were approved by the Ethical Committee for Human-Subject Research at the Toyohashi University of Technology, and all methods were carried out in accordance with the relevant guidelines and regulations.

Apparatus

The movements of the two participants were measured by a motion capture system (Vicon Bonita10, 12 cameras, 1024 × 1027 pixels, 250 fps). Two computers with the same specifications received the processed information of the motion capture data and presented the virtual environment on head-mounted displays (HMD: HTC VIVE Pro Eye, 1440 × 1600 pixels per eye, 90 × 110 deg, 90 Hz refresh) of both participants. The virtual environment and experiment tasks were created using Unity (2017.4.1f1). BIOPAC MP 160 and wireless PPG and EDA amplifiers (BN-PPGED) were used to record the skin conductance response (SCR). A wireless transmitter (BN-PPGED) was placed on each participant's wrist. Two disposable electrodes (EL507) were pasted to the distal phalanges of their middle and ring fingers. Two lead cables (BN-EDALEAD2) connected the wireless transmitter to the electrodes. The SCR data was recorded at 1000 Hz.

Stimuli and Conditions

The experiment consisted of three conditions. In each session, one participant controlled the left side of the joint avatar while the other controlled the right side throughout the experiment, both in first-person view. The virtual avatar used in this study was an Asian male avatar since 90% of the participants were Asian (Japanese) males. We named the three conditions "Same goal", "Different goals: visible", and "Different goals: invisible". In the "same goal condition", one yellow target appeared in front of the joint avatar and participants were asked to collaborate and touch the target with both hands of the joint avatar as shown in Fig. 4A. In the different goals: visible condition, two targets (one blue and one red) appeared in front of the avatar and participants were asked to touch the blue target with the right hand and red target with the left hand of the joint avatar as shown in Fig. 4B. Different goals: invisible condition was the same as different goals: visible condition, but the target of their partner was invisible for each participant. Fig. 4C shows the different goals: invisible condition from the perspective of the participant who controls the right arm of the joint avatar. All targets were spheres of 5 cm diameter and were erased 200 ms after reached appropriately for each condition. After erasing, the next target appeared 2 s later.

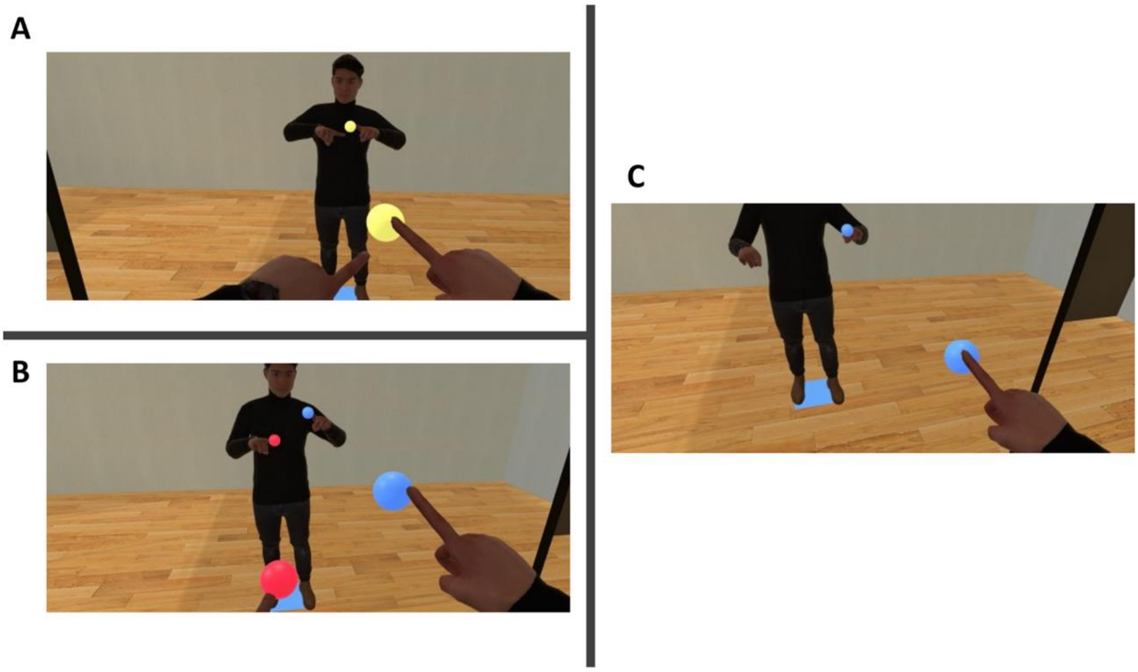

Figure 4: Experiment conditions

The targets appeared at random positions inside the areas shown in Fig. 6. In the Same goal condition, yellow targets appeared at random positions inside the area shown in yellow Fig. 6A. In the different goals: visible and different goals: invisible conditions, the red targets that were to be reached with the left hand of the joint avatar appeared at random positions inside the area shown in red, and the blue targets that were to be reached with the right hand of the joint avatar appeared at random positions inside the area shown in blue in Fig. 6B. Each session consisted of 100 reaches per participant and on the final reach of each session, a stimulus of a knife stabbing either the left or the right hand of the joint avatar was displayed as shown in Fig. 5.

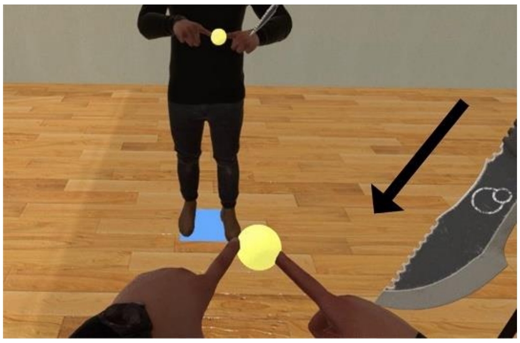

Figure 5: Knife stimulus at the end of each session

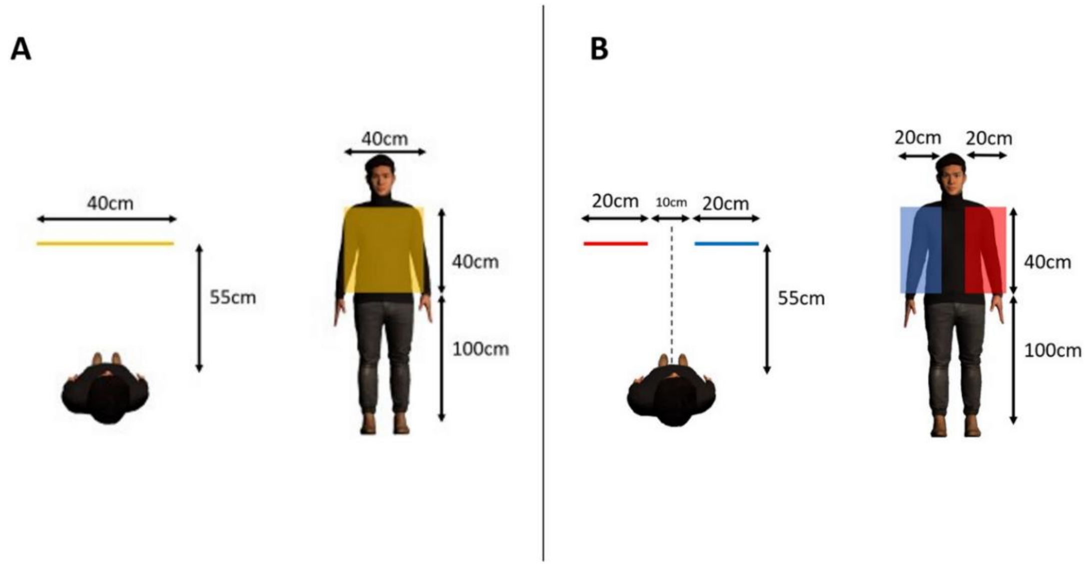

Figure 6: Target areas of the reaching tasks

Procedure

The participants were instructed to reach the targets and keep the hand touching the target until it erases before returning their hands back to the original position. In the last target reach at the end of each session, we displayed a stimulus of a knife stabbing one of the hands of the joint avatar (see Fig. 5). To make the knife visible to both participants, the last target position was pre-chosen to be towards the center of the avatar in a clearly visible position and the final target/two targets was/were not erased on touch hence requiring the participants to keep touching the targets. We measured skin conductance response of participants during the stimulus of the knife to assess embodiment towards each arm of the avatar in each condition.

The experiment consisted of six sessions (3 conditions × 2 repetitions). Each condition was blocked as a session. In the two repetitions for each condition, left hand was stabbed at the end of one repetition while the right hand was stabbed in the other. The order of sessions was randomized for each dyad.

One session lasted 5–7 min and after each session, both participants answered a questionnaire regarding how they felt about the left and right arms of the joint avatar. The questionnaire was based on a previous study (Table 1) (Peck & Gonzalez-Franco, 2021). Questionnaire answers were accepted in a 7-point Likert scale from − 3 to + 3 where − 3 meant "Strongly disagree" and + 3 meant "Strongly agree".

Table 1: Questionnaire items

Q1	The movements of the virtual left arm seemed to be my movements
Q2	I felt as if the virtual left arm I saw was my own left arm
Q3	It seemed as if I felt the touch of the target sphere at the end of my left index finger
Q4	The movements of the virtual right arm seemed to be my movements
Q5	I felt as if the virtual right arm I saw was my own right arm
Q6	It seemed as if I felt the touch of the target sphere at the end of my right index finger

Using the answers, senses of ownership and agency towards left and right sides of the joint avatar for each condition were calculated as follows referring the Avatar embodiment standardized questionnaire by Peck, & Gonzalez-Franco (2021).

Sense of agency towards the left arm = Q1

Sense of body ownership towards the left arm = (Q2+Q3)/2

Sense of agency towards the right arm = Q4

Sense of body ownership towards the right arm = (Q5+Q6)/2

4.3 Experiment 1: Results

Senses of body ownership and agency towards the non-controlled arm were higher in same goal and different goals: visible conditions compared to the different goals: invisible condition

The data were categorized as "controlled arm" (the arm the participant controlled) and "non-controlled arm" (the arm that was controlled by the partner of the participant). For example, the ownership score towards the right arm of the joint avatar given by the participant who controlled the right arm of the joint avatar was categorized as the ownership for the "controlled arm" while his ownership score for the left arm of the joint avatar was categorized as ownership for the "non-controlled arm" (and vice versa for the participant who controlled the left arm of the joint avatar). Fig. 7 and Fig. 8 summarize the results of the questionnaires.

We calculated the sense of body ownership (Fig. 7) towards the two arms of the joint avatar in the three conditions (Same goal, Different goals: Visible, Different goals: Invisible). For the questionnaire scores of both body ownership and agency, we first tested if the data violated normality, and then

applied non-parametric ANOVA (2 controlled/non-controlled arms x 3 goal conditions) if the data deviated from normality. All simple main effects were tested if the interaction was significant, and the post-hoc multiple comparisons were performed among three goal conditions if the simple main effect was significant. These procedures of analysis were determined before conducting the experiment.
A two-way repeated measures ANOVA with ART (aligned rank transformation) procedure (Wobbrock et al., 2011) was conducted since some of the data significantly deviated from normality according to the results of Shapiro-Wilk tests (controlled arm for Same goal: W=0.958, p=0.500, non-controlled arm for Same goal: W=0.933, p=0.180, controlled arm for Different goals: Visible: W=0.874, p=0.014, non-controlled arm for Different goals: Visible: W=0.914, p=0.076, controlled arm for Different goals: Invisible: W=0.911, p=0.067, non-controlled arm for Different goals: Invisible: W=0.844, p=0.004). There was a significant interaction between the condition and arm (F(2,38)=7.622, p=0.002, η_p^2=0.286).

Significant simple main effects on the side condition were obtained in all goal conditions, and the sense of ownership was higher in the controlled arm condition than the non-controlled arm condition (the Same goal: F(1,19)=78.641, p<0.001, η_p^2=0.805, the Different goals: Visible: F(1,19)=96.404, p<0.001, η_p^2=0.835, the Different goals: Invisible: F(1,19)=113.49, p<0.001, η_p^2=0.857).

Significant simple main effects on the goal condition were seen only in the non-controlled arm (F(2,38)=9.292, p<0.001, η_p^2=0.328). Tukey post hoc tests confirmed that ownership was significantly higher in the Same goal condition compared to Different goals: Invisible condition (p=0.0015, d=1.201), and significantly higher in the Different goals: Visible condition compared to Different goals: Invisible condition (p=0.0021, d=1.159).

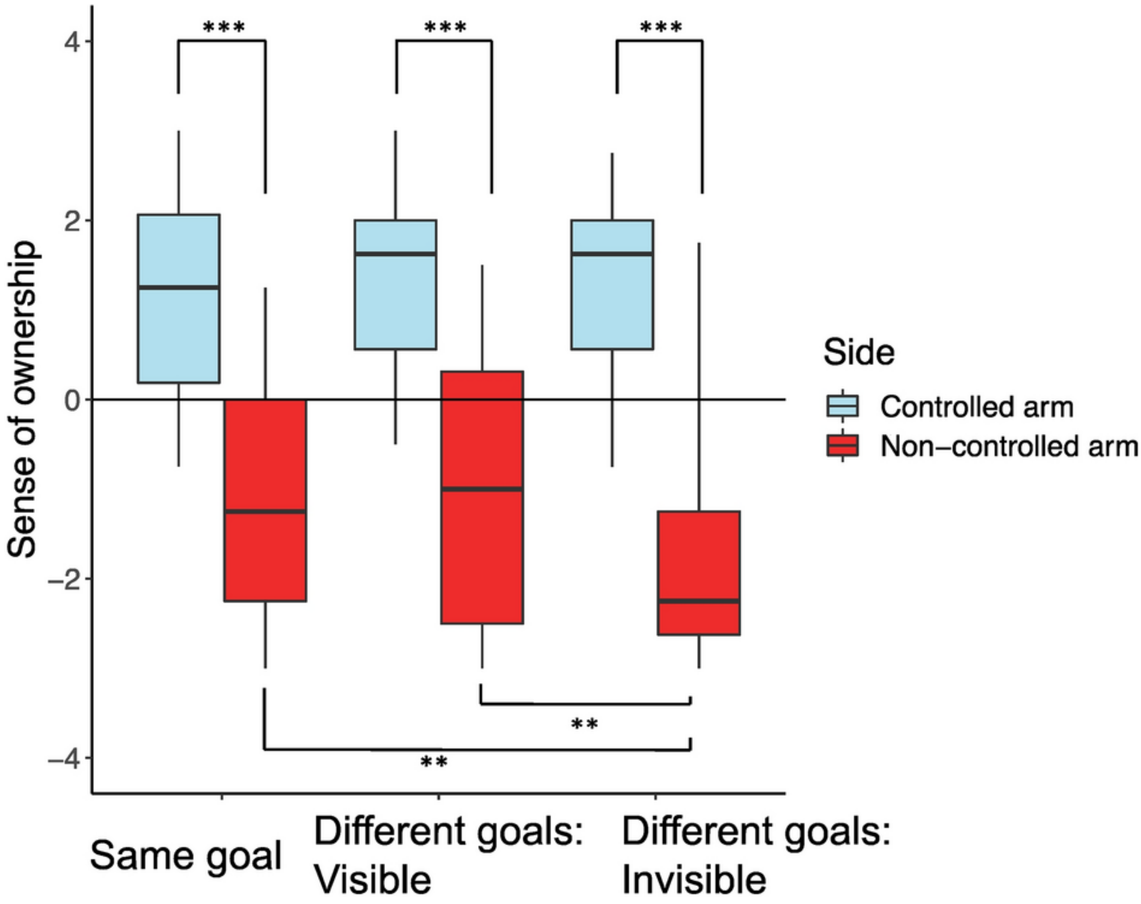

Figure 7: Sense of body ownership results

We calculated the sense of agency (Fig. 8) towards the two arms of the joint avatar in the three conditions (Same goal, Different goals: Visible, Different goals: Invisible). A two-way repeated measures ANOVA with ART (aligned rank transformation) procedure (Wobbrock et al., 2011) was conducted since some of the data significantly deviated from normality according to the results of Shapiro-Wilk tests (controlled arm for Same goal: W=0.827, p=0.002, non-controlled arm for Same goal: W=0.935, p=0.194, controlled arm for Different goals: Visible: W=0.755, p<0.001, non-controlled arm for Different goals: Visible: W=0.907, p=0.055, controlled arm for Different goals: Invisible: W=0.815, p=0.001, non-controlled arm for Different goals: Invisible: W=0.872, p=0.013). There was a significant interaction between the condition and arm (F(2,38)=8.141, p=0.001, η_p^2=0.300).

Significant simple main effects on the side condition were obtained in all goal conditions, and the sense of agency was higher in the controlled arm condition than the non-controlled arm condition (the Same goal: F(1,19)=94.509, p<0.001, η_p^2 =0.833, the Different goals: Visible: F(1,19)=157.38, p<0.001, η_p^2=0.892, the Different goals: Invisible: F(1,19)=174.04, p<0.001, η_p^2=0.902).

Significant simple main effects on the goal condition were seen only in the non-controlled arm (F(2,38)=0.211, p=0.011, η_p^2=0.211). Tukey post hoc tests confirmed that agency was significantly higher in the Same goal condition compared to Different goals: Invisible condition (p=0.0181, d=0.906), and significantly higher in the Different goals: Visible condition compared to Different goals: Invisible condition (p=0.0308, d=0.837).

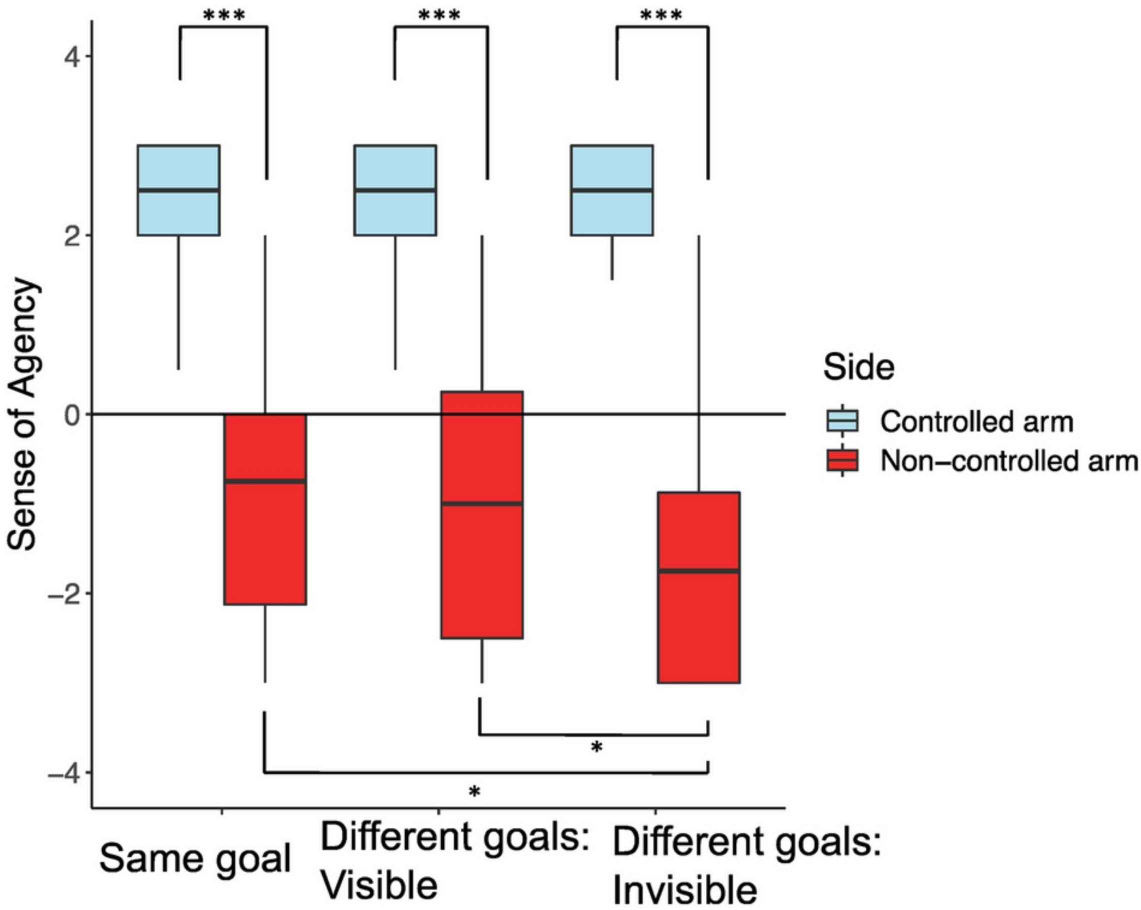

Figure 8: Sense of agency results

Skin conductance responses were higher in the control arm than the non-control arm, but not different among goal conditions.

Skin conductance response of each participant was calculated every time the threatening stimulus (virtual knife) appeared, as the difference between the maximum value detected in a 10s post-stimulus time window and the baseline calculated as the average value of a 5s pre-stimulus time window at a sample rate of 1000Hz. We assumed the SCR data as parametric data and applied the parametric ANOVA. We firstly tested the sphericity of the data, and if there was a lack of sphericity, the reported values were adjusted using the Greenhouse-Geisser correction. Two-way repeated measures ANOVA showed no significant interaction between the goal condition and the arm. A significant main effect in the arm showed that the skin conductance response towards the controlled arm was significantly higher than that towards the non-controlled arm (F(1,19)=6.8201, p=0.017, η_p^2=0.264). However, no main effect of the goal condition or the interaction was observed. Fig. 9A shows the calculated average skin conductance values when the controlled/non-controlled arm of the joint avatar was stabbed with the virtual knife; The three goal conditions were merged (Fig. 9B) because neither the main effect of goal condition nor the interaction was significant.

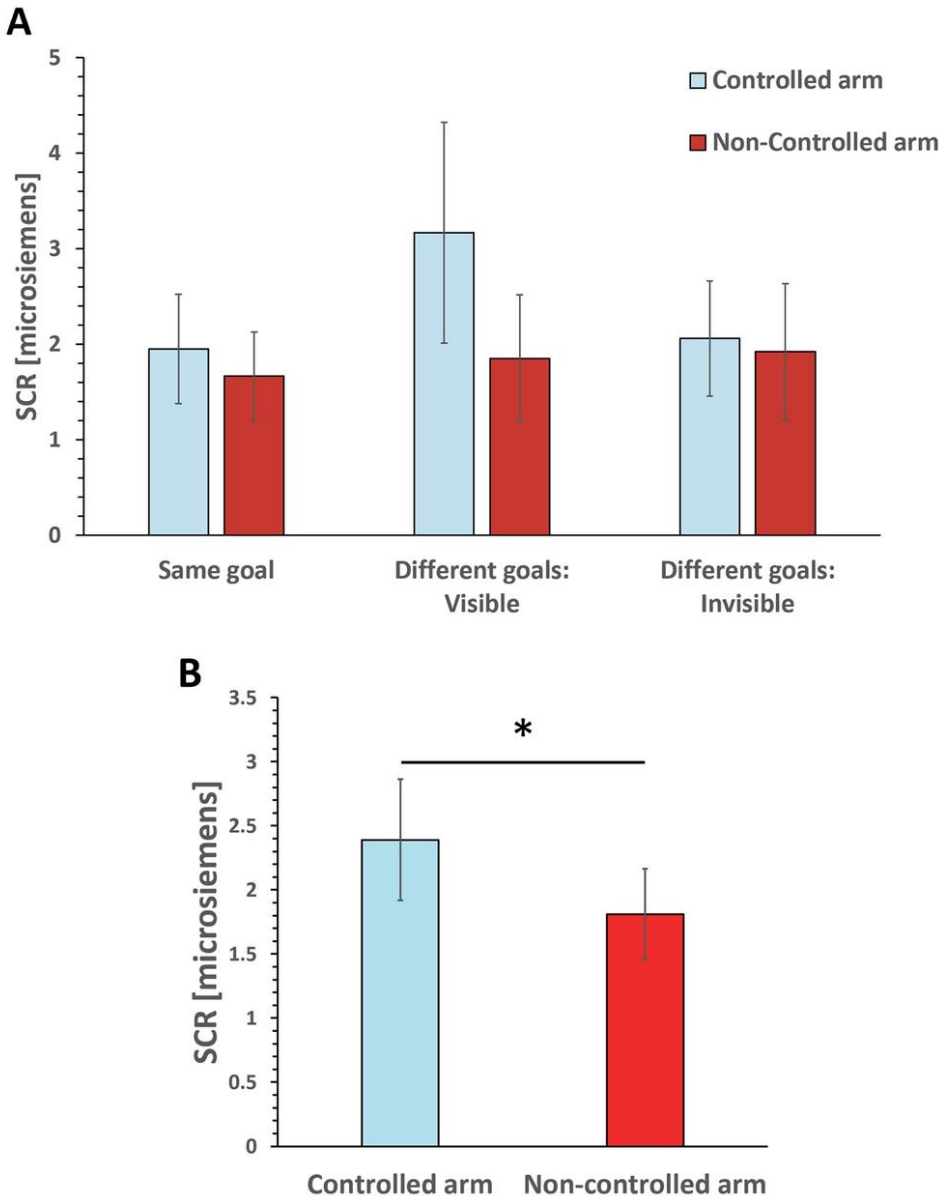

Figure 9: SCR results

(A) Skin conductance response when the knife stabbed controlled or non-controlled arm at the end of each condition. (B) The three goal conditions were merged because neither the main effect of goal condition nor the interaction was significant. The skin conductance response was higher when the knife stabbed the controlled arm compared to when it stabbed the non-controlled arm.

Exploratory analyses including effects of dyads

The experiment was performed by 10 dyads. Participants were assigned randomly to right side or left side of the joint avatar. Thus, we performed additional statistical tests including the effect of dyads as exploratory analyses.

For the sense of body ownership, a three-way repeated measures ANOVA with ART was performed with 2 controlled/non-controlled arm conditions, 3 goal conditions (same goal, different goals: visible, different goals: invisible), and 2 dyad roles (right/left) since the data deviated from the normality (Shapiro-Wilk tests, $p<0.05$). The sample size was 10 dyads. We found the main effect of the arm condition ($F(1,9)=405.76$, $p<0.001$, $\eta_p^2=0.978$) and a significant interaction between the condition and arm ($F(2,81)=5.876$, $p=0.004$, $\eta_p^2=0.127$). There was another interaction between the arm and dyad role ($F(1,81)=6.894$, $p=0.010$, $\eta_p^2=0.078$). Significant simple main effects on the arm at goal condition were obtained in all goal conditions, and the sense of ownership was higher in the controlled arm condition than the non-controlled arm (the Same goal: $F(1,29)=30.421$, $p<0.001$, $\eta_p^2=0.512$, the Different goals: Visible: $F(1,29)=31.465$, $p<0.001$, $\eta_p^2=0.520$, the Different goals: Invisible: $F(1,29)=62.676$, $p<0.001$, $\eta_p^2=0.684$). Significant simple main effects on the goal condition were seen neither in the controlled arm ($F(2,48)=0.143$, $p=0.867$, $\eta_p^2=0.006$) nor the non-controlled arm conditions ($F(2,48)=2.292$, $p=0.112$, $\eta_p^2=0.005$). A significant simple main effect on the dyad role was observed on the controlled arm condition where participants who controlled the left arm of the joint avatar showed a significantly higher ownership towards the controlled arm compared to participants who controlled the right arm ($F(1,49)=23.234$, $p<0.001$, $\eta_p^2=0.322$).

For the sense of agency, a three-way repeated measures ANOVA with ART was performed with 2 control/non-control arm conditions, 3 goal conditions (same goal, different goals: visible, different goals: invisible), and 2 dyad roles (right/left) since the data deviated from normality (Shapiro-Wilk tests, $p<0.05$). We found the main effect of the arm condition ($F(1,9)=322.64$, $p<0.001$, $\eta_p^2=0.973$). We found a nearly significant interaction between the condition and arm ($F(2,81)=3.001$, $p=0.055$, $\eta_p^2=0.069$). However, no significant simple main effects were observed. There was a significant main effect on arm meaning sense of agency towards the controlled arm was higher compared to the sense of agency towards the non-controlled arm.

For the SCR data, a three-way repeated measures ANOVA was performed with 2 control/non-control arm conditions, 3 goal conditions (same goal, different goals: visible, different goals: invisible), and 2 dyad roles (right/left). We found no significant interaction between the goal condition and the arm. A significant main effect in the arm showed that the skin conductance response towards the controlled arm was significantly higher than that towards the non-controlled arm (F(1,9)=7.86, p=0.021, η_p^2=0.466). There were no main effects of the dyad or the goal condition, or the interactions. The results were consistent with the original analysis.

4.4 Discussion

Summary of results

We investigated whether sharing a goal or being able to see the partner's goal affects the senses of body ownership and agency towards an arm controlled by a partner when two individuals perform three types of reaching tasks together using a joint avatar in VR, of which one individual fully controls the movements of the left arm while the other fully controls the movements of the right arm. Our main interest was on how the visibility and sharing of the partner's goal affects the embodiment towards the arm controlled by the partner. We found that the sense of ownership and the sense of agency towards the partner-controlled arm were significantly higher when the goal was common or when the partner's target was different and visible compared to when the partner's goal was different and invisible to the participants. The hypothesis H1 has been partly supported by the findings since the sense of ownership and the sense of agency towards the non-controlled arm were significantly higher in the common goal condition compared to the invisible different goals condition but were not higher compared to the visible different goals condition. The hypothesis H2 has been supported since the sense of ownership and the sense of agency towards the non-controlled arm were significantly higher in the visible different goals condition compared to the invisible different goals condition. Taken together, we conclude that whether the partner's goal is visible or not is critical to increase the virtual embodiment towards the limb controlled by the partner.

Intention sharing and sense of agency

According to Wegner's theory of apparent mental causation (Wegner & Wheatley, 1999), sense of agency which is a main sub-component of sense of embodiment, arises if (1) an intention precedes an observed action (priority), (2) the intention is compatible with this action (consistency), and (3) the intention is the most likely cause of this action (exclusivity). Although these three conditions apply when the intention and the action belong to the same person, would sense of agency arise if a partner moves an arm of a person's avatar to match with the intention of the person? Results from our experiment provide an answer to this question. During sharing one goal (same goal condition) as well as knowing the position of the partner's goal while having two separate goals (different goals: visible condition), the agency towards the arm controlled by the partner (non-controlled arm) was significantly increased compared to the control condition in which the partner's target was invisible while having two separate goals (different goals: invisible condition). This shows that sense of agency does indeed increase when a partner moves an arm of a person's avatar to match with the intention of the person. Interestingly, in addition to sense of agency, ownership towards the partner's arm was also significantly increased in a similar manner between the three conditions. Overall, these results suggest that being able to see the partner's target increases sense of embodiment towards the arm controlled by the partner satisfying the hypothesis H2 described in the introduction.

No difference in embodiment between goal sharing and intention sharing with different goals

However, among the same goal and different goals: visible conditions, there were no significant differences in ownership or agency towards the non-controlled arm. This suggests that being able to know the partner's objective increases embodiment towards the arm controlled by the partner regardless of the shared or divided nature of the task (equally increased in both cases compared to the control condition). The previously mentioned (in "Introduction" section) study in the real environment has shown that hearing instructions followed by consistent action increases the feeling of control towards another's hand (vicarious agency) (Wegner et al., 2004). In our experiment, allowing the participants to see the partner's target (while sharing one goal or having two separate goals) provides instructions visually regarding the action about to be performed by the partner-controlled hand and the results showed that it does indeed increase the feeling of control (sense of agency). Thus, our results are basically consistent with the vicarious-agency study while introducing a visual method of giving instructions instead of language/auditory instructions. However, it is an open question whether the language instruction and the visual target have the same level of effects or whether they are based on the same mechanisms. This issue should be further investigated in a future study.

Comparison with embodiment towards the controlled arm

Furthermore, the senses of agency and ownership were both significantly higher towards the controlled arm than towards the non-controlled arm in all three conditions. Supporting these questionnaire results physiologically, skin conductance levels were also significantly higher when the controlled arm was virtually stabbed with a knife compared to when the virtual non-controlled arm was stabbed in all three conditions. Thus, the hypothesis H3 is supported by these results. However, between the three conditions there was no significant difference among the skin conductance levels towards either of the arms of the joint avatar as we hypothesized. Therefore, hypothesis H4 is not supported.

Knowing the intention behind partner's movements enhances embodiment

In general, these results show that embodiment towards an arm fully controlled by a partner was still significantly lower compared to a fully controlled arm even with goal sharing or knowing the partner's intentions behind arm movements. Therefore, while we conclude visibility of the partner's target (which conveys the partner's intention for arm movements) to be a factor affecting embodiment, we also do point out that visibility alone is not sufficient to induce a level of ownership or agency to an equal level felt towards a fully controlled arm. To the best of our knowledge, there is no comparable study investigating senses of ownership and agency towards an arm controlled by another to evaluate the effect of knowing the partner's intentions. However, the asynchronous condition in González-Franco et al. (2010) is similar to our non-controlled condition due to the use of pre-recorded motion which simulates a closer movement to a partner-controlled limb. They (Gonzalez-Franco et al., 2010) reported scores 1.5 and 2.3 (depending on order of conditions) for body ownership and, 1.2 and 2.2 for sense of agency on the scale from 1 (disagree strongly) to 5 (agree strongly). The transformed values of their results to our 7-point Likert scale are − 2.25 and − 1.05 for body ownership and − 2.7 and − 1.2 for sense of agency. Our median values for the body ownership were − 1.25 (same goal), − 1.0 (visible different goal), and − 2.25 (visible different goal), and data for the sense of agency were − 0.75 (same goal), − 1.0 (visible different goal), and − 1.75 (visible different goal). It is difficult to compare these results due to differences of purpose and methods, but our result of the same goal and the visible different goal conditions might be slightly higher than the previous study. Even though the embodiment towards partner-controlled arms is low in general, coupled with other factors affecting embodiment towards such limbs, it may be possible to increase embodiment further. In the present study, we utilized the shared goal or intention based on the joint action studies (Sebanz et al., 2006) and the vicarious agency study (Frischen & Tipper, 2004; Tollefsen, 2005), but assuming by the low ownership and agency scores towards the partner-controlled arm, the dyads in the current joint body avatar may not have felt a strong "we-mode" (Gallotti & Frith, 2013) feeling overall. Therefore, future studies investigating other factors affecting embodiment towards limbs such as personality traits/behavior of the partner, different kinds of haptic feedback towards the limbs or body, level of trust between the dyads etc. must be considered. Investigating such factors in isolation as well as coupled together in various combinations may provide further insights on enhancing we-mode and sense of embodiment towards limbs controlled by others.

Left arm dominance in body ownership for the controlled arm

One may argue that the participants were not independent since they were organized in dyads where the partner's behavior may have had an effect on levels of embodiment. Thus, we exploratorily analyzed the data by adding the dyad role (the role of controlling either the left or the right arm of the avatar) as an independent variable and analyzed the results as dyads. The results were similar to the original analyses, but some results were different. For the body ownership, the interaction between the arm and dyad role was significant, but the simple main effects on the goal condition were significant neither in the controlled arm nor the non-controlled arm conditions. This may be due to the small sample size of dyads (N = 10). The left-am participants felt higher body ownership than the right-arm participants only in the controlled arm condition. This may be caused by the right hemisphere (and the left hand) dominance of the sense of body ownership (Ocklenburg et al., 2011). For the sense of agency, the interaction between arm and goal conditions did not show significance. This may also be due to the small sample size of dyads. Our experimental plan including the sample size was based on similar studies of virtual co-embodiment where experiments were performed by participant dyads (Fribourg et al., 2020; Hagiwara et al., 2020). Therefore, while the main analysis of this study assumes each participant to be independent, we need to consider the effect of dyads or dependency of embodiment of participants on their partners in future studies regarding co-embodiment.

Action-effect delay and sense of agency

According to some previous research, avatar tracking error (Toothman & Neff, 2019) and motion artifacts (Koilias et al., 2019) have been known to decrease user experience and sense of agency toward a self-avatar. The action-effect delay is widely used to disrupt the sense of agency (Wen. 2019). It is an interesting question whether the sense of agency can be improved if we consider the tracking errors, motion artifacts, or delay as system's or computer's intention and know them visually or with other modalities. More generally, it should be investigated whether the shared intention for increasing sense of agency in the joint avatar must originate from human partners or not in the future.

Chapter 5

Virtual co-embodiment enhanced by connection force feedback

5.1 Introduction

When we try to induce embodiment towards an artificial limb or a prosthetic limb of an amputee, the passive synchronous movements of the artificial limb (or the autonomous prosthetic limb) will not provide proprioceptive feedback of the whole limb movements to the amputee. Limb movements will only lead to forces and hence movements of the body since the artificial limb is physically connected to the user's body. It is unknown whether such connection induced body movements caused by the connection forces can increase the sense of ownership and/or agency towards partner-controlled limbs while the user/amputee observes its movements.

To investigate this issue, we developed a novel virtual joint avatar setup where two individuals could be immersed/co-embodied within the same avatar in first-person perspective while each controlled the limbs on one side of the body (left-side and right-side limbs). The joint avatar setup in this study included a novel back brace setup (Fig. 10A), that connected the dyad partner's shoulders, ensuring that the changes in upper body posture due to the movement of an arm by one partner was transmitted to the other. Therefore, in our setup, the upper body of an individual moved not only when the participant made arm movements, but also when the individual saw the other arm being moved by participant's partner (and similar to how it would have moved if he/she had made arm movement himself/herself).

In previous studies related to avatar embodiment in VR, conventionally one-to-one scenarios where one individual embodies one full avatar, or a robot, controlling its movements alone have been reported mostly. A few studies (Fribourg et al., 2021; Hagiwara et al., 2020) have examined "shared" avatars, whose movements were determined by averaging two individual's motions in real time. However, there is no reported study that investigates embodiment, especially ownership towards limbs or parts of an avatar attached to a person, but completely controlled by another when it comes to VR or robotics experiments. That is, embodiment towards limbs fully controlled by a different person from which one does not get any direct tactile or proprioceptive information from the limb except the connection force feedback (forces due to the physical connection between the arm and the upper body) and the resulting passive upper body movements (Fig. 10C). One study by Wegner et al. (2004) on vicarious agency (that did not use virtual avatars or robotics) has reported proof about experiencing control over the movements of others with a setup where participants watched themselves in a mirror while another person behind them, hidden from view, extended hands forward on each side where participants' hands would normally appear and performed a series of movements. They have shown that hearing instructions previewing hand movements causes an enhanced feeling of controlling the hands (Wegner et al., 2004). However, factors other than verbal instructions that may affect control or ownership towards limbs controlled by others remain unexplored.

Using the proposed joint avatar in this study, we conducted an experiment with a two person (dyad) 'joint task' in VR. Dyads in our joint task stood with their backs to each other and received the first-person view from the eyes of the same 'joint avatar'. Each partner in the dyad controlled one arm of the joint avatar. The right arm of the joint avatar copied the movements of the right arm of one dyad partner (tracked using optical marker positions read from a Vicon motion capture system), and the left arm of the joint avatar copied the left arm of the other dyad partner. The task presented to the dyads required them to reach targets presented to the left side (in front of them) with the right hand of the avatar, and conversely, reach targets presented to the right side of the avatar, with the left hand of the avatar. All reaches thus required them to twist their upper bodies. The novel back brace setup shown in Fig. 10A along with the pre-determined target positions for the reaching task were crucial to accurately convey or receive the upper body posture to/from the partner to the upper bodies of the participants in synchrony with the visual feedback of the joint avatar movements simulating a feeling of the upper body being dragged along with the movements of the partner-controlled virtual arm. Since our experiment involved healthy participants, we immobilized their real arms, on the side where they experienced the virtual avatar arm moved by the partner, by tying it to their motion capture suits so that there would be close to no proprioception from that arm. Participants were asked to relax and not use their immobilized arm during the experiment.

Each time the participant controlling the right side of the joint avatar moved his right arm to reach the targets, the back brace ensured that the real right shoulder of his partner was synchronously pushed to the front. Similarly, each time the participant controlling the left side of the joint avatar moved his left arm to the front to reach targets, the left shoulder of his partner was pushed to the front synchronously due to the back brace.

We evaluated the senses of ownership and agency perceived by the participants towards the arm they controlled (controlled arm) and towards the arm controlled by their partner (non-controlled arm) in two conditions. The Tied condition (Fig. 10A and Fig. 10C), where they received connection induced upper body movements from the non-controlled arm, and the Separated condition (Fig. 10B and Fig. 10D) in which each dyad participant was attached to a mannequin during the reaching task, again using the back brace.

Body representation refers to perception, memory, and cognition related to the body and is updated continuously by sensory input (Wen et al., 2016). Ownership may be measured using changes in arousal levels using galvanic skin resistance. However, GSR measures are noisy especially in tasks like ours that involve movement. On the other hand, several studies have shown that embodiment and or ownership are often correlated with changes in body representations like proprioceptive drift (Botvinick & Cohen, 1998; Tsakiris & Haggard, 2005) and visual localization of the real body (Blanke & Metzinger, 2009; Erro et al., 2018). Proprioceptive drift measures changes in the so called 'body schema', while the visual tests show changes in the 'body image' of the participant. Here motivated by these studies we conducted three behavioral tests to find and compare changes in the body representation after the experience of our joint avatar and corresponding connection induced upper body movements. Specifically, we purposely presented the non-controlled arm and shoulder displaced by 10 cm from a participant's real shoulder, expecting to find possible differences in changes in their perceived shoulder location and shoulder width between the Tied and Separated conditions.

Joint/shared/co-embodied avatars and robots can provide means for people with different physical disabilities to combine their strengths with others and work together in one complete avatar/robot to perform complicated tasks effectively while minimizing their physical disabilities at the same time. For example, a person missing a left arm can pair up with a person missing a right arm to co-embody one joint avatar and control different sides together as one whole avatar in VR. However, in such cases, since one half of the body is completely controlled by another, it becomes necessary to figure out ways to increase the sense of embodiment (induce illusory embodiment) to body parts controlled by the partner to minimize discomfort. It is difficult to imagine that two persons are physically connected in the real world. However, the force on the upper body could be conveyed to a person at a distant place with appropriate devices. It is much easier than conveying detailed proprioceptive senses of the whole limb. Thus, our experimental paradigm will contribute to developing joint avatars and robots in the future.

In summary, the purpose of this experiment was to simulate a feeling similar to the movements felt on the torso of an amputee wearing a prosthetic arm when the prosthetic arm moves by itself and to investigate if such movements influence the senses of ownership and agency felt towards the prosthetic arm. Therefore, we made the following two hypotheses regarding the Tied condition in which such upper body movements were present and the Separated condition in which such upper body moves were absent while the partner-controlled arm moved.

H1: Senses of ownership and agency towards the virtual non-controlled arm would be higher in the Tied condition compared to the Separated condition.

H2: Proprioceptive drifts towards the virtual non-controlled arm would be higher in the Tied condition compared to the Separated condition.

5.2 Experiment 2: Methods

Participants

24 male participants (mean/S.D. age: 23.6±1.8) took part in the experiment. Participants were recruited from the university and were naïve with respect to the purpose of the experiment and had normal or corrected-to-normal vision. All volunteers provided written informed consent before the experiment. This study was approved by the Ethical Committee on Human-Subject Studies of Toyohashi University of Technology, and all methods were carried out in accordance with the relevant guidelines and regulations. The sample size was determined by a power analysis with an effect size (f) of 0.25 (medium), an alpha of 0.05, and power of 0.80 using G*Power 3.1 (Faul et al., 2007; Faul et al., 2009).

Setup and apparatus

The participants took part in the experiment as dyads. Each dyad was chosen in a way that the height difference of the two participants was never more than 5 cm. The movements of the two participants were measured by a motion-capture system (Vicon Bonita10, 12 cameras, 1024 x 1027 pixels, 250 fps, focal length: 4–12 mm, F/1.4-CLOSE, angle of view: 26.41 x 26.41 deg), and processed in a computer (HP Z440 Workstation, OS: Windows7, CPU: Intel(R) Xeon E5-1620 v3, 3.5GHz, RAM: 32GB, GPU: NVIDIA Quadro 5000 (2560MB GDDR5)) with middle-level software (Vicon Blade 3.4.1, Vicon Pegasus 1.2.2). Two computers with same specifications (DELL XPS 8930, OS: Windows10, CPU: Intel(R) Core i7-9700 3.0GHz RAM: 32GB, GPU: NVIDIA GeForce RTX 2060 SUPER) received the processed information of the motion capture data and presented the virtual environment on head mounted displays (HMD: HTC VIVE Pro Eye, 1440 x 1600 pixels per eye, 90 x 110deg, 90 Hz refresh) of both participants. The virtual environment was created using Unity (2017.4.1f1).

Stimuli and conditions

The experiment was conducted in a virtual environment using a male avatar of height 175 cm (hand length 62 cm). The full body movements of the two participants (excluding the finger movements) were read using a Vicon motion capture system at a rate of 250 fps and were reflected on to the joint avatar in a way that one participant controlled the left side limbs (left arm and the left leg) of the joint avatar (left participant), while the other participant controlled the right side of the avatar body (the right participant). The position of the joint avatar (center bone/spine) was calculated to be the mean position of the two participants. Both participants were allowed to freely move their heads and look around in the virtual environment from the first-person perspective of the joint avatar through their Head-Mounted displays (HMDs).

The experiment was conducted under two conditions as shown in Fig. 10. Here the movements of the partner were read using the motion capture system and rotated by 180° in unity to match the direction of the joint body since the participants faced opposite directions during the experiment.

In the tied condition, the two participants were asked to stand leaning on to two 'support poles' set behind them (see Fig. 10A and Fig. 10 2C). They were connected to each other's upper body backs using two solid rectangular frames (back braces) as shown in Fig. 10A. These back braces were pasted to the bodies of the participants with hook and loop fastener and also tied around the shoulders with elastic bands to fit their bodies and make firm connections.

This set up induced passively moved the participants to adjust their upper body postures to match the posture of the joint avatar experienced in VR. Each support pole acted as an axis around which the participants could rotate their upper bodies during the exchange of forces between each other. The targets were set to appear at positions that required the participants to change their upper body posture and reach further than their hands can reach alone towards the targets in order to reach them (See Fig. 11 for the target positions).

In the separated condition, each participant was connected to a mannequin set to their partner's height in the same way they were connected to their partner in the tied condition (see Fig. 10B and Fig. 10D). The posture of the mannequin could be changed through forces conveyed to it through the back braces by the participants. Both participants were connected to mannequins while in VR they performed the same reaching task as in the tied condition. Therefore, in the separated condition, the participants' postures were not affected by their partners' movements during the reaching task. However, they could give force feedback to the mannequin while reaching as they did in the tied condition.

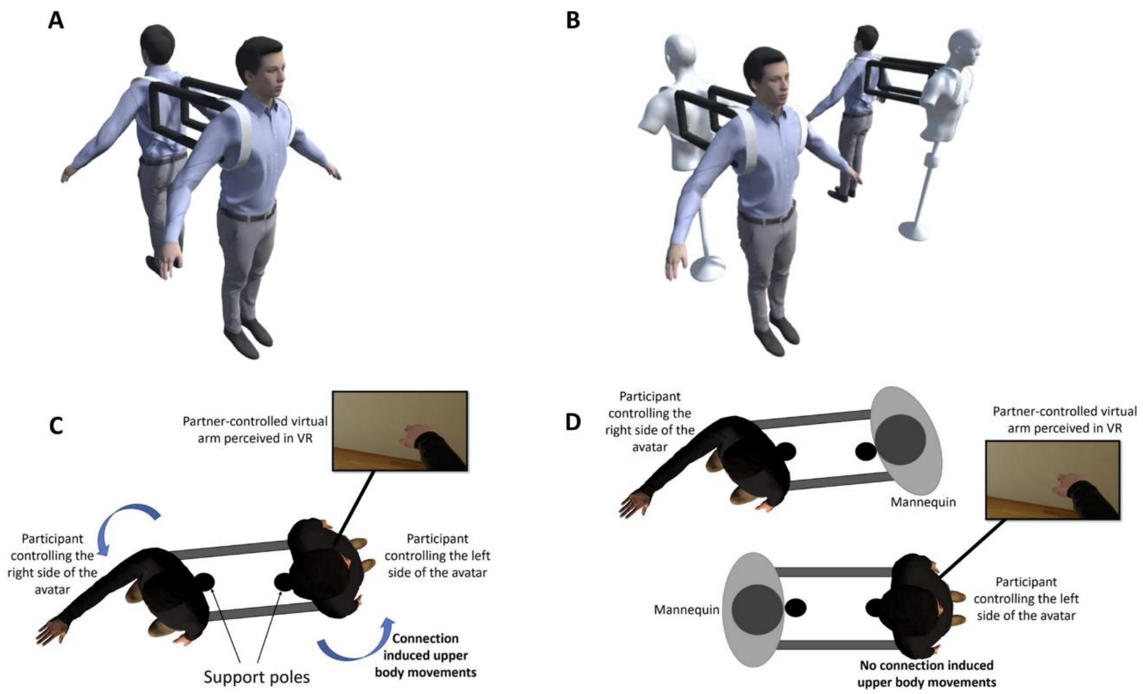

Figure 10: Experiment setup for tied and separated conditions

The left shoulder position of the virtual joint avatar viewed by the right participant was shifted 10 cm away from the head during both conditions such that the avatar shoulder was wider than the real shoulders of the participant. Similarly, the right shoulder position of the joint avatar viewed by the left participant was shifted 10 cm away from the avatar head. This shift was used to measure changes in the participant's perception of their real shoulder position.

The real arm of the participant that required no movement (non-controlled arm) was fixed on the motion capture suit with magic tape and the participants were asked to relax and not use that arm during the experiment. This was to ensure that the participants do not move the real arm and therefore possibly minimize the mismatches of sense of location of the perceived virtual arm controlled by the partner and the real arm of the participant.

In each condition, the participants performed 100 trials (reaches) as a team (50 reaches each). In each trial one of the participants was presented with a target in front of him and was required to reach the target as quickly as possible. The target was a sphere of 5 cm that appeared at a random position in the virtual environment at a reachable distance with the hands of the joint avatar. The target disappeared 200 ms after the tip of the index finger of the joint avatar reached it (at the instant where the velocity of the finger first dropped below 1 cm/s roughly within the volume of the sphere). 2 seconds later the next target appeared. The reach movement made by the joint avatar was however visible to both participants in first person perspective. Both participants had total control over the head movements (in first person perspective) separately even though one half/side of the avatar body below the neck was totally controlled by the partner.

The target for the participant controlling the right side of the joint body, always appeared in front of the left side of body, and vice-versa for the participant controlling the left side of the joint body (Fig. 11). This ensured that a participant would have to rotate his shoulders around the support pole pulling the left shoulder of the partner and pushing the right shoulder of the partner through the back braces. This enables the partner to receive a connection induced upper body movement synchronized with the movement of the joint avatar he views (where he will see the right arm moving forward while experiencing a push from behind to his right shoulder synchronized with the movement of the virtual limb). Similarly, when the target appeared to the participant controlling the left half of the joint avatar, it always appeared in front of him towards his right making it necessary for him to provide a synchronized passive movement to the shoulders of his partner when he reaches for the target. The participants were asked to relax their bodies and let their partners pull/push their shoulders during the task when it was not their turn to perform the reaching and were asked to observe the movements of the virtual limb controlled by their partner. We instructed them to move the shoulders and reach for the targets as necessary when it was their turn to reach, since it makes the reaching easier and also provides a well synchronized passive movement to the upper body of the partner.

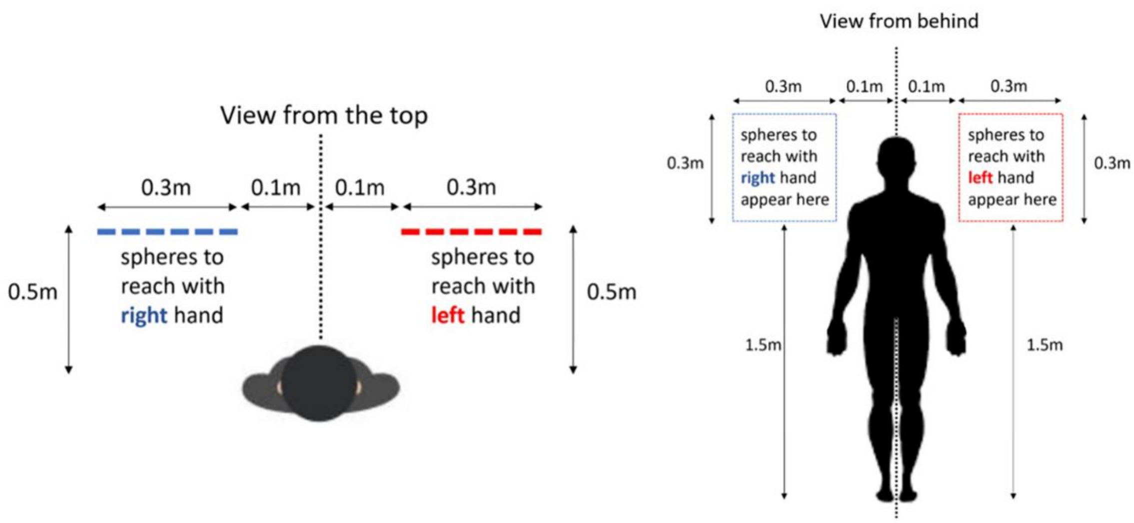

Figure 11: Target areas of the reaching tasks

Procedure

Behavioral tests to measure embodiments were performed before and after the reaching task as pre and post-test tasks. We carried out three tests, two (Test 1 and Test 2) that quantified changes in the body image related to the participant's shoulder, and one (Test 3) that estimated the body schema related to the position of the participant's shoulder.

We shifted the position of the shoulder controlled by the partner 10 cm away from the head of the virtual avatar (participants were not informed of this shift). We hypothesized that the answered positions of a participant in the three tests would drift more towards the outer side of the body (after the reaching task compared to before) if the avatar is embodied by the participant.

The three tests were carried out in the order of test 1, test 2, and test 3 (Fig. 15). In Test 1, the position of the real shoulder of the non-controlled arm was measured by visual pointing on the front-parallel plane in front of the participants (Fig. 15A). A wall of height 3m appeared 1m in front of each participant parallel to their bodies (shoulders) and the avatar was made invisible. On the wall, a horizontal straight line appeared at a random height within the range of ±10 cm vertically from the shoulder position of the participant (shoulder height was read from the motion capture marker pasted on the shoulder of each participant). A controller was handed to the controlled hand of each participant, and they were asked to point on the line, the position that corresponds to the edge of their non-controlled shoulder. The participants confirmed their location answer by pulling the trigger button on the controller. When the answer was detected, the screen was made to black out for 2 seconds and the next test was started.

In Test 2, the width of the real shoulder was measured by adjusting an aperture width in front of the participants (Fig. 15B). A wall of height 3m appeared 2m in front of the participants and the avatar was made invisible. On the wall a door of height 2m and width 30 cm appeared within the range of ±10 cm horizontally from the center of the body. Using the touch pad buttons of the controllers given to each participant, they were asked to adjust the width of the door to match the width of their real bodies. The participants confirmed their answers by pulling the trigger button of their controllers and the width of the door at that point was recorded. When the answer was detected, the screen was made to back out for 2 seconds and the next test started.

In Test 3, the perceived proprioceptive position of the real shoulder of the non-controlled arm was measured by asking the participants to point at their non-controlled shoulder with their controlled hand (Fig. 15C). During this test, the HMD was blacked out to avoid the participants seeing anything in VR or their real bodies. They were asked to move their controlled hand to place the motion capture marker on the knuckle of that hand just in front of the end of the shoulder of the non-controlled shoulder of their real bodies (participants were asked to remember the position of the specific motion capture marker pasted on the knuckle of the controlled arm before the experiment started). They were instructed to make the localization in one smooth movement and not to touch/search for the shoulder. The participants confirmed their answers by pulling the trigger button on the controller and the horizontal distance between the real shoulder end of the non-controlled arm hand and the answered position was recorded.

Each test was carried out 3 times in the order of test 1, test 2, test3 and the median value for each test from the 3 repetitions was used for analysis of drift in each test.

There were two sessions in the experiment, one trial of 5–7 minutes (depending on the response times of the participants) in the Tied condition and one trial of similar length in the Separated condition (Fig. 12). Each session consisted of the pre-test task, the reaching task, and the post-test task explained above followed by a questionnaire in the end. Half the dyads started with the Tied condition while the other half started with the Separated condition (to eliminate any influence by experiencing either of the conditions first).

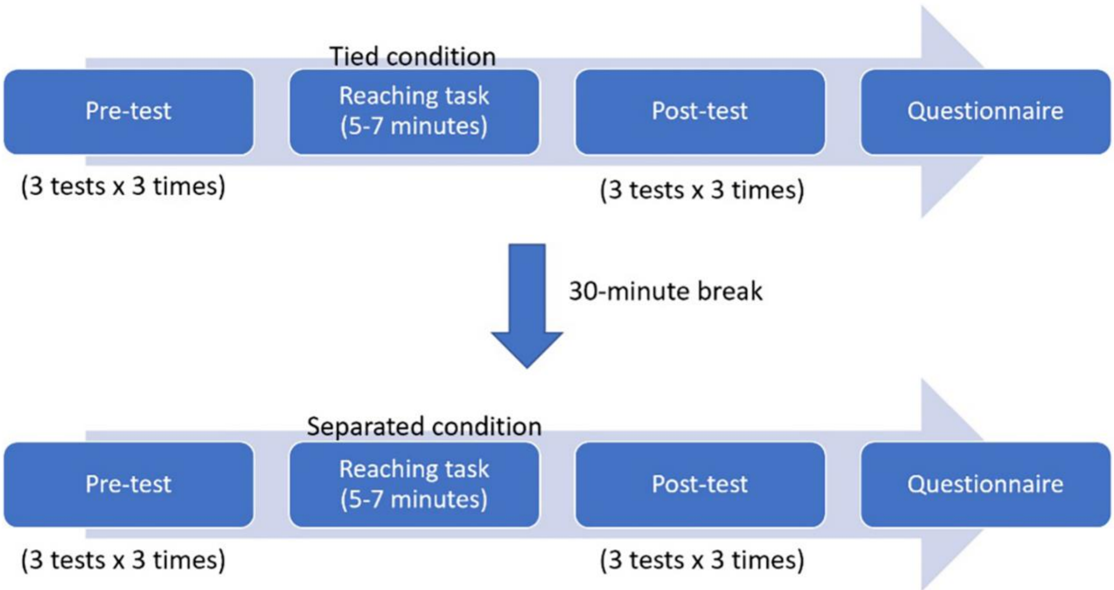

Figure 12: Design flow of the experiment

During the reaching task, the participants were asked to reach a target sphere as quickly as possible. The target disappeared 200ms after the reaching, and another target appeared at a different position. The target appeared 5 times consecutively for each participant (to provide enough time for the partner to feel his virtual hand being controlled and reduce the chances of being too focused on the target and losing focus on the virtual hand controlled by the partner and the passive upper body movements from the non-controlled arm). After 5 reaches, a recorded voice instruction was played through the HMD headphones of both participants saying “change”, meaning it is the turn for the other participant to perform the reaching 5 times (using the other limb of the joint avatar). This way, 20 sets of 5 reaches were performed in the order L, R, L, R (where L: appeared to the left participant, and R: appeared to the right participant). Therefore, each participant performed 50 reaches and observed 50 movements by their partner during one session.

The participants were instructed to relax their bodies and let the passive movements from the non-controlled arm guide their body movements while observing the movement of the virtual hand in the Tied condition. In both the Tied and Separated conditions, both participants were awarded points during the reaching task as a team (0 points if the response time was longer than 1.5 seconds, in other cases, if the target error was less than 3 cm: 30 points, if the target error more than 3 cm but less than 10 cm: 15 points). The total score was displayed on the wall in front of the avatar and each time the target was reached, the number of points gained was announced through the headphones of the HMDs of both participants using pre-recorded voice recordings (e.g.- “zero”, “thirty” etc.). This was done to motivate the participants to work as a team and perform the reaching as quickly as possible with little reaching errors.

In between the two sessions, we gave the participants a break of 30 minutes. At the end of the session, the participants were asked to answer a questionnaire regarding how they felt about the left and right hands of the joint virtual avatar during the reaching task. The questionnaire consisted of 8 items, 4 regarding the left hand and 4 regarding the right hand. Participants answered all the questions.

Q1. I felt as if the virtual left hand I saw was my left hand
Q2. It felt as if the virtual left hand I saw was someone else
Q3. It felt like I could control the virtual left hand as if it were my own left hand
Q4. I felt as if the virtual left hand was moving by itself
Q5. I felt as if the virtual right hand I saw was my right hand
Q6. It felt as if the virtual right hand I saw was someone else
Q7. It felt like I could control the virtual right hand as if it were my own right hand
Q8. I felt as if the virtual right hand was moving by itself

Questionnaire answers were performed in a 7-point Likert scale from -3 to +3 where -3 meant “Strongly disagree” and +3 meant “Strongly agree”.

5.3 Experiment 2: Results

Sense of body ownership towards the non-controlled arm became less negative in Tied condition over Separated condition

The questionnaire at the end of each session consisted of 8 questions, 4 regarding the left hand and 4 regarding the right hand. Participants answered all the questions (Q1. I felt as if the virtual left hand I saw was my left hand, Q2. It felt as if the virtual left hand I saw was someone else, Q3. It felt like I could control the virtual left hand as if it were my own left hand, Q4. I felt as if the virtual left hand was moving by itself, Q5. I felt as if the virtual right hand I saw was my right hand, Q6. It felt as if the virtual right hand I saw was someone else, Q7. It felt like I could control the virtual right hand as if it were my own right hand, Q8. I felt as if the virtual right hand was moving by itself). Questionnaire answers were conducted in a 7-point Likert scale from -3 to +3 where -3 meant "Strongly disagree" and +3 meant "Strongly agree".

Using the answers to the questionnaires, senses of ownership and agency towards left and right sides of the joint virtual avatar were calculated as follows referring to (Gonzalez-Franco & Peck, 2018).

Sense of body ownership towards the left side = Q1 – Q2
Sense of agency towards the left side = Q3 – Q4
Sense of body ownership towards the right side = Q5 – Q6
Sense of agency towards the right side = Q7 – Q8

The results were grouped for the 'controlled arm' (sense of ownership or agency towards the side a participant controlled) and 'non-controlled arm' (sense of ownership or agency towards the side that was not controlled by the individual). Fig. 13 and 14 summarize the results of the questionnaires.

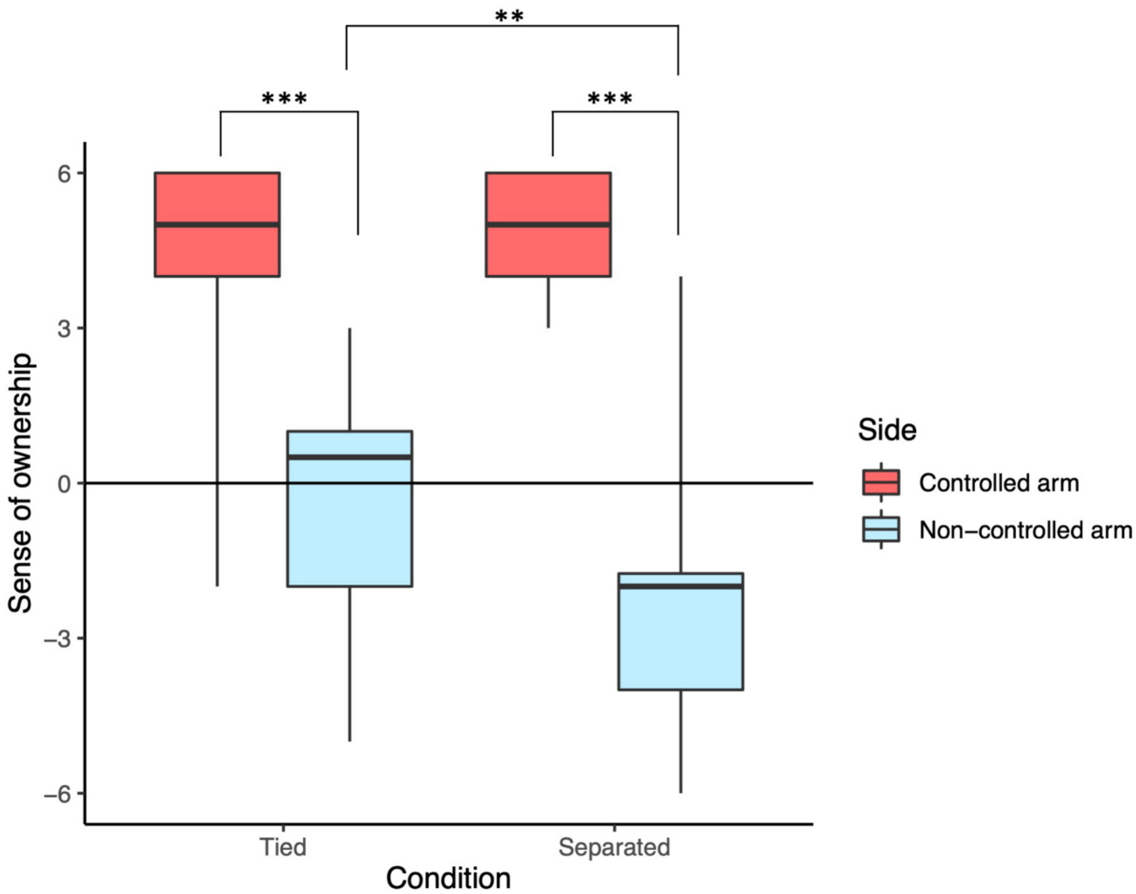

Figure 13: Sense of body ownership results

We calculated the sense of body ownership towards the controlled and non-controlled arms of the virtual joint avatar in the Tied and Separated conditions (Fig. 13). A two-way repeated measures ANOVA with ART (aligned rank transformation) procedure (Wobbrock et al., 2011) was conducted since the data significantly deviated from normality according to the results of Shapiro-Wilk tests (controlled arm for Tied: W = 0.718, p < 0.001, non-controlled arm for Tied: W = 0.927, p = 0.085, Controlled arm for Separated: W = 0.851, p = 0.002, non-controlled arm for Separated: W = 0.892, p η_p^2=0.015). There was a significant interaction between the condition and the arm (F(1,23) = 28.457, p < 0.001, η_p^2 = 0.55). Simple main effects analysis showed that the ownership for the non-controlled arm in the Tied condition was significantly higher than the ownership for the non-controlled arm in the Separated condition (F(1,23) = 11.837, p = 0.002, η_p^2 = 0.34). In both Tied and Separated conditions, the ownership for the controlled arm was higher than the ownership for the non-controlled arm (Tied: F(1,23) = 108.62, p < 0.001, = 0.825, Separated: F(1,23) = 111.3, p < 0.001, η_p^2= 0.829).

Sense of agency towards the non-controlled arm became less negative in Tied condition over Separated condition

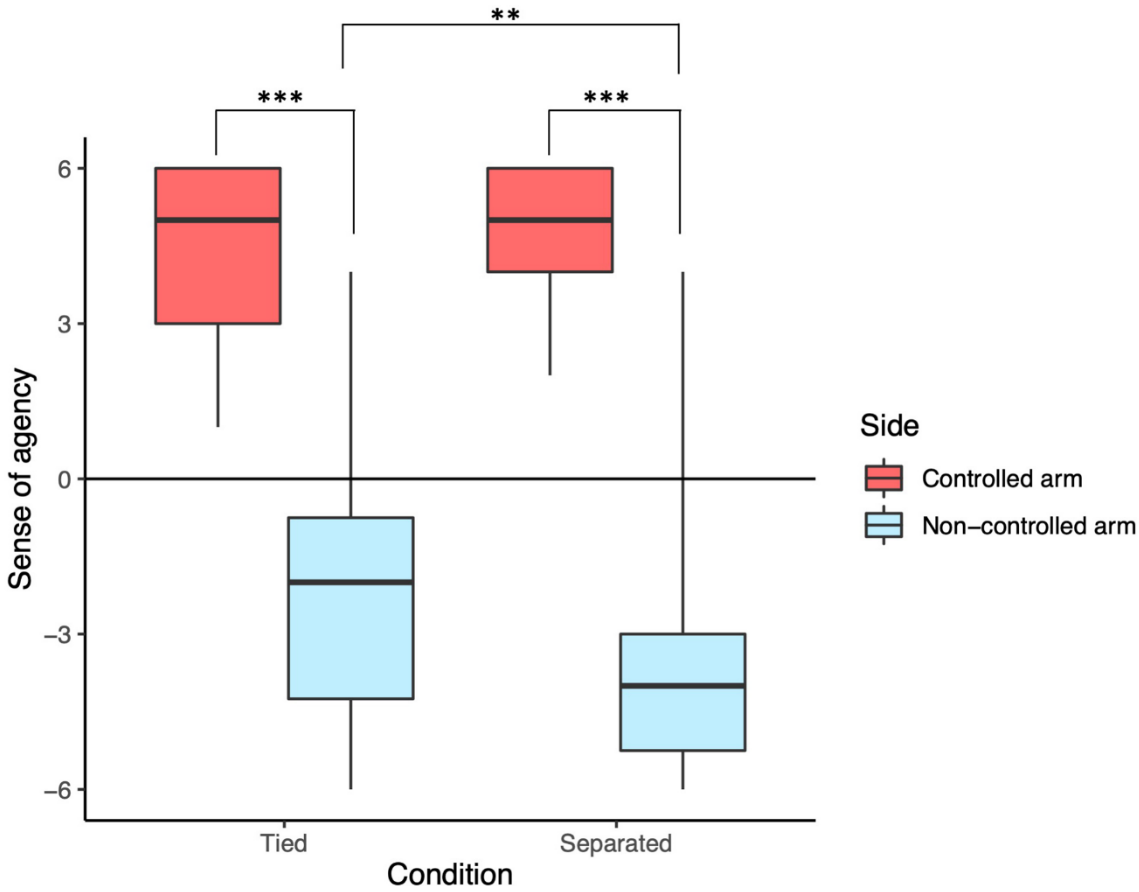

Figure 14: Sense of agency results

We calculated the sense of agency towards the controlled and non-controlled arms of the virtual avatar in the Tied and Separated conditions (Fig. 14). A two-way repeated measures ANOVA with ART (aligned rank transformation) procedure (Wobbrock et al., 2011) was conducted since the data significantly deviated from normality according to the results of Shapiro-Wilk tests (controlled arm for Tied: $W = 0.829$, $p < 0.001$, non-controlled arm for Tied: $W = 0.942$, $p = 0.183$, Controlled arm for Separated: $W = 0.890$, $p = 0.013$, non-controlled arm for Separated: $W = 0.793$, $p < 0.001$). There was a significant interaction between the condition and the side ($F(1,23) = 13.095$, $p = 0.0014$, $\eta_p^2 = 0.363$). Simple main effects analysis showed that the agency for the non-controlled arm in the Tied condition was significantly higher than the agency for the non-controlled arm in the Separated condition ($F(1,23) = 16.512$, $p < 0.001$, $\eta_p^2 = 0.418$). In both Tied and Separated conditions, the agency for the controlled arm was higher than the agency for the non-controlled arm (Tied: $F(1,23) = 106.94$, $p < 0.001$, $=$ 0.823, Separated: $F(1,23) = 121.76$, $p < 0.001$, $\eta_p^2 = 0.841$).

Proprioceptive drift towards the non-controlled shoulder occurred only after the Tied condition

In this experiment, we conducted three behavioral tests to quantify possible changes in the body representation that may accompany the sense of ownership towards the joint avatar. These tests were concentrated on testing the participant's spatial perception of their shoulder above the non-controlled arm (non-controlled shoulder), which was purposely shown displaced by 10 cm (away from the head, and along the axis of the participant's shoulder) from the actual location of the participant's shoulder. We hypothesized the spatial perception of the non-controlled shoulder by the participants to be affected differently in the Tied and Separated conditions. The three tests (see Fig. 15) were carried out to test the perceived position of the real shoulder of the non-controlled side using a pointer in test 1, perceived real shoulder width in test 2, and perceived position of the real non-controlled side shoulder pointed with the real controlled arm in test 3.

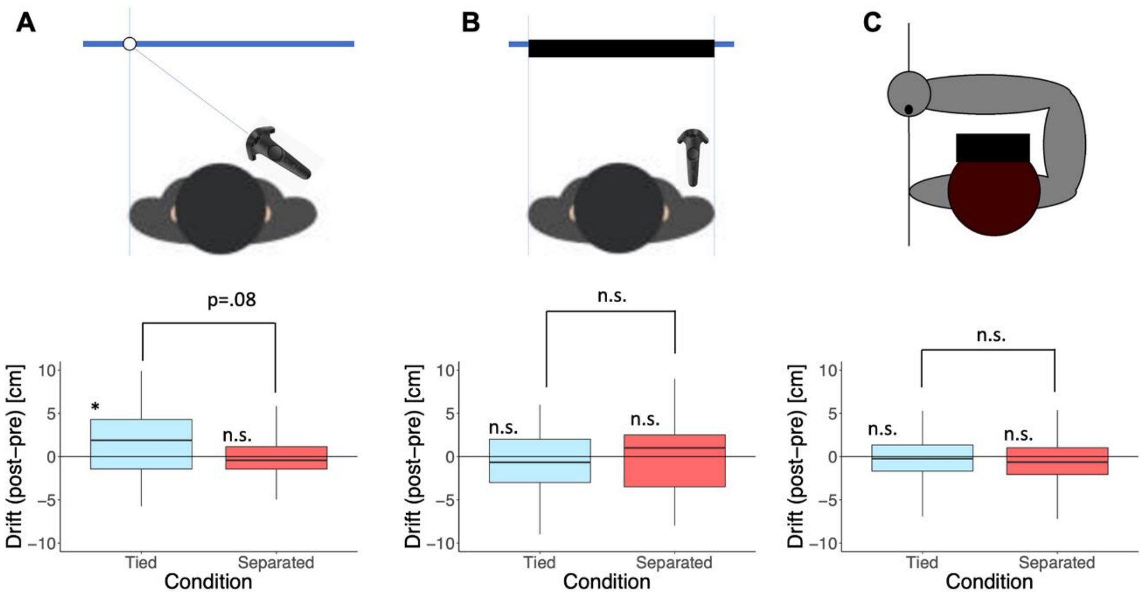

Figure 15: Behavioral test results

The pointed virtual shoulder position drifted significantly larger than 0, while the mean in the Separated condition was not significantly different from 0, suggesting that there was a drift towards the virtual shoulder position only after the Tied condition. However, the difference in drift between the two conditions did not reach significance. No significant changes were observed in (B) Test 2, and (C) Test 3.

Fig. 15 shows the results of the three tests in the pre and post tasks that were carried out to measure the drifts in proprioception after experiencing the reaching task with a non-controlled shoulder drift of 10 cm towards the outer side of the body. In Fig. 15, positive values indicate a higher drift towards the virtual avatar's shoulder position in the post-test than in the pre-test.

Since Shapiro-Wilk tests showed that the Separated condition deviated from normality (Tied: W = 0.976, p = 0.808, Separated: W = 0.885, p = 0.011), Wilcoxon signed rank tests were performed for the data of Test 1. Wilcoxon signed rank test showed that the difference in drifts in the post and pre-tests towards the virtual shoulder position was nearly significantly higher in the Tied condition compared to that in the Separated condition (W(23) = 200.000, p = 0.080, effect size r = 0.333). One sample tests (Student t-test for Tied and Wilcoxon signed rank test for Separated) showed that the mean in the Tied condition was significantly larger than 0 while the mean in the Separated condition was not significantly different from 0 (Tied: t(23) = 2.134, p = 0.022, d = 0.436, Separated: W(23) = 130.000, p = 0.584, effect size r = -0.133), meaning that there was a drift towards the virtual shoulder position only after the Tied condition.

Results of Test 2 showed a normal distribution (Tied: W = 0.966, p = 0.342, Separated: W = 0.970, p = 0.671; Shapiro Wilk test). A paired samples t-test showed that the difference in drifts in the post and pre-tests towards the virtual shoulder position was not significantly different in the Tied condition compared to that in the Separated condition (t(23) = -0.303, p = 0.765, d = -0.062; Fig. 15B). One sample t-tests showed that the means of both conditions were not significantly different from 0 (Tied: t(23) = -1.016, p = 0.32, d = -0.207, Separated: t(23) = -0.417, p = 0.681, d = -0.085).

Results of Test 3 also showed a normal distribution (Tied: W = 0.982, p = 0.927, Separated: W = 0.988, p = 0.991; Shapiro Wilk test). A paired samples t-test showed that the difference in drifts in the post and pre-tests towards the virtual shoulder position was not significantly different in the Tied condition compared to that in the Separated condition (t(23) = 0.100, p = 0.921, d = 0.020; Fig. 15C). One sample t-tests showed that the means of both conditions were not significantly different from 0 (Tied: t(23) = -0.746, p = 0.463, d = -0.152, Separated: t(23) = -0.843, p = 0.408, d = -0.172).

5.4 Discussion

Summary of results

In this study, we investigated whether just the upper-body movements induced by the movements of a virtual arm controlled by another, can affect/enhance embodiment towards it. We developed a joint avatar for this investigation, in which the left and right-limbs were controlled by two different individuals. We compared the senses of body ownership and agency towards the two arms (the controlled arm and the non-controlled arm) of the joint virtual avatar under Tied (with connection induced synchronized upper body movements) and Separated (without passive synchronized upper body movements) conditions. The results showed that the sense of body ownership towards the non-controlled arm was significantly less negative when the participants were provided connection induced upper body movements synchronized with the movements of the partner-controlled arm during the reaching task compared to when they were not provided any passive movements. Furthermore, the sense of agency towards the non-controlled arm was also less negative when passive synchronized upper body movements were present. Thus, H1 was supported, but the effects of passive synchronized upper body movements or connection force were not large and limited.

Proprioceptive drift towards the virtual partner-controlled arm in Test 1

To quantify the sense of ownership and agency during co-embodiment, in addition to questionnaires, we utilized three behavioral tests where we tried to measure possible changes in the body representation in the participants when they embodied the joint avatar. Tests 1 and 2 are related to body image since these tests quantified the participant's perception of their body (specifically location and width of the shoulder in our case) in the visual space. On the other hand, our Test 3 tried to analyze changes in body schema, which refers to the internal (non-visual) representation of one's body in the proprioceptive and haptic space. In Test 3, participants had their HMDs blacked out (similar to eyes closed) and they used their sensory-motor function of the controlled side arm to point at the shoulder position making test 3 related to body schema. We conducted three types of tests to ensure no changes in body representation goes unobserved due to possible limitations of any one of the tests. While we could observe tendencies of changes in the localization of the non-controlled shoulder in Test 1 (in which the localization was done with a pointer), the difference between the tied and separated conditions was not significant. Thus, H2 was partly supported, but we need further discussion and future investigation. Proprioceptive drifts are known to occur in both active (participant moves the rubber hand) and passive (experimenter simultaneously moves the rubber hand and the participant's corresponding hand) rubber hand illusions (in the spatially congruent condition of Kalckert & Ehrsson (2012) (Kalckert & Ehrsson, 2012), suggesting that similar levels of ownership are induced regardless of whether the movements were active or passive when the rubber hand is presented in an anatomically congruent posture (Kalckert & Ehrsson, 2012). The proprioceptive drift of the non-controlled limb in the Tied condition of Test 1 in our experiment is somewhat consistent with this and interestingly suggests that a certain level of ownership can be induced to limbs even by passive synchronous movements of the upper body (instead of the limb itself).

Inconclusive results from Test 2 and Test 3

However, we did not observe any body-representation changes in Test 2 (localization of the shoulder width) and Test 3 (localization of non-controlled shoulder with the controlled hand). Thus, the results of the behavioral tests were not conclusive. This may be due to a several reasons. First, the passive upper body movements were not natural enough. While our back brace setup could provide appreciable passive movement, it had its limitations. The brace provides a forward push on the non-controlled shoulder and a backward pull on the controlled shoulder creating an overall rotational movement of the upper body. This is different from the pure forward pull that would be expected on the non-controlled shoulder if the non-controlled arm was really fixed to one's body. Furthermore, while we tried to strategically place the targets so that the participants had to twist their bodies (and hence provide a force and upper body postural feedback to their partner) to reach them, we observed that some participants could still reach some targets without much movement of the upper body. We speculate these limitations in the setup limited the induced sense of ownership in our experiment. To test this speculation, using the body position data of participants recorded during the reaching task, we calculated the distances moved by the real shoulder of participants in the non-controlled side each time the partner performed the reaching in the Tied condition. The average movement of the shoulder (how much the shoulder was pushed by the partner in average) for all participants was calculated and we checked the correlation of this variable with ownership of the non-controlled arm, agency of the non-controlled arm, and drifts in tests 1, 2, and 3 in the tied condition. However, no correlations were seen (Ownership: $r(22)=0.095$, $p=0.330$, Agency: $r(22)=0.057$, $p=0.396$, Test 1: $r(22)=-0.126$, $p=0.724$, Test 2: $r(22)=0.275$, $p=0.097$, Test 3: $r(22)=-0.268$, $p=0.898$). Therefore, this exploratory correlation analysis between the amount of movement and the subjective/behavioral results does not support our speculation. The second reason for insignificant results in tests 2 and 3 maybe the fact that we used the same order of tests; All participants did Test 1 first, followed by Test 2 and Test 3, with each test taking a few minutes, and (related to the first reason) possible changes in body representation probably decreased over time. And finally, in Test 3, our measure of participant shoulder localization may have been affected by the possible uncertainties participants had regarding the marker (that they point to with their controlled arm) position on their shoulder. Overall, these observations suggest that the use of better tests may be required to measure change of body representation due to embodiment of joint avatars.

Comparison with previous work

Previous studies have shown the requirement of multi-sensory stimulation and/or agency to be a key 'bottom up' requirement for the sense of ownership (Ehrsson et al., 2004; Tsakiris & Haggard, 2005). Popularly these studies have utilized visuo-haptic or visuo-proprioceptive stimulation that are spatially coincident in the vision space (Botvinick & Cohen, 1998; Dummer et al., 2009; Kalckert & Ehrsson, 2014). That is, the haptic or proprioceptive sensation comes from the arm you are observing. We believe that this is very different from the feedback in the present study. This is because the passive movement is felt not on the embodied limb but on the shoulders or upper body. Even though the passive movement is already known to induce ownership of artificial limbs (Walsh et al., 2011; Kalckert & Ehrsson, 2014; Kalckert and Ehrsson, 2012), in those previous studies the experimenter has passively moved an artificial finger connected to the real finger of the participant and shown that it induces ownership towards the artificial finger. The sense of agency towards the passively moved finger was less negative when the actual hand and the rubber hand were placed anatomically congruent than when they were incongruent (Kalckert & Ehrsson, 2012). If we match these to our experiment, it will be similar to a scenario where the real arm of the participant in the non-controlled side is passively moved (by the partner or the experimenter) along with the virtual limb. However, instead here we provide the participants with only the connection induced movements and forces on their shoulder and upper body. Therefore, our study focuses on passive movement of the upper body (or the place where the virtual limb is supposed to join the body) as a result of limb movements by the partner. This result has important ramifications for the understanding limb embodiment, as it suggests physical connection and/or postural change of upper body as a factor affecting the senses of ownership and agency. Our results can provide new insights into the perception of prosthetic limbs or robotics supernumerary limbs that are physically attached to a user's body, even in the absence of controllability and sensory feedback, or even when the device is passive.

Previous research has shown that verbal information previewing movements of another's arms placed to seem like a person's own arms can induce vicarious agency to those arms (Wegner et al., 2004). While it is possible that the passive upper body movements conveyed cues previewing the movements of the partner's arm to some degree, the verbal information previewing movement is more cognitive and detailed (for example, "wave hello with your right hand") compared to the passive upper body movements in our study that informs only the movement timing, direction, and force. Furthermore, the targets reached by the partner were invisible to participants in our experiment making it harder to guess exactly where in space the partner-controlled arm would move. Therefore, influence from previewing information regarding the arm movements was controlled as possible in our experiment. If previewing verbal information about arm movements are also provided along with the passive upper body movements we can expect an even higher score for sense of agency for partner-controlled limbs. This has to be explored in future studies.

Higher-order cognitive comparisons

Since the differences between Tied and Separated conditions are clearly recognizable to the participants, one may argue that the differences of the sense of ownership and agency between these conditions could be caused by higher-order cognitive comparisons and not by the difference of perceptual embodiment itself. If so, the effect of the order would be large. To test this possibility, we performed an exploratory analysis separating the data into two different ordered groups and compared them. If the comparison between the conditions as a between participant design showed a difference irrespective of the first or second session, it supports that the significant difference between conditions found in this study were caused by the strength of the sense of ownership and agency themselves and not by the relative difference by some higher-order cognitive judgment. On the other hand, if there was no effect in the first half session and a clear effect in the latter half, the significant difference may possibly be caused by cognitive comparisons. We performed a mixed-design three-way ANOVA-ART (Wobbrock et al., 2011) with the condition order (ST: Separated condition first, Tied condition second, TS: Tied condition first, Separated condition second) as a between-subject variable, the condition (Separated condition, Tied condition) as a within-subject variable, and the side (Controlled arm, Non-controlled arm) as a within-subject variable for both the senses of ownership and agency. For the sense of ownership, we found main effects of the condition ($F(1,22)=10.015$, $p=0.004$, $\eta_p^2=0.315$) and the side ($F(1,22)=131.71$, $p<0.0001$, $\eta_p^2=0.857$), and an interaction between the condition and the side ($F(1,22)=26.605$, $p<0.0001$, $\eta_p^2=0.507$), consistent with the original 2-way ANOVA. We did not find a 3-way interaction between condition, side and order ($F(1,22)=0.277$, $p=0.604$, $\eta_p^2=0.012$), suggesting that the condition order did not affect the ownership towards the non-controlled arm in the Tied condition over the Separated condition. We found an interaction between the order and condition ($F(1,22)=6.91$, $p=0.015$, $\eta_p^2=0.239$). However, no simple effects were significant, and the difference between Tied and Separated conditions was larger when the Separated condition was performed first than when the Tied condition was performed first (ST: $F(1,35)=2.339$, $p=0.135$, $\eta_p^2=0.063$, TS: $F(1,35)=0.115$, $p=0.736$, $\eta_p^2=0.003$). For the sense of agency, we found main effects of the condition ($F(1,22)=10.537$, $p=0.004$, $\eta_p^2=0.324$) and the side ($F(1,22)=134.37$, $p<0.0001$, $\eta_p^2=0.859$), and an interaction between the condition and the side ($F(1,22)=16.343$, $p=0.0005$, $\eta_p^2=0.426$), consistent with the original 2-way ANOVA. We did not find a 3-way interaction between condition, side and order ($F(1,22)=0.331$, $p=0.571$, $\eta_p^2=0.015$), suggesting that the condition order would not affect the agency towards the non-controlled arm in the Tied condition over the Separated condition. We did not find any other effects.

To test the effect of order further in detail, we separated the data into the first session and the second session (accordingly the force condition (Tied/separated) is between-subject in this analysis) and performed another exploratory analysis. We performed a mixed-design two-way ANOVA-ART with the condition (Separated condition, Tied condition) as a between-subject factor, and the side (Controlled arm, Non-controlled arm) as a within-subject factor for both senses of ownership and agency. Analyses were performed separately for the first session and the second session. For the sense of ownership, we found a main effect of the side ($F(1,22)=99.33$, $p<0.0001$, $\eta_p^2=0.819$) and an interaction between condition and side ($F(1,22)=4.833$, $p=0.0387$, $\eta_p^2=0.180$) for the first session, similar to the original analysis. However, the simple effect analysis showed that the condition effect on the sense of ownership towards the non-controlled arm in the Tied condition compared to the Separated condition was not significant (F(1,22)=2.490, p=0.129, η_p^2=0.102). This may be due to the data division. In the second session, we obtained main effects of condition (F(1,22)=5.350, p=0.030, η_p^2=0.196) and side (F(1,22)=89.037, p<0.0001, η_p^2=0.802), but the interaction between condition and side was not significant (F(1,22)=3.912, p=0.0606, η_p^2=0.151) for the second session. For the sense of agency, we found a main effect of the side (F(1,22)=116.49, p<0.0001, η_p^2=0.841), but the interaction between condition and side was not significant (F(1,22)=2.680, p=0.1159, η_p^2=0.109) for the first session. In the second session, we obtained main effects of condition (F(1,22)=5.433, p=0.0293, η_p^2=0.198) and side (F(1,22)=99.766, p<0.0001, η_p^2=0.819), but the interaction between condition and side was not significant (F(1,22)=3.278, p=0.0839, η_p^2=0.130) for the second session. To summarize, we cannot conclude that the effect of order never affects the results. However, the results cannot be solely explained by the higher-order cognitive bias because the effect of order was small, and the interaction between the condition and side was significant in the first session, where participants did not know both Separated and Tied conditions.

Chapter 6

Virtual co-embodiment with machines

6.1 Introduction

While prosthesis use is seen necessary by many for restoration of near-normal appearance, and functional independence, the embodied experience of prosthesis use is little explored. On the other hand, Virtual Reality (VR) has been widely used for measuring the Sense of Embodiment (SoE) associated with various virtual bodies (Kilteni et al., 2012). First-person view experiences with high-resolution head-mounted displays and full body motion capture in real-time can simulate highly immersive virtual experiences where participants can move their avatars in virtual environments the way they move their real bodies. Here, we propose using such technology to study user perception to gain insights into developing autonomous prosthetic limbs with a high sense of embodiment and usability with minimum discomfort. VR studies have shown that knowing the intention behind autonomous movements (Hapuarachchi & Kitazaki, 2022; Wegner et al., 2004), and synchronous force feedback applied to the body (Hapuarachchi et al., 2023) can induce a certain amount of embodiment even towards limbs that move by themselves. Studies on the perception of robots show that social attributes towards robots can change depending on their movement speeds (Pan et al., 2019). Here, we investigated how the movement speed of an autonomous prosthetic limb affects its SoE as well as the usability, and other social attributes adopted from previous studies (Pan et al., 2019).

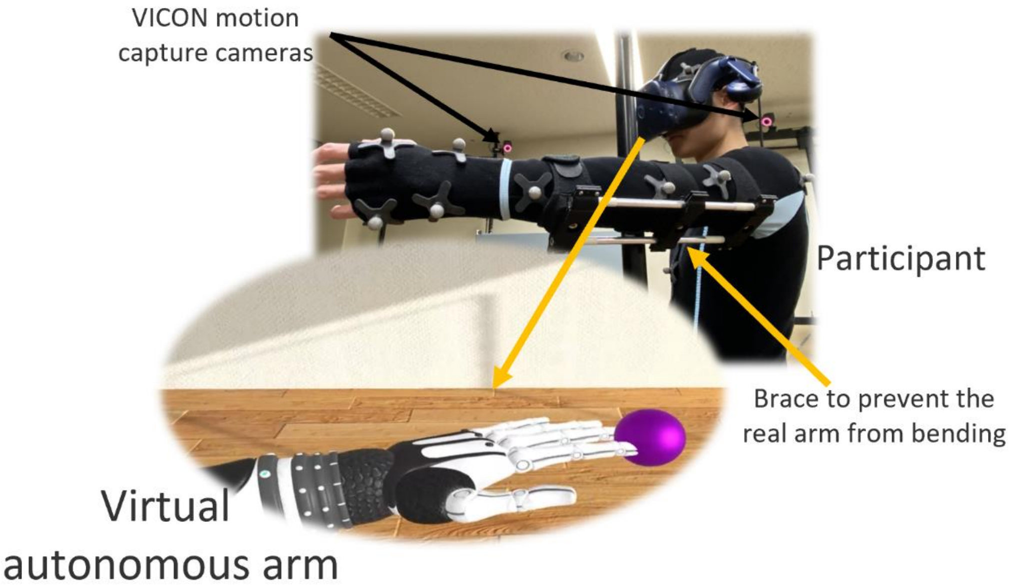

Figure 16: Experiment setup

6.2 Experiment 3: Methods

Participants

Nineteen male university students (mean age 24.15, SD 2.61) with normal or corrected-to-normal eyesight participated in the experiment. Participants were recruited from the university and were naïve with respect to the purpose of the experiment and had normal or corrected-to-normal vision. All volunteers provided written informed consent before the experiment. This study was approved by the Ethical Committee on Human-Subject Studies of Toyohashi University of Technology, and all methods were carried out in accordance with the relevant guidelines and regulations. The sample size was determined by a power analysis with an effect size (f) of 0.25 (medium), an alpha of 0.05, and power of 0.80 using G*Power 3.1 (Faul et al., 2007; Faul 2009).

Apparatus

The movements of the participants were measured with a motion capture system consisting of 12 VICON Bonita 10 Cameras, at 250 Hz. The virtual environment and experiment task were created using Unity 2021.3.8f1 and displayed through a high-resolution head-mounted display (Varjo Aero: 2880 x 2720 pixels per eye, at a 90 Hz refresh rate). A solid brace was attached to the left arm of the participants as shown in Fig. 16 to prevent them from bending the arm from the elbow joint during the experiment task.

Stimuli and conditions

A male avatar with a left lower arm amputation was rendered in a virtual room as shown in Fig. 17. The participants could control in first-person perspective, the full body of their avatar other than the amputated lower arm.

Figure 17: Virtual avatar amputated with the autonomous prosthesis

When the elbow was moved by the participant towards the target (a sphere with a 5 cm diameter), the prosthetic arm autonomously bent in a minimum jerk trajectory calculated using previous work (Flash & Hogan, 1985) as shown in equation (1) when the participant moved the elbow of the autonomous prosthetic arm towards the target and the distance between the elbow and the target was less than the length of the lower arm (from elbow to fingertip of the middle finger). We differentiated (1) to calculate the velocity of the fingertip of the autonomous prosthetic arm and calculated the angle bent per frame $d\theta$ by the autonomous arm from the elbow joint to move it in the virtual environment.

$$x(t) = x_i + (x_f - x_i)\left\{10\left(\frac{t}{d}\right)^3 - 15\left(\frac{t}{d}\right)^4 + 6\left(\frac{t}{d}\right)^5\right\} \quad (1)$$

$$\dot{x}(t) = \frac{30(x_f - x_i)t^2}{d^3}\left(1 - \frac{2t}{d} + \frac{t^2}{d^2}\right) \quad (2)$$

Here,

x_i: Initial position of fingertip

x_f: Final position of fingertip (position of the target)

t: time since the beginning of autonomous movement

d: time taken to move from x_i to x_f

$x(t)$: Displacement of fingertip

$\dot{x}(t)$: Velocity of fingertip

Equation (3) shows the derived equation to calculate $d\theta$, the angle bent by the virtual arm per frame in degrees so that the fingertip of the arm travels in a minimum jerk trajectory as shown in Fig. 19. Here θ (as shown in Fig. 18) is calculated as the angle between the two vectors $pos_{elbow} - pos_{shoulder}$ and $pos_{target} - pos_{elbow}$ at the first frame the distance between the elbow and the target becomes less than the length of the lower arm.

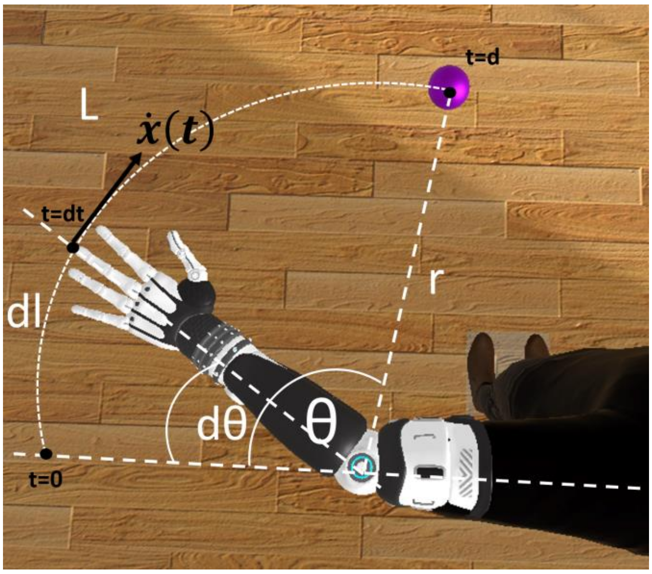

Figure 18: Movement trajectory of the autonomous arm

$$d\theta = 180dt \cdot \frac{30r\theta t^2}{d^3}\left(1 - \frac{2t}{d} + \frac{t^2}{d^2}\right)/\pi r \quad (3)$$

Here,

$d\theta$: angle bent from the elbow joint per frame

dt: time between two frames (for this experiment, $dt = 0.02$ s)

θ: Angle between the lines joining the target and initial fingertip position to the elbow

t: time since the beginning of autonomous movement

d: time taken to move from x_i to x_f

r: *distance from elbow joint to the fingertip*

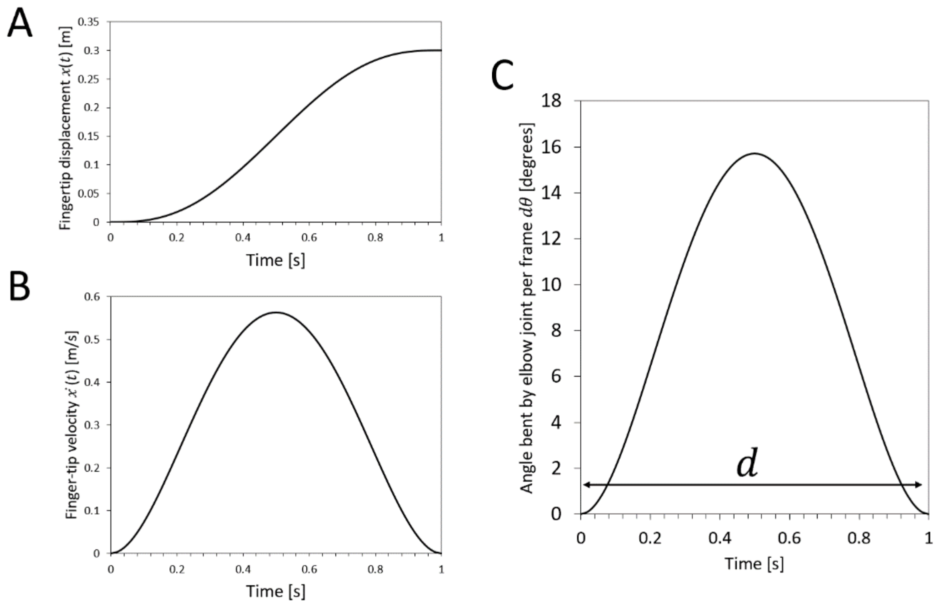

Figure 19: Minimum jerk trajectory when fingertip moves 30 cm in 1 s

The targets were erased 1 s after they were reached by the tip of the middle finger of the autonomous arm and the arm returned back to the original position in the same minimum jerk trajectory. A solid pole was set in front of the participant in the real room as well as in front of the avatar in the virtual room at the same overlapping positions and targets appeared towards the right side of the avatar at random positions to make the participants use the bending feature of the autonomous arm (without reaching with a stretched, unbent arm). The time taken by the autonomous arm to bend towards the target in a minimum jerk trajectory was chosen as the independent variable of the experiment. Therefore, the experiment consisted of six conditions where the motion time was set to be 125 ms, 250 ms, 500 ms, 1 s, 2 s, and 4 s.

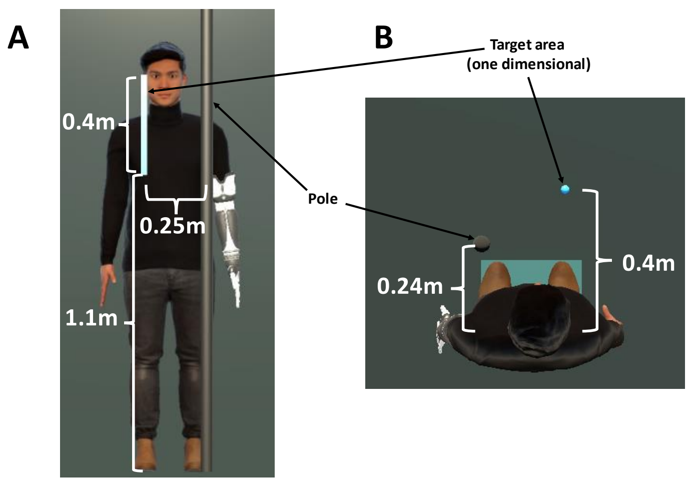

Figure 20: Target area for the reaching task

Procedure

The participants wore motion capture suits, HMD, and a solid brace on the left arm and performed the reaching task in the virtual environment. Each session consisted of 15 target reaches and they were asked to reach the targets as quickly as possible. The targets appeared in front of the avatar in random positions inside a fixed one-dimensional line shown in Fig. 20. Each participant performed 12 sessions in a randomized order that included two repetitions of each condition. After each session, the participants answered a questionnaire. The questionnaire items were presented in a randomized order and were adopted from previous studies on embodiment, system usability scale (Brooke, 1996), and Robotic Social Attributes Scale (RoSAS) (Carpinella et al., 2017).Table 2 and table 3 show the embodiment and SUS items respectively for our study. Embodiment question items were answered in a 7-point Lickert scale, SUS items in a 5-point Lickert scale. Table 4 shows the components of RoSAS. Participants rated each item of RoSAS on a 9-point scale.

Table 2: Embodiment questionnaire

Q1	The movements of the virtual prosthetic arm seemed to be my movements
Q2	I felt as if the virtual prosthetic arm I saw was my own left arm

Sense of agency towards the autonomous arm = Q1

Sense of ownership towards the autonomous arm = Q2

Table 3: SUS Questionnaire

Q1	I think that I would like to use this prosthetic arm frequently.
Q2	I found the prosthetic arm unnecessarily complex.
Q3	I thought the prosthetic arm was easy to use.
Q4	I think that I would need the support of a technical person to be able to use this prosthetic arm.
Q5	I found the various functions in this prosthetic arm were well integrated.
Q6	I thought there was too much inconsistency in this prosthetic arm.
Q7	I would imagine that most people would learn to use this prosthetic arm very quickly.
Q8	I found the prosthetic arm very cumbersome to use.
Q9	I felt very confident using the prosthetic arm.
Q10	I need to learn a lot of things before I could get going with this prosthetic arm.

Table 4: RoSAS components

Competence	**Warmth**	**Discomfort**
Reliable	Organic	Awkward
Competent	Sociable	Scary
Knowledgeable	Emotional	Strange
Interactive	Compassionate	Awful
Responsive	Happy	Dangerous
Capable	Feeling	Aggressive

SUS score was calculated referring to previous work (Brooke, 1995), and RoSAS was divided into the main components Competence, Warmth, and Discomfort referring previous work (Carpinella et al., 2017).

6.3 Experiment 3: Results

Fig. 21 demonstrates the overall results of the experiment. Friedman tests (due to non-parametric data according to Shapiro-Wilk test results with $p<0.05$) showed that motion time had a significant effect on the sense of agency ($X^2(5)=26.876$, $p=<0.001$), ownership ($X^2(5)=22.634$, $p<0.001$), and discomfort ($X^2(5)=27.104$, $p<0.001$) and it had a nearly significant effect on warmth ($X^2(5)=10.079$, $p=0.073$). One-way repeated measures ANOVA showed that motion time had a significant effect on usability ($F(2.02,36.37)=6.647$, $p=0.003$) and competence ($F(2.03,36.62)=3.916$, $p=0.028$). Post hoc tests showed that agency, ownership, and usability gradually increased as motion time increased from 125 ms to 1 s ($p<0.05$ between motion times 125 ms and 1 s), and gradually decreased from 1 s to 4 s ($p<0.05$ between motion times 1 s and 4 s) and showed no significant difference between 125 ms and 4 s ($p>0.05$). Competence was significantly higher at 1 s compared to 2 s and 4 s but the difference between faster movements (125 ms, 250ms, 500ms) and 1 s were not significant ($p>0.05$). Discomfort gradually decreased from 125 ms to 1 s ($p<0.001$ between 125 ms and 1 s) and gradually increased from 1s to 4 s ($p<0.05$ between 1 s and 4 s). Discomfort at the fastest motion time, 125 ms was significantly higher than discomfort at 4 s ($p<0.01$).

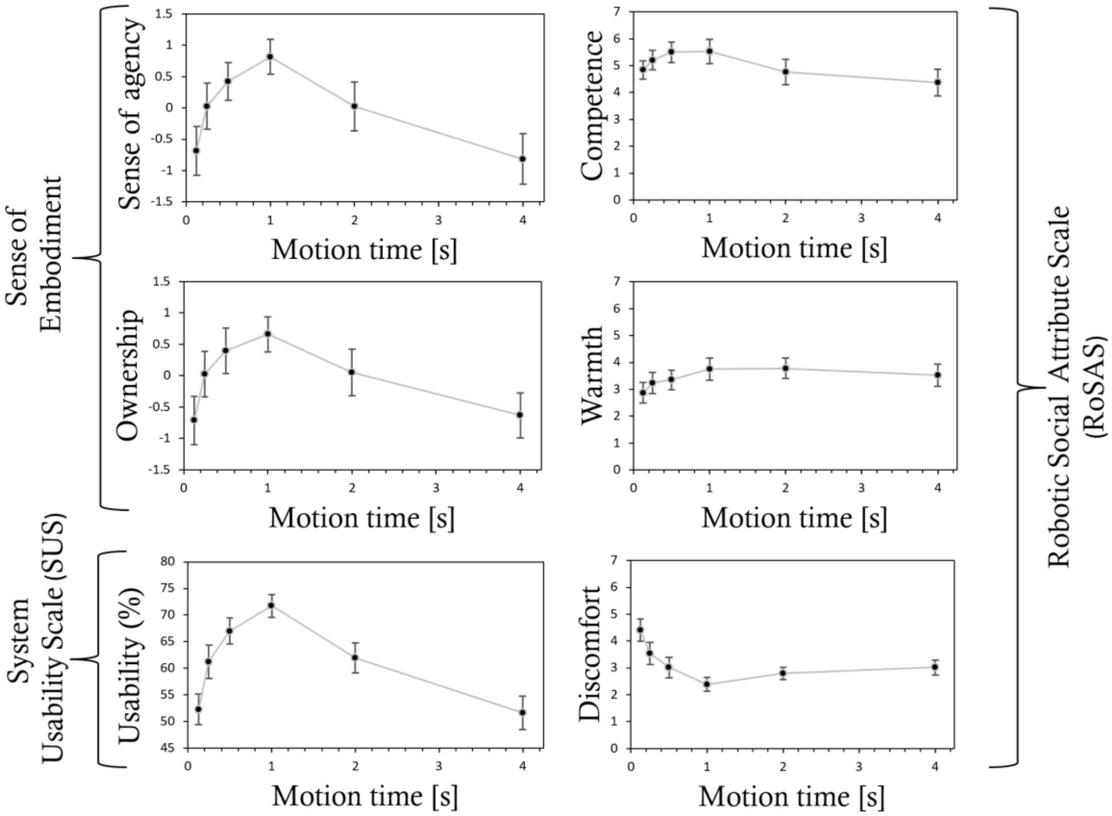

Figure 21: Experiment results of embodiment, SUS and RoSAS

6.4 Discussion

Sense of agency, ownership, and usability changed with motion time in a similar pattern, where it peaked at 1 s and gradually decreased as the movements got faster or slower. Extremely fast movements (motion time 125 ms), as well as extremely slow movements (motion time 4 s), showed similar levels of embodiment and usability. Counter-intuitively to the thought of faster movements showing higher usability, these results show that the level of usability is closely associated with the amount of sense of embodiment and discomfort. Discomfort was lowest when the embodiment peaked (at 1 s), meaning that embodiment negatively affects discomfort associated with autonomous arms. However, competence was not significantly different between moderate and faster movements while slower movements were perceived as less competent. Overall, the results suggest that the movement speed of autonomous limbs affects their embodiment, usability, competence, and discomfort and moderate speeds (motion time 1 s in the current study) tend to show favorable results associated with user perception.

Chapter 7

Virtual embodiment of biomechanically impossible arms

7.1 Introduction

Most previous embodiment studies have investigated the temporal effect of visuomotor synchrony on the sense of embodiment while being limited to the physical constraints of the human body and maintaining the human-like nature of the virtual movements (Gonzalez-Franco et al., 2010; Sanchez-Vives et al., 2010; Weijs et al., 2021). Although temporally synchronous visuomotor stimulations are known to induce a sense of embodiment even towards various types of bodies, such as bodies with different skin colors (Peck et al., 2013), sizes (Banakou et al., 2013), and invisible bodies (Kondo et al., 2018; Kondo et al., 2020a), the movements of the avatars and participants have been spatially congruent in those studies too, where virtual limb positions and orientations spatially coincide with real limb positions and orientations (in synchronous conditions). Here, we were interested in understanding how manipulating the spatial aspects of visuomotor synchrony affects the sense of embodiment.

A previous study on spatially scrambled body parts has shown that spatial alteration of limb positions disrupts full body illusions while maintaining ownership for the scrambled (individual) body parts (Kondo et al., 2020a). However, in the scrambled body experiment by Kondo et al., while the hands and feet were presented in scrambled locations in a virtual environment, the motion directions of the virtual hands and feet were the same as those of the participant (Kondo et al., 2020a). Here, we were interested in understanding how embodiment is affected when movements are altered instead of the positions of the individual limbs. Would temporal visuomotor synchrony induce a sense of embodiment even towards bodies with such biomechanically impossible body movements? And how would temporal synchrony in the absence of spatial synchrony compare to spatial synchrony in the absence of temporal synchrony when it comes to sense of embodiment? To find answers to these questions, in a within-subjects design experiment, we had twenty-four participants perform a reaching task in a virtual environment controlling an avatar that bent the lower arms from the elbow joints in the direction opposite to their real lower arms (see Fig. 22).

We investigated how temporal visuomotor synchrony affects embodiment of such an "unnatural avatar" compared to a "natural avatar" that moved with the unaltered movements of the participant. The experiment consisted of two synchronicity conditions, the "synchronous" condition, where the timing of the virtual movements matched the timing of the real movements, and the "asynchronous" condition, where the virtual movements were delayed for one second from the real movements. Participants performed the reaching task in both synchronous and asynchronous conditions using the unnatural avatar as well as the natural avatar, and we measured their sense of embodiment, and skin conductance in response to a visual stimulus of a knife threatening the lower arms of the avatar at the end of each session (see Fig. 23).Sense of embodiment is known to consist of three subcomponents (Kilteni et al., 2012): the sense of self-location, which is the ability to perceive the location of one's body parts (Blanke & Metzinger, 2009; Lenggenhager et al., 2009), the sense of agency, which is the sense of having control of motion (Blanke & Metzinger, 2009; Haggard, 2005), and the sense of body ownership, which refers to one's self-attribution of the body (Gallagher, 2000). Therefore, to get a broader idea of sense of embodiment, in this study, we measured the sense of agency as well as the sense of body ownership of the participants using questionnaire items based on the avatar embodiment questionnaire by Gonzalez-Franco and Peck (Gonzalez-Franco and Peck, 2018).

Studies on visuomotor adaptation suggest that our brain is highly flexible in integrating visual and motor information to maintain accurate motor outputs (Held, & Hein, 1958; Redding, & Wallace, 1993; Redding, Rossetti, & Wallace, 2005; Krakauer, 2009) and visual stability (Stratton, 1896; Welch, 1969; Becklen, Wallach, & Nitzberg, 1984; Wallach, 1987; Kitazaki, 2013). When the visual feedback of a movement mismatches the proprioceptive feedback, the brain often recalibrates to minimize the discrepancy, leading to a shift in the perceived body ownership towards the visual representation (Synofzik et al., 2006; Synofzik et al., 2008). Studies on virtual co-embodiment also have shown that individuals prioritize the observed movements of their virtual avatar over their own movements even when the actual movement of participant deviates from the avatar's movement (Hagiwara et al., 2020). If the brain prioritizes such visual information over proprioceptive feedback during visuomotor mismatches, such adaptability may also have implications on our perception of body ownership and sense of agency with biomechanically impossible movements. Therefore, we predicted that participants will still adapt to the arms bending in opposite directions and feel a sense of embodiment towards the unnatural avatar in our study, as long as the visual movements temporally match their body movements. Based on our sensitivity to temporal discrepancies in multisensory integration

(Berger et al., 2023), we predicted that temporal visuomotor synchrony will play a more dominant role than spatial synchrony in inducing sense of embodiment. In other words, even if the movements are spatially incongruent, as long as they are temporally synchronous, we predict the participants will experience a sense of embodiment stronger than what they feel with natural movements with a temporal delay. We also hypothesized there to be a significant increase in both sense of agency and sense of body ownership towards the unnatural avatar (as well as towards the natural avatar) in the synchronous condition compared to the asynchronous condition. However due to the mismatches between proprioception and visual feedback while using the unnatural avatar, we hypothesized the sense agency and body ownership scores towards the unnatural avatar to be significantly lower than those towards the natural avatar.

Changes in Skin Conductance in response to threatening stimuli to rubber hands (Armel & Ramachandran, 2003; Honma et al., 2009; Tsuji et al., 2013) as well as virtual avatars (Yuan & Steed, 2010; Petkova & Ehrsson, 2008; Petkova et al., 2011; Hapuarachchi & Kitazaki, 2022) have been measured in embodiment related studies as a physiological measure of body ownership. Following such work, as a measure of sense of body ownership, we measured the physiological response to a threat to the virtual lower arms using Skin Conductance Response (SCR), expecting a higher SCR at experiment conditions that induced a higher sense of body ownership towards the avatar (Fig. 23).

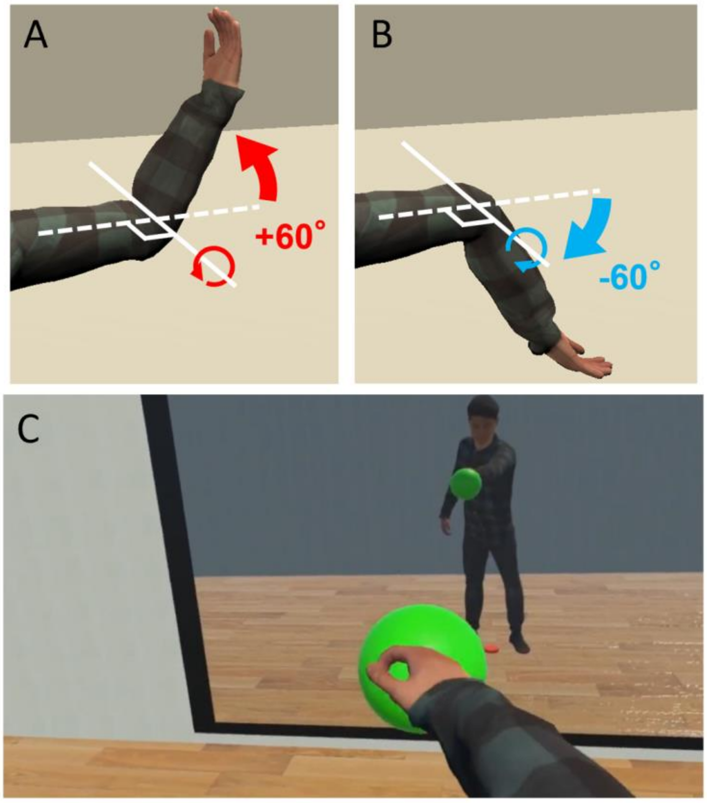

Figure 22: Natural and unnatural avatars and the reaching task

The two types of avatars used in the experiment and the experiment task: (A) Natural avatar: Lower arms of the avatar bent in the same direction as the participant, (B) Unnatural avatar: Lower arms of the avatar bent in the opposite direction of the participant's movement. (C) Experiment task: Participants controlled natural and unnatural avatars in first-person perspective in a virtual environment to perform a reaching task.

Figure 23: Virtual knife stimulus

7.2 Experiment 4: Methods

Participants

Twenty-four university students (all males, mean age 21.2, SD 1.04) participated in the experiment. The sample size was determined by a power analysis with repeated measures ANOVA (4 within factors: 2 × 2 conditions), an effect size (f) of 0.25 (medium), an alpha of 0.05, and power of 0.80, and an expected correlation of 0.5 between repeated measures using G*Power 3.1 (Faul et al., 2007; Faul et al., 2009). All participants had normal or corrected-to-normal eyesight, and the study procedures were designed to minimize disclosure of the experimental hypothesis (participants were not told what the hypotheses or the objectives of the study were). They provided informed consent before the experiment. The methods of the experiment were approved by the Ethical Committee for Human-Subject Research at the Toyohashi University of Technology, and all experiments were carried out in accordance with the relevant guidelines and regulations.

Setup and Apparatus

The movements of each participant were measured by a motion capture system (OptiTrack FLEX 3, 100 Hz). The virtual environment and the avatar were displayed through a head-mounted display (HMD: HTC VIVE Pro Eye, 1440 × 1600 pixels per eye, 90 × 110deg, 90 Hz refresh). The virtual environment and experiment task were created using Unity (2017.3.0f3). Two vibration motors that vibrated at 217 Hz were attached to the two palms of the participants that vibrated each time the corresponding virtual hand of the avatar reached the targets. BIOPAC MP 160 and wireless PPG and EDA amplifiers (BN-PPGED) were used to record the SCR data. A wireless transmitter (BN-PPGED) was placed on each participant's wrist. Two disposable electrodes (EL507) were pasted on the distal phalanges of their middle and ring fingers. Two lead cables (BN-EDALEAD2) connected the wireless transmitter to the electrodes. The SCR data were recorded at 1000 Hz.

Stimuli and Conditions

Participants controlled a male avatar of height 175 cm in a virtual room to perform a reaching task that involved reaching spherical targets of 15 cm diameter. The targets appeared at random positions inside the 3D space shown in Fig. 24. Since the targets appeared randomly around the avatar including the back, we placed a mirror of height 150 cm and width 200 cm, 200 cm in front of the avatar. The mirror was placed to guide the participants to the targets while also allowing them to see a full body reflection of their avatar. The participants were instructed to watch the target directly while reaching instead of only looking through the mirror. The vibration motor on the corresponding palm vibrated for 3 ms on each successful target reach and the target erased. The next target appeared 3 s later. This repeated for 5 min in each session. There were natural and unnatural sessions as well as synchronous and asynchronous sessions for each avatar type. In the natural avatar sessions, the movements of the participants read from motion captures in real time were reflected onto the avatar without any alterations. In the unnatural avatar sessions, the lower arms of the virtual avatar were programmed to bend in reverse directions. In the synchronous sessions, the timing of the movements of the virtual avatar matched the timing of the movements of the participants. In the asynchronous sessions, the movements of the virtual avatar were delayed for a second compared to the movements of the participant. At the end of each reaching task session, a knife appeared in the virtual environment and penetrated the lower arm of the avatar as shown in Fig. 23. HMD was blacked out 10 s after the knife appeared and the session ended.

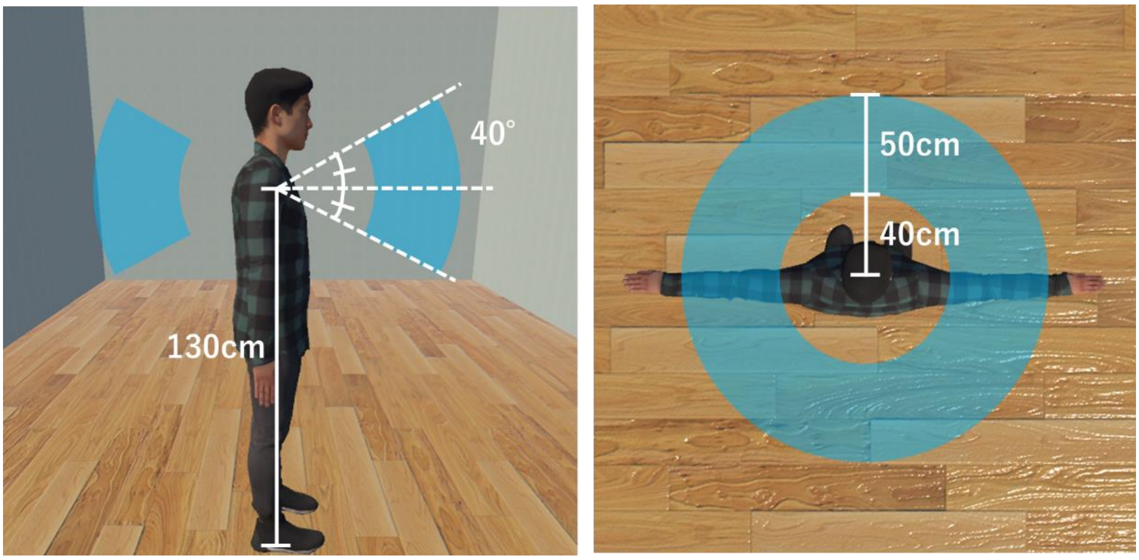

Figure 24: Target areas for the reaching task

Target areas in each condition. The targets appeared at random points inside a ring-like 3-dimensional volume which was a selected section of a sphere that had its center at the center of the avatar, 130 cm above the floor level as shown in blue. The cross section of the selected volume is shown on left (only the volume making an angle of 40° with the floor plane upwards and downwards) and included only the volume ranging from 40 cm to 50 cm radius as shown on right.

Procedure

The experiment consisted of 8 sessions (2 avatar types x 2 synchronicity conditions x 2 repetitions). Each participant performed the experiment on two separate days where they controlled either the natural avatar, or the unnatural avatar only on each day. Half of the participants controlled the natural avatar on their first day while the other half controlled the unnatural avatar on their first day. Synchronous and asynchronous sessions were performed in a randomized order. Participants wore motion capture suits, the HMD, the vibration motors on their palms, and transmitter to measure skin conductance on their wrists (with cables attached to electrodes on their fingers) and performed the reaching task while standing in each session. Skin conductance response was calculated as the difference between the maximum value detected in a 5 s post-stimulus (knife) time window and the baseline calculated as the average value of a 2 s pre-stimulus time window (for both participants in each session). At the end of each session, they answered an embodiment questionnaire. The order of the questions was randomized each time for each participant. Answers were accepted in a 7-point Likert scale from -3 to +3 where -3 meant “Strongly disagree” and +3 meant “Strongly agree”. Questionnaire items were created referring to previous work (Gonzalez-Franco & Peck, 2018) and are shown in table 5. Senses of body ownership and agency were calculated as follows.

Table 5: Questionnaire items

Q1	I felt as if the virtual body I saw was my own body
Q2	I felt as if the virtual body I saw was someone else
Q3	I felt as if the virtual body I saw in the mirror was my own body
Q4	I felt as if the virtual body I saw in the mirror was someone else
Q5	I felt like I could control the virtual body as if it were my body
Q6	I felt like the virtual body was moving by itself

Sense of body ownership = (Q1 - Q2) + (Q3 - Q4)
Sense of agency = Q5 - Q6

7.3 Experiment 4: Results

Senses of body ownership and agency for both avatars were higher in the synchronous condition compared to the asynchronous condition.

Fig. 25 and Fig. 26 summarize the results of the questionnaires. For the questionnaire scores of both body ownership and agency, we first tested if the data violated normality, and then applied non-parametric 2-way ANOVA (2 natural/unnatural x 2 synchronous/asynchronous) if the data deviated from normality. These procedures of analysis were determined before conducting the experiment. The ownership questionnaire (Q1 to Q4) had a Cronbach’s alpha of 0.879 showing a good internal consistency. Negative items Q2, and Q4 of the questionnaire were reversed for the calculation of Cronbach’s alpha.

First, we calculated the sense of body ownership (Fig. 25) towards the two avatars (natural, and unnatural) in the two synchronicity conditions (synchronous, and asynchronous). A two-way repeated measures ANOVA was conducted since the data were normally distributed according to the results of Shapiro-Wilk tests (asynchronous condition of natural avatar: W=0.920, p=0.058, synchronous condition of natural avatar: W=0.929, p=0.095, asynchronous condition of unnatural avatar: W=0.959, p=0.426, synchronous condition of unnatural avatar: W=0.930, p=0.099). There was a significant main effect on the avatar type (F(1,23)=8.876, p=0.007, η_p^2=0.279), a significant main effect on synchronicity (F(1,23)=49.872, p<0.001, η_p^2=0.684), and a significant interaction between the avatar type and synchronicity (F(1,23)=5.833, p=0.024, η_p^2=0.202), and three significant simple main effects were observed. First, the ownership towards the natural avatar was significantly higher in the synchronous condition than in the asynchronous condition (F(1,23)=55.208, p<0.001, η_p^2=0.706). Next, the ownership towards the unnatural avatar was also significantly higher in the synchronous condition than in the asynchronous condition (F(1,23)=25.357, p<0.001, η_p^2=0.524). Lastly, in the synchronous condition, the ownership towards the natural avatar was significantly higher than that towards the unnatural avatar (F(1,23)=12.465, p=0.002, η_p^2=0.352). In the asynchronous conditions, there was no significant difference in ownership between the natural and unnatural avatars (F(1,23)=2.558, p=0.123, η_p^2=0.100). Furthermore, Holm's post-hoc comparisons revealed that the ownership towards the unnatural avatar in the synchronous condition was significantly higher than the ownership towards the natural avatar in the asynchronous condition (t(22)=2.651, p=0.029).

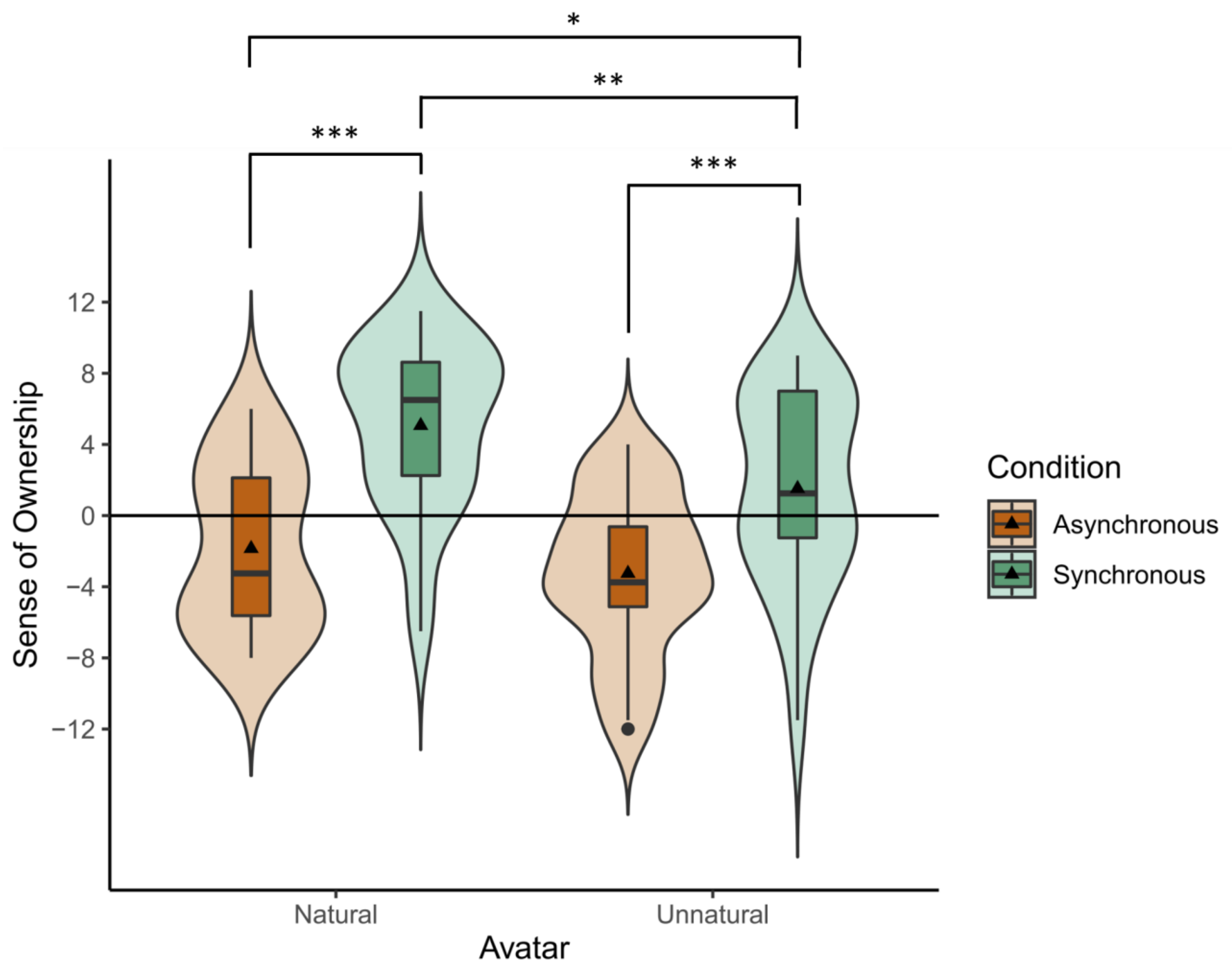

Figure 25: Sense of body ownership results

Sense of body ownership towards natural and unnatural avatars in asynchronous and synchronous conditions. Each box indicates the interquartile range (IQR), the range between 25th and 75th percentiles. The horizontal lines and the solid triangles in the boxes indicate medians and means respectively. The whiskers extend from the hinge to the largest and smallest values no further than 1.5 * IQR from the hinge. Outliers are shown in black dots. Surrounding violin plots depict the kernel density distributions. The ownership towards both avatars were significantly higher in the synchronous condition than in the asynchronous condition. In the synchronous condition, the ownership towards unnatural avatar was lower than that towards the natural avatar.

Next, we calculated the sense of agency (Fig. 26) towards the two avatars (natural, and unnatural) in the two synchronicity conditions (synchronous, and asynchronous). The sense of agency questionnaire (Q5 to Q6) had a Cronbach's alpha of 0.832 showing a good internal consistency. Negative item Q6 of the questionnaire was reversed for the calculation of Cronbach's alpha.

A two-way repeated measures ANOVA with ART (aligned rank transformation) procedure (Wobbrock et al., 2011) was conducted since some of the data significantly deviated from normality according to the results of Shapiro-Wilk tests (asynchronous condition of natural avatar: W=0.943, p=0.189, synchronous condition of natural avatar: W=0.827, p<0.001, asynchronous condition of unnatural avatar: W=0.907, p=0.030, synchronous condition of unnatural avatar: W=0.951, p=0.281). There was no significant interaction between the avatar type and synchronicity (F(1,23)=3.420, p=0.077). However, there were significant main effects for both the avatar type, and synchronicity with the sense of agency towards the natural avatar being significantly higher than that towards the unnatural avatar (F(1,23)=21.031, p<0.001, η_p^2=0.478) for both synchronicity conditions, and the sense of agency in the synchronous condition being significantly higher than the sense of agency in the asynchronous condition (F(1,23)=99.985, p<0.001, η_p^2=0.813) for both avatars.

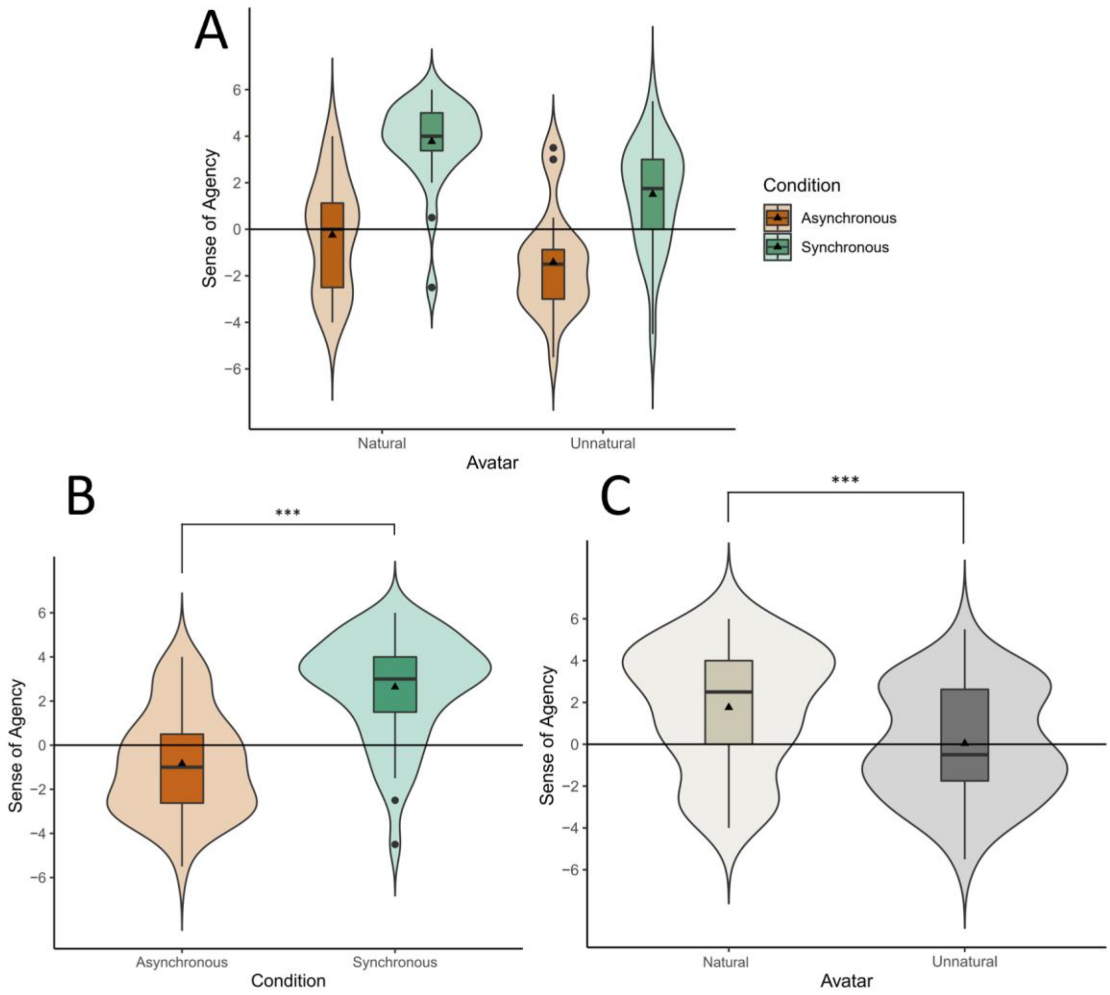

Figure 26: Sense of agency results

Sense of agency towards natural and unnatural avatars in asynchronous and synchronous conditions. Each box indicates the interquartile range (IQR), the range between 25th and 75th percentiles. The horizontal lines and the solid triangles in the boxes indicate medians and means respectively. The whiskers extend from the hinge to the largest and smallest values no further than 1.5 * IQR from the hinge. Outliers are shown in black dots. Surrounding violin plots depict the kernel density distributions. (A) Sense of agency of each avatar in each condition. (B) Main effect on synchronicity: the overall sense of agency in the synchronous condition was higher than that in the asynchronous condition. (C) Main effect on avatar type: the overall sense of agency towards the natural avatar was higher than that towards the unnatural avatar.

Skin conductance response did not show significant differences among avatar type or synchronicity.

Fig. 27 summarizes the results of skin conductance response. Skin conductance response of each participant was calculated when the threatening stimulus (the virtual knife) appeared, as the difference between the maximum value detected in a 5 s post-stimulus time window and the baseline calculated as the average value of a 2 s pre-stimulus time window.

A two-way repeated measures ANOVA with ART (aligned rank transformation) procedure (Wobbrock et al., 2011) was conducted since some of the data significantly deviated from normality according to the results of Shapiro-Wilk tests (asynchronous condition of natural avatar: $W=0.820$, $p<0.001$, synchronous condition of natural avatar: $W=0.945$, $p=0.212$, asynchronous condition of unnatural avatar: $W=0.819$, $p<0.001$, synchronous condition of unnatural avatar: $W=0.833$, $p=0.001$). There was no significant interaction between the avatar type and synchronicity ($F(1,23)=2.386$, $p=0.136$). There were no significant main effects either (Avatar type: $F(1,23)=1.288$, $p=0.268$, Synchronicity: $F(1,23)=3.522$, $p=0.073$).

One sample tests (student t-tests for normally distributed data, and Wilcoxon signed-rank tests for data that violated normality) showed that the skin conductance of participants significantly increased ($p<0.001$) in response to the knife stimulus compared to the calculated baseline in all conditions (asynchronous condition of natural avatar: $V=300$, $p<0.001$, effect size=1.000 , synchronous condition of natural avatar: $t(23)=6.445$, $p<0.001$, $d=1.316$, asynchronous condition of unnatural avatar: $V=300$, $p<0.001$, effect size=1.000, synchronous condition of unnatural avatar: $V=300$, $p<0.001$, effect size=1.000).

Next, we checked if there were correlations between SCR and ownership in each condition. Here, we first conducted Shapiro-Wilk tests for bivariate normality and calculated Spearman's rho for the data that violated normality assumptions and Pearson's r for the data that did not violate normality assumptions (asynchronous condition of natural avatar: $W=0.825$, $p<0.001$, synchronous condition of natural avatar: $W=0.921$, $p=0.061$, asynchronous condition of unnatural avatar: $W=0.824$, $p<0.001$, synchronous condition of unnatural avatar: $W=0.858$, $p=0.003$). No significant positive correlations between ownership and SCR were observed in any condition (asynchronous condition of natural avatar: rho=-0.338, $p=0.947$, synchronous condition for natural avatar: $r=-0.195$, $p=0.820$, asynchronous condition of unnatural avatar: rho=-0.227, $p=0.857$, synchronous condition of unnatural avatar: rho=0.019, $p=0.465$).

Next, we checked if there were positive correlations between SCR and sense of agency in each condition. Here, we first conducted Shapiro-Wilk tests for bivariate normality and calculated Spearman's rho for the data that violated normality assumptions and Pearson's r for the data that did not violate normality assumptions (asynchronous condition of natural avatar: W=0.815, p<0.001, synchronous condition of natural avatar: W=0.829, p<0.001, asynchronous condition of unnatural avatar: W=0.819, p<0.001, synchronous condition of unnatural avatar: W=0.938, p=0.145). No significant positive correlations between ownership and SCR were observed in any condition (asynchronous condition of natural avatar: rho=-0.234, p=0.864, synchronous condition for natural avatar: rho=-0.083, p=0.651, asynchronous condition of unnatural avatar: rho=0.024, p=0.455, synchronous condition of unnatural avatar: r=-0.238, p=0.868).

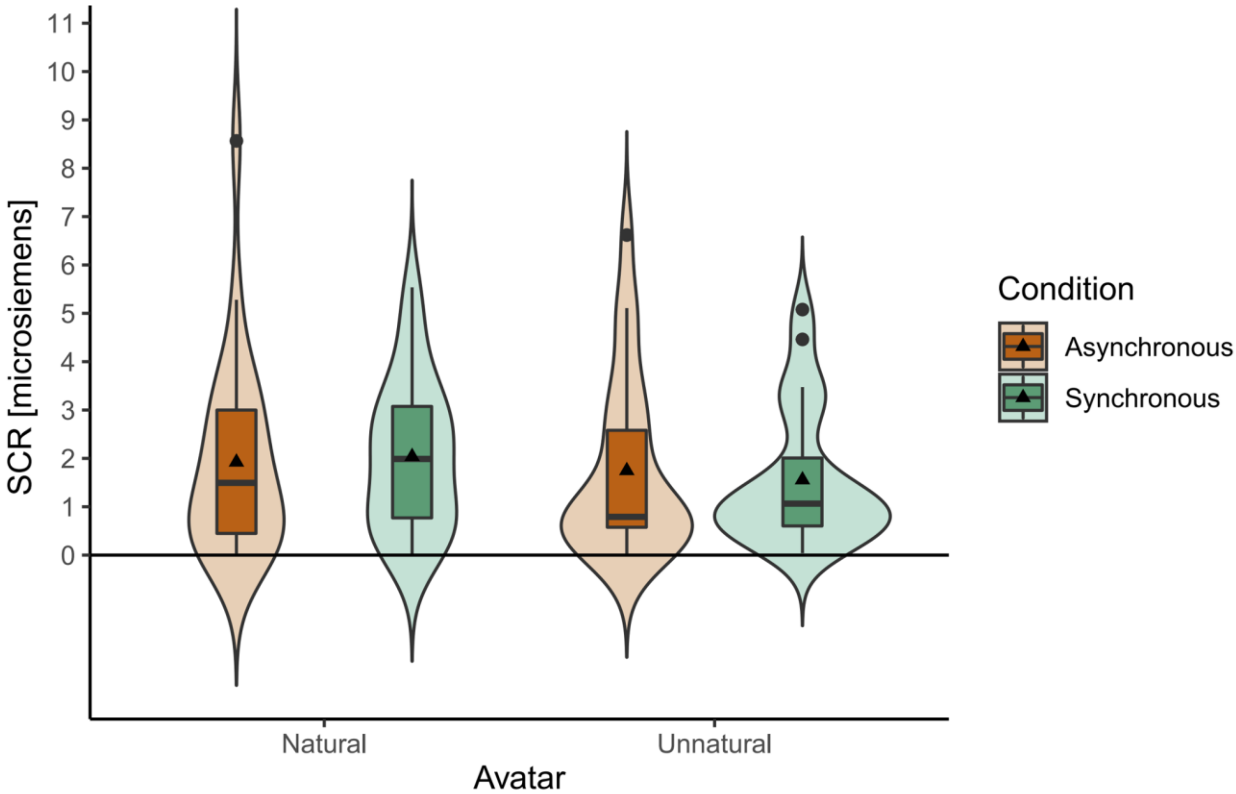

Figure 27: SCR results

Skin conductance response of participants when the knife stabbed the arm of the natural and unnatural avatars in asynchronous and synchronous conditions. Each box indicates the interquartile range (IQR), the range between 25th and 75th percentiles. The horizontal lines and the solid triangles in the boxes indicate medians and means respectively. The whiskers extend from the hinge to the largest and smallest values no further than 1.5 * IQR from the hinge. Outliers are shown in black dots. Surrounding violin plots depict the kernel density distributions. No significant differences were observed between the avatars or synchronicity conditions.

7.4 Discussion

Summary of results

We experimentally investigated how temporal visuomotor synchrony affects the sense of embodiment towards an avatar of which the spatial visuomotor synchrony of lower arms was disrupted with inversed, biomechanically impossible movements. We compared the senses of body ownership and agency towards this unnatural avatar against those towards a natural avatar in the presence and absence of temporal visuomotor synchrony. The results showed that temporal visuomotor synchrony causes a significant increase in sense of body ownership towards the unnatural avatar in a similar manner shown towards a natural avatar, suggesting that body ownership illusions can be created even when movements of an avatar are spatially altered from the movements of its user in a way that is biomechanically impossible as a human, as long as the real movements temporally synchronize with the virtual movements. However, in the presence of temporal visuomotor synchrony, the sense of body ownership towards the natural avatar was higher than that towards the unnatural avatar suggesting that both spatial and temporal visuomotor synchronizations are necessary for strong inductions of body ownership.

Lower sense of embodiment towards the unnatural avatar compared to the natural avatar

As possible reasons behind the lower sense of embodiment towards the unnatural avatar, two main factors can be thought of. First, since sense of embodiment is related to visuoproprioceptive synchrony (Dummer et al., 2009; Tsakiris et al., 2006; Walsh et al., 2011; Kalckert & Ehrsson, 2012; Kalckert & Ehrsson, 2014) as well in addition to the visuomotor synchronizations, the multi-sensory conflict arising from the felt proprioception as well as the motor feedback from the real arm not coinciding with the observed virtual arm can be pointed out as a reason. Second, a number of previous studies point to the difficulty of humans/infants to correctly recognize bodies with inversions, physically impossible structures, or biomechanically impossible body movements (Reed et al., 2003; Petit & Harris, 2010; Inoue & Kitazaki, 2010; Morita et al., 2012). Our sense of body ownership may depend on recognizing the stimuli as well as understanding the coherence of the current sensory input with the pre-existing cognitive representations of the body (Tsakiris & Haggard, 2005). In the case of the unnatural avatar, biomechanically impossible movements conflict with the body recognition as well as pre-existing cognitive representation we have for human arms making it a possible reason behind the lower embodiment despite the temporal synchrony. However, further studies are required to conclude whether body recognition is correlated to embodiment of first-person avatars, and also whether long-term training with such biomechanically impossible movements can lead to higher embodiment.

Higher ownership for the synchronous unnatural avatar than the asynchronous natural avatar

Another interesting observation we made in this study is the fact that the sense of body ownership towards the unnatural avatar with temporal synchrony was significantly higher compared to that towards the natural avatar without temporal synchrony, suggesting that temporal visuomotor synchrony in the absence of spatial visuomotor synchrony results in higher sense of body ownership compared to having spatial synchrony in the absence of temporal visuomotor synchrony. Therefore, while we conclude that spatiotemporal visuomotor synchronizations are necessary to induce stronger body ownership illusions, we also highlight the superiority of temporal visuomotor synchrony compared to spatial visuomotor synchrony when it comes to body ownership.

No significant differences in SCR

As a physiological measurement of body ownership, we also recorded the skin conductance of participants. They did respond to the threatening stimulus to the lower arm with a significant arousal that caused an increase in their skin conductance levels. However, the increase in skin conductance showed no significant differences between the experiment conditions suggesting that the knife moving towards the lower arm of the avatar itself was perceived threatening regardless of the synchronicity or the avatar type. A reason for this could be the fact that the knife appeared in front of the participants and moved towards them possibly threatening the self-location of the real body of the participants in all conditions. We observed no correlations between skin conductance and body ownership or between skin conductance and sense of agency. While changes in skin conductance may be a good measure of body ownership towards objects like separate rubber hands (Armel & Ramachandran, 2003; Tsuki et al., 2013), and partner-controlled limbs (Wegner et al., 2004; Hapuarachchi & Kitazaki, 2022), it may not be very reliable for measuring full body illusions according to our results due to lack of evidence supporting the subjective ratings for body ownership. Therefore, other measurements such as proprioceptive drifts (Botvinick & Cohen, 1998; Costantini & Haggard, 2007; Tsakiris & Haggard, 2005, Tosi et al., 2023) and changes in body schema and representation (Matamala-Gomez et al., 2020; Hapuarachchi et al., 2023; Bertoni et al., 2023) following previous work may better suit as alternative objective measurements for body ownership in future experiments.

Higher sense of agency in synchronous condition for both avatars

Sense of agency did not show a significant interaction between the avatar type and synchronicity. However, the overall sense of agency for both avatars was higher with visuomotor synchrony, compared to having a time delay between visual and real movements. This suggests that temporal visuomotor synchrony significantly enhances the sense of agency for both natural and unnatural avatars meaning that even when the movements are spatially mismatched, temporal synchrony between virtual and real movements plays an important role in making participants feel like they are in control of the movements of their avatars. Previous studies have shown that in cases of discrepancies, the altered sensory feedback might nevertheless be accepted as the sensory outcome of one's own movement and can be used for the essential continuous recalibration of one's action predictions and motor behavior (Synofzik et al., 2006). Our results expand this understanding of sense of agency by adding the necessity of temporal synchrony for enhancing such motor adaptations. However, the overall sense of agency was higher for the natural avatar compared to that for the unnatural avatar regardless of temporal visuomotor synchrony. These results suggest that while inversing lower arm movements do cause a significant drop in sense of agency compared to having natural movements, presence of visuomotor synchrony improves sense of agency for both types of avatars.

Insights into visuomotor synchrony

Overall, while previous studies have shown that synchronous visuomotor stimulations can induce a sense of ownership over virtual arms or bodies, our study expands this understanding by demonstrating that temporal synchrony can enhance sense of embodiment even when the avatar's movements are biomechanically impossible and spatially mismatching. Our results also point out that for body ownership illusions, temporal synchronies may be superior to spatial synchronies. However, to gain a deeper understanding on visuomotor adaptations with and without temporal and spatial synchronies, further experiments have to be conducted in the future that also monitor learning and changes in perceived body ownership and agency over time.

Chapter 8

Empathy towards humans and robots in virtual environments

8.1 Introduction

Only a few studies regarding empathic embarrassment (feeling embarrassed for others even though one's own social identity is not threatened) exist so far. Miller (1987) experimentally showed that participants experienced embarrassment while another person performed a series of remarkably atypical behaviors in public such as singing, dancing, throwing a tantrum etc. at the request of the experimenter (Miller, 1987). The results portrayed social embarrassment as a robust, pervasive phenomenon that nevertheless affects some people more than others (Miller, 1987). Embarrassment is sometimes accompanied by distressing symptoms such as blushing, sweating, fumbling, and stuttering leading to changes in physiology of those experiencing it. Miller used skin conductance response of participants while observing the actors engaging in the embarrassing behavior as a method of measuring empathic embarrassment. We adapted this method in our study while also collecting participants' subjective ratings to quantitively analyze empathic embarrassment and cognitive empathy. Stocks et al. (2011) revealed that when a socially desirable person is involved in an embarrassing situation, the degree of empathic embarrassment increases (Stocks et al., 2011). Thus, humans do not exhibit the same degree of empathic embarrassment for everyone. With the increasing use of robots in physical spaces and social interactions with avatars in virtual environments nowadays, it is important to know whether humans can empathize with robots or virtual avatars in embarrassing situations. Moreover, empathic embarrassment requires observers to infer whether the target agent is aware of witnesses and evaluate itself. Thus, if humans feel empathic embarrassment to robots, it suggests that humans assume the robots can be aware of being witnessed and have higher cognitive abilities such as self-reflection and self-evaluation. Therefore, studying empathic embarrassment for robots contributes to the advancement of scientific research on human perception of robots.

We utilized Virtual Reality (VR) to simulate a virtual environment in which participants were immersed with a robot character or a human character going through embarrassing situations among a crowd of people (virtual human avatars). As a control condition, we also created non-embarrassing scenes for the same situations and compared with the subjective ratings and skin conductance responses collected in the embarrassing condition. In VR literature, the capability of the VR system to elicit realistic responses is associated with the so-called Place Illusion (sense of being here despite knowing for sure one is not) and Plausibility Illusion (sense of things happening to the user despite knowing for sure they are not) (Slater, 2009; Slater et al., 2022). The Plausibility Illusion is often affected by virtual characters and whether they are perceived realistic (Slater, 2009; Slater et al., 2022; Neyret et al., 2020). The failure to elicit these illusions would diminish realistic responses in users (such as feeling embarrassment towards virtual characters in our study). Therefore, in Experiment 2, we checked the plausibility of the stimuli of our Experiment 1. Both experiments were exploratory since we made no hypotheses.

8.2 Experiment 5-1

8.2.1 Methods

Participants

Twenty-four participants (22 males and 2 females, mean age 22.291, SD 2.911) participated in the experiment. All participants had normal or corrected-to-normal vision. Informed consent was obtained from all the participants prior to the experiment. The experimental methods were approved by the Ethical Committee for Human-Subject Research at the Toyohashi University of Technology, and all methods were performed in accordance with the relevant guidelines and regulations. The sample size was determined via a priori power analysis using G*Power 3.1 (Faul et al., 2007; Faul et al., 2009) with a medium effect size $f = 0.25$, $\alpha = 0.05$, power $(1-\beta) = 0.8$, repeated measures ANOVA (two avatar conditions × two embarrassment conditions).

Apparatus

Visual stimuli were presented using a head-mounted display (HMD; HTC VIVE Pro Eye, 1440 [width] × 1600 [height] pixels, refresh rate, 90 Hz) while the participants were seated on a chair. The stimuli were created using Unity 2019.3.0a3 on a computer (Intel Corei5 6400, NVIDIA GeForce GTX 1080 8 GB). BIOPAC MP 160 and a wireless PPG and EDA amplifier (BN-PPGED) was placed on the participants' wrist. Two disposable electrodes (EL507) were pasted on to the distal phalanges of the participants' index and middle fingers.

Stimuli and conditions

Two types of main actor avatars, a human avatar and a robot avatar were used for the participants to observe in 4 types of situations, walking in a crowded place, passing through an automatic door, a scenario in a classroom, and a dancing scene (Fig. 28). In each situation, the actor went through an embarrassing scenario as well as a non-embarrassing scenario. Table 6 summarizes the content in each scenario.

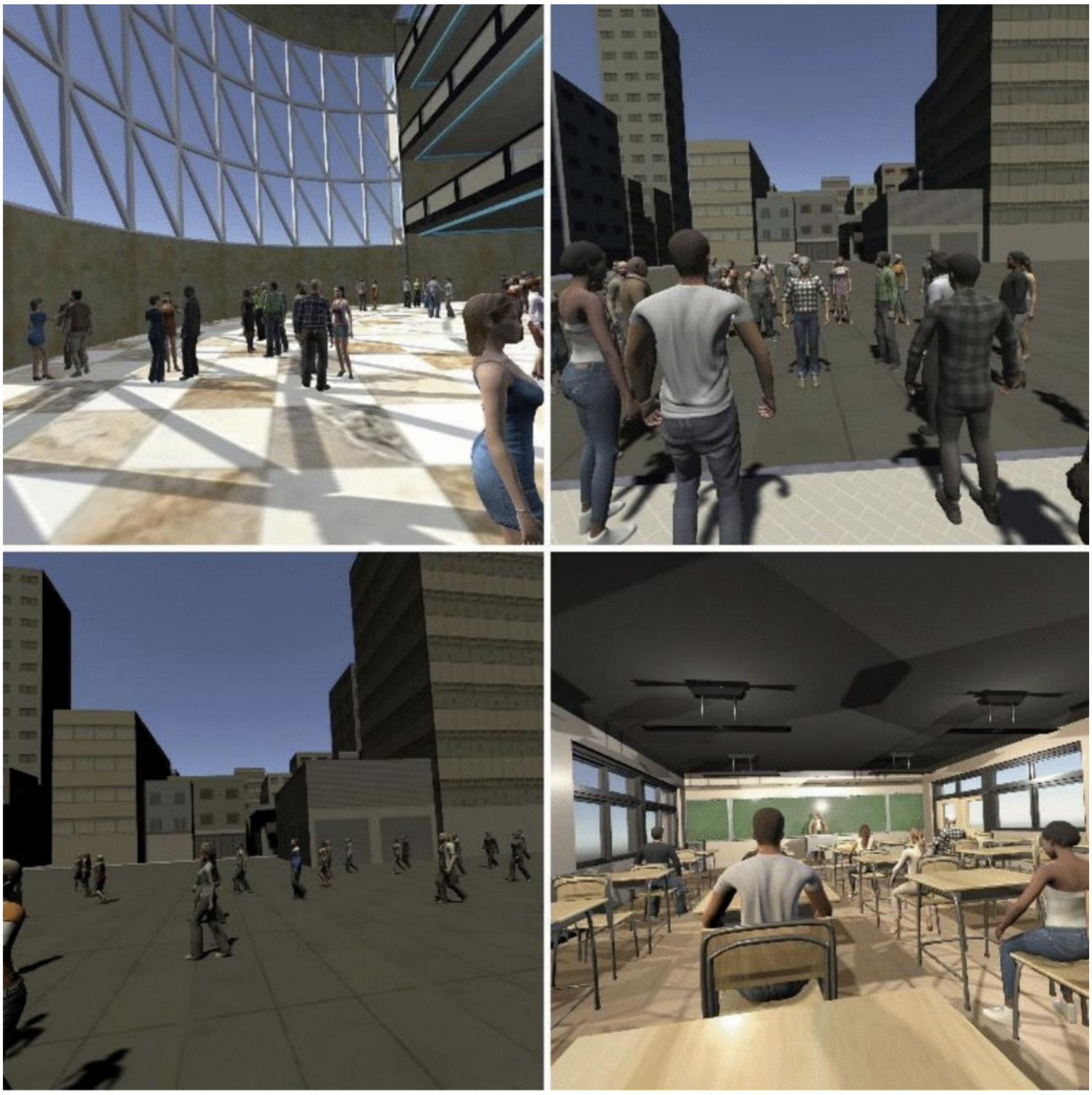

Figure 28: Virtual environments in the study

Participant's point of view before an embarrassing or non-embarrassing scene in each situation (top-left: passing through a door, bottom-left: walking in a crowded place, top-right: dance, bottom-right: classroom). The figures were created using unity2019.3.0a3 (https://unity3d.com/get-unity/download/archive).

Table 6: Embarrassing and non-embarrassing situations

Situation	Embarrassing situation	Non-embarrassing situation
Passing through a door	Bump into the door before it opens	Wait for the door to open and pass through
Walking in a crowded place	Stumble	Pick something up
Classroom	Doze off	Raise hand
Dance	Dance unskillfully in front of many people	Dance unskillfully in an empty space

There were 16 types of stimuli (avatar type of actor: human/robot x Embarrassment: embarrassed/non-embarrassed x situation: passing through a door, walking in a crowded place, classroom, dance) in the experiment as shown in Fig. 29. However, the scores/skin conductance of the 4 situations were averaged into one for each combination of avatar type and embarrassment condition, giving a total of 4 conditions. In each situation, many people (avatars) were placed around the actor.

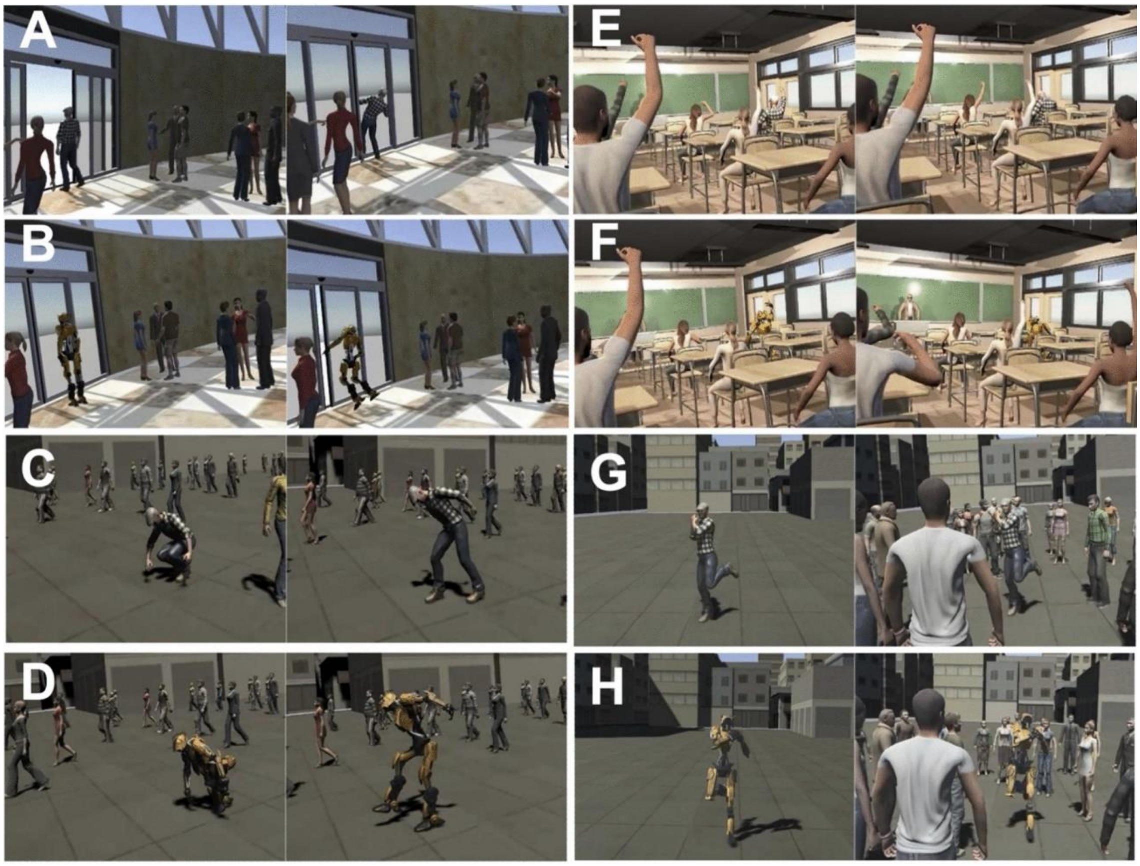

Figure 29: Embarrassed and non-embarrassed situations

(A) Human avatar passing through a door (left: non-embarrassing scenario, right: embarrassing scenario). (B) Robot avatar passing through a door (left: non-embarrassing scenario, right: embarrassing scenario). (C) Human walking in a crowded place (left: non-embarrassing scenario, right: embarrassing scenario). (D) Robot walking in a crowded place (left: non-embarrassing scenario, right: embarrassing scenario). (E) Human in classroom (left: non-embarrassing scenario, right: embarrassing scenario). (F) Robot in classroom (left: non-embarrassing scenario, right: embarrassing scenario). (G) Human dancing (left: non-embarrassing scenario, right: embarrassing scenario). (H) Robot dancing (non-embarrassing scenario, right: embarrassing scenario). The figures were created using unity2019.3.0a3 (https://unity3d.com/get-unity/download/archive).

Questionnaire

Participants rated their self-embarrassment (the participant's own feeling) and actor-embarrassment (actor's feeling guessed or perceived by the participant) at the end of each trial using the touch pad and the trigger button of the controller. The answers were recorded in a 7-point Likert scale where the scores from -3 to 3 corresponded to the answers shown below in Table 7.

Table 7: Answers for self or actor embarrassment and corresponding scores

Score in Likert scale	Feeling
-3	Extremely embarrassing
-2	Embarrassing
-1	Slightly embarrassing
0	Neither embarrassing nor proud
1	Slightly proud
2	Proud
3	Extremely proud

A 7-point Likert scale was chosen over a 5-point Likert scale since 7-point scales provide a more accurate measure of a participant's true evaluation and are more appropriate for assessing usability according to some previous studies (Joshi et al., 2015; Finstad, 2010). Furthermore, the fact that only two questionnaire items were asked in our experiment gives participants enough time to discreetly choose an answer from a 7-point scale.

Procedure

The subjects were presented with 16 scenarios (2 avatar types × 2 embarrassment conditions × 4 situations), one at a time in a random order while they were seated immersed in the virtual environment corresponding to each situation. At the beginning of each trial, the participants were asked to look around and spot the actor and focus on the actor till the end of the trial. Fifteen to seventeen seconds into each trial, an embarrassing or a non-embarrassing event occurred to the actor. Each session lasted thirty to forty seconds, and skin conductance was measured throughout the session. At the end of the trial, participants answered a questionnaire regarding how they felt in the trial. Additionally, during each trial, the skin conductance levels of participants were measured and recorded using a wireless transmitter attached to the wrist of the participant that was connected to two electrodes on the fingers.

8.2.2 Results

Self-embarrassment (empathic embarrassment)

We calculated the self-embarrassment (see Fig. 30) towards the human and robot actors in embarrassed and non-embarrassed conditions. A two-way repeated measures ANOVA with ART (aligned rank transformation) procedure43 was conducted since some of the data significantly deviated from normality according to the results of Shapiro–Wilk tests (embarrassed condition for human avatar: $W = 0.967$, $p = 0.594$, non-embarrassed condition for human avatar: $W = 0.819$, $p < 0.001$, embarrassed condition for robot avatar: $W = 0.868$, $p = 0.005$, non-embarrassed condition for robot avatar: $W = 0.792$, $p < 0.001$). No significant interaction was observed between the avatar type and embarrassment condition ($F(1,23) = 0.079$, $p = 0.781$, η_p^2=0.003). However, significant main effects were observed for the avatar type ($F(1,23) = 8.279$, $p = 0.009$, η_p^2 =0.265) as well as for the embarrassment condition ($F(1,23) = 11.248$, $p = 0.003$, η_p^2 =0.328). These indicated that the self-embarrassment was significantly higher (higher negative score) towards the human avatar compared to the robot avatar in both embarrassed and non-embarrassed conditions, and significantly higher in the embarrassed condition compared to the non-embarrassed condition for both human actor and robot actor.

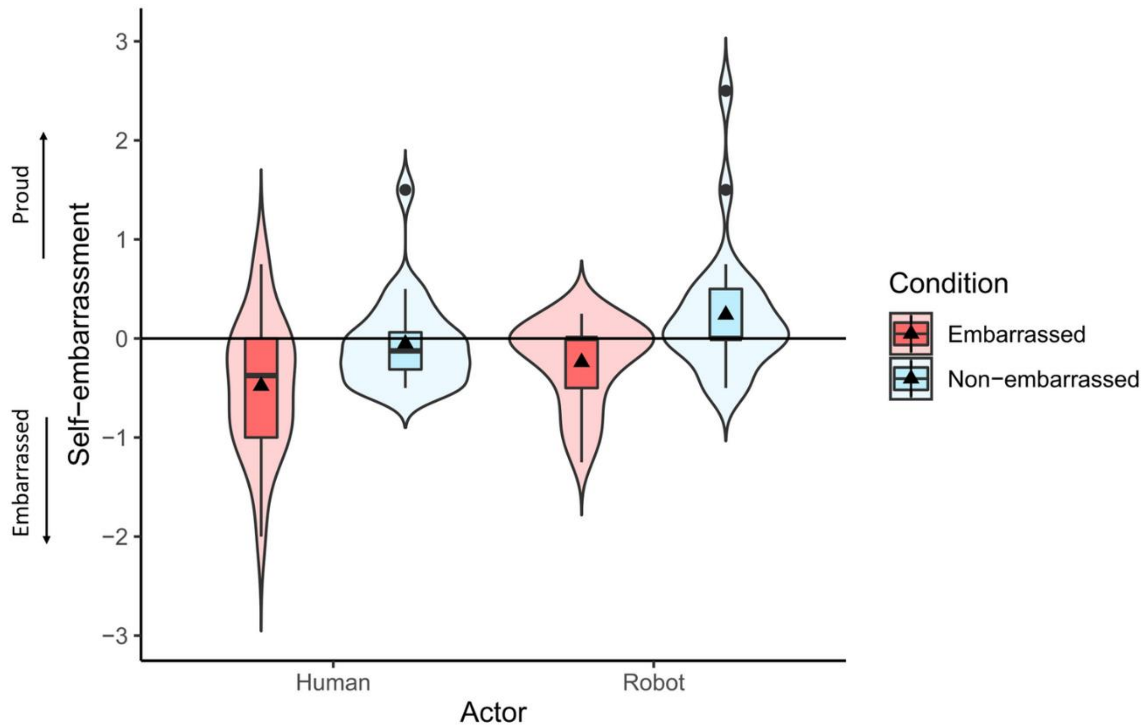

Figure 30: Results of self-embarrassment

Actor-embarrassment (cognitive empathy)

Next, we calculated actor-embarrassment (see Fig. 31) towards the human and robot actors in embarrassed and non-embarrassed conditions. A two-way repeated measures ANOVA with ART (aligned rank transformation) procedure was conducted since some of the data significantly deviated from normality according to the results of Shapiro–Wilk tests (embarrassed condition for human avatar: $W = 0.963$ $p = 0.496$, non-embarrassed condition for human avatar: $W = 0.947$, $p = 0.233$, embarrassed condition for robot avatar: $W = 0.902$, $p = 0.024$, non-embarrassed condition for robot avatar: $W = 0.867$, $p = 0.005$). A significant interaction was observed between the avatar type and embarrassment condition ($F(1,23) = 33.447$, $p < 0.001$, $\eta_p^2 = 0.593$). Simple main effects analysis showed that the actor-embarrassment was significantly higher (higher negative score) towards the human actor than towards the robot actor in the embarrassed condition ($F(1,23) = 54.135$, $p < 0.001$, $\eta_p^2 = 0.702$). Furthermore, for both human and robot actors, actor-embarrassment was significantly higher (higher negative value) in the embarrassed condition compared to the non-embarrassed condition (human actor: $F(1,23) = 101.14$, $p < 0.001$, $\eta_p^2 = 0.815$, robot actor: $F(1,23) = 71.196$, $p < 0.001$, $\eta_p^2 = 0.756$).

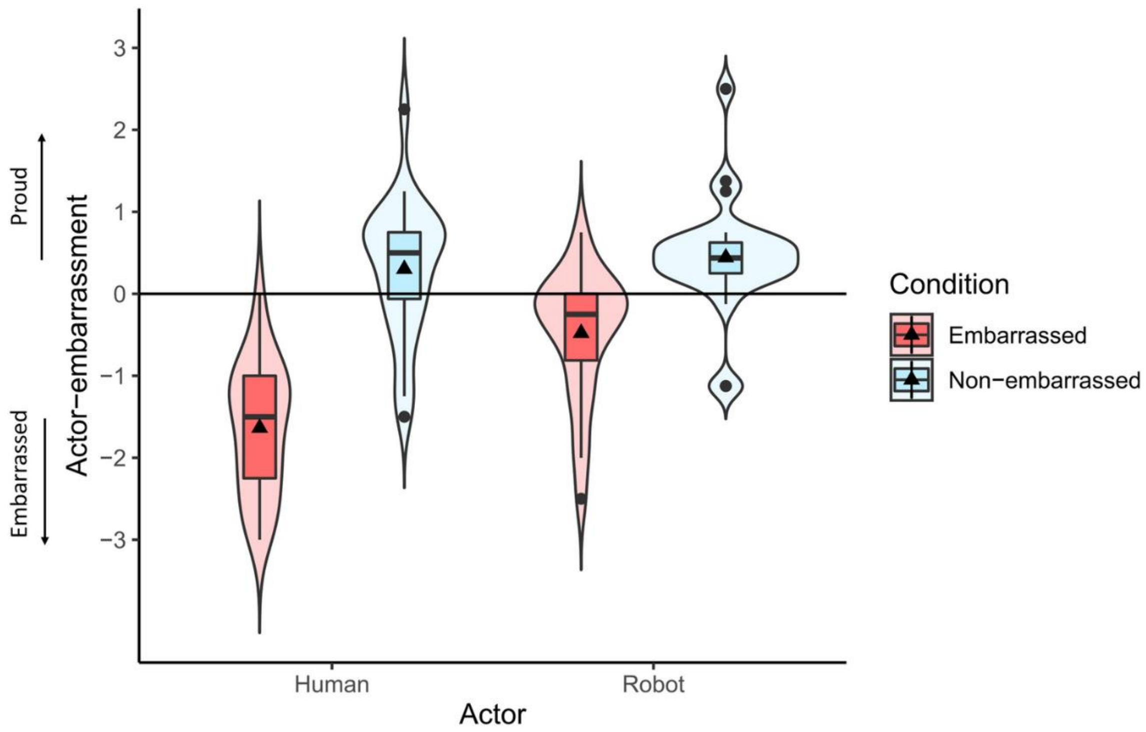

Figure 31: Results of actor-embarrassment

Skin conductance response (SCR)

Skin conductance response of 17 participants were analyzed, removing the data of 7 participants due to high noise ratios or technical errors in reading the data during the experiment. The average of skin conductance read in 3 s just before the embarrassing or the non-embarrassing event occurred was first calculated as the baseline. For each condition, the difference between the baseline and the maximum skin conductance read in the first 5 s since the beginning of the embarrassing/non-embarrassing event was calculated and averaged. Fig. 32 shows the summary of the calculated results in microsiemens.

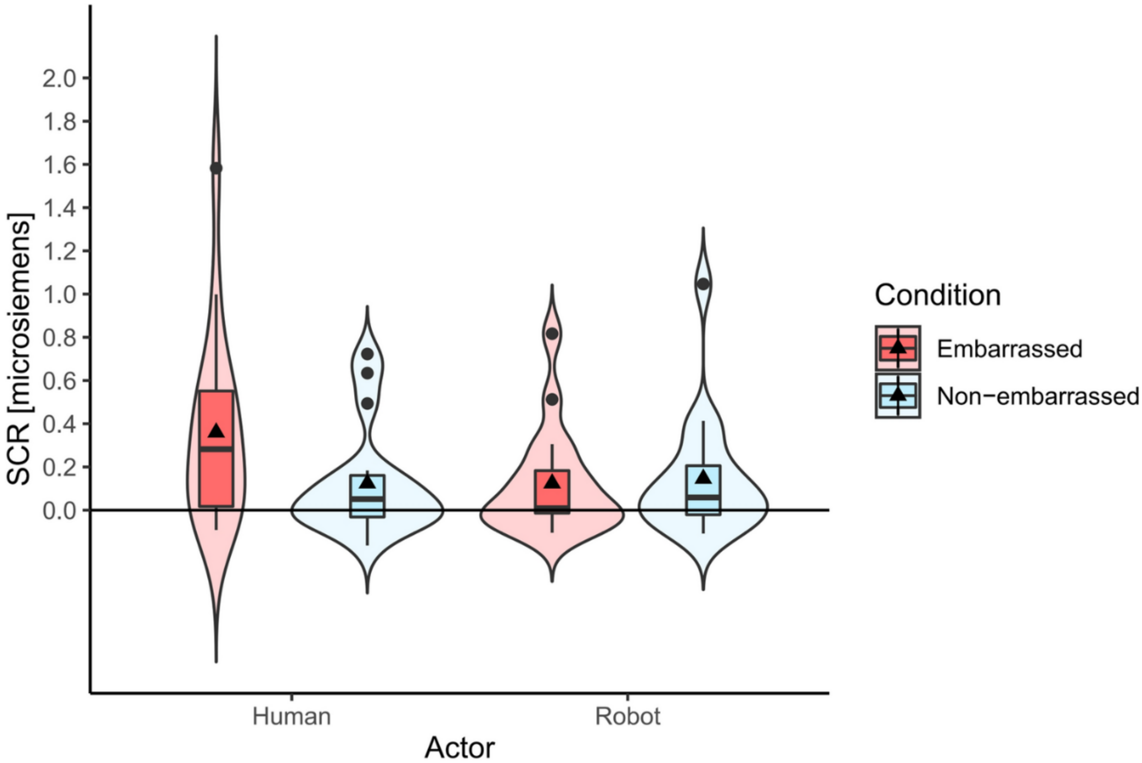

Figure 32: SCR Results

Skin conductance response. Maximum skin conductance detected in the first five seconds after the embarrassing event compared to the baseline calculated before the embarrassing event.

A two-way repeated measures ANOVA was conducted, and a marginally significant interaction was observed between the avatar type and embarrassment condition (F(1,16)=3.088, p=0.098, η_p^2=0.162). Simple main effects analysis showed that the skin conductance response was marginally significantly higher in the embarrassed condition compared to the non-embarrassed condition for the human avatar (F(1,16) = 3.949, p=0.0643, η_p^2 =0.198). Furthermore, compared to the robot avatar, the skin conductance response towards the human avatar in the embarrassed condition was also marginally significantly higher (F(1,16) = 4.299, p= 0.055, η_p^2=0.212).

8.3 Experiment 5-2

8.3.1 Methods

Participants

Twenty-four participants (all males, mean age 23.875, SD 3.261) participated in the experiment. All participants had normal or corrected-to-normal vision. Informed consent was obtained from all the participants prior to the experiment. The experimental methods were approved by the Ethical

Committee for Human-Subject Research at the Toyohashi University of Technology, and all methods were performed in accordance with the relevant guidelines and regulations. Similar to Experiment 1, the sample size was determined via a priori power analysis using G*Power 3.1 (Faul et al., 2007; Fau; et al., 2009) with a medium effect size f = 0.25, α = 0.05, power (1- β) = 0.8, repeated measures ANOVA (two avatar conditions × two embarrassment conditions).

Apparatus

Apparatus was the same as in Experiment 1. However, Skin Conductance was not measured in Experiment 2.

Stimuli and conditions

The same visual stimuli used in Experiment 1 were used in randomized order for each participant. The conditions were the same as those in Experiment 1.

Questionnaire

Participants answered the questions shown in Table 8 at the end of each trial in a 7-point Likert scale ranging from -3 (Not at all) to + 3 (Totally). The question order was randomized each time for each participant. The questionnaire items were adapted from a recent previous study that measured plausibility of virtual events of an experiment conducted in VR (Neyret et al., 2020).

Table 8: Questions relating to plausibility, that the events observed in VR were really happening. All scores are on a -3 (Not at all) to +3 (Totally) scale.

Variable Name	Question
real	To what extent did you behave, and respond as if the situation were real?
emotion	To what extent was your emotional response the same as if the situation had been real?
thoughts	To what extent were the thoughts you had the same as if the situation had been real?
auto real	To what extent did you find yourself surprisingly behaving as if the situation were real even though you knew it was not real?
actor real	To what extent did you behave, and respond as if the main actor were a real person/robot?
emotion to actor	To what extent were your emotional responses to the main actor the same as if he/it were real?
thoughts to actor	To what extent were your thoughts in relation to the main actor the same as if he/it were real?

Procedure

The subjects were presented with the same 16 scenarios from Experiment 1 (2 avatar types × 2 embarrassment conditions × 4 situations), one at a time in a random order while they were seated immersed in the virtual environment corresponding to each situation. At the beginning of each trial, the participants were asked to look around and spot the actor and focus on the actor till the end of the trial. Fifteen to seventeen seconds into each trial, an embarrassing or a non-embarrassing event occurred to the actor. At the end of the trial, participants answered a questionnaire regarding plausibility.

8.3.2 Results

Results of the plausibility questionnaire

Fig. 33 shows the results for each questionnaire item in Table 8. All data gathered with the plausibility questionnaire were confirmed to be normally distributed according to Shapiro-Wilk tests (p=0.995 ~ 0.114). Therefore, two-way repeated measures ANOVAs were conducted for each questionnaire item. First, for the real item of the questionnaire, a two-way repeated measures ANOVA was conducted. Any main effect or interaction was not found (Avatar type: F(1,23)=3.186, p=0.088, η_p^2=0.122; Embarrassment condition: F(1,23)=0.579, p=0.455, η_p^2=0.025; Interaction: F(1,23)=3.412, p=0.078, η_p^2=0.129).

Next, a two-way repeated measures ANOVA was conducted for the emotion item of the questionnaire. Any main effect or interaction was not found (Avatar type: F(1,23)=3.893, p=0.061, η_p^2=0.145; Embarrassment condition: F(1,23)=0.038, p=0.847, η_p^2=0.002; Interaction: F(1,23)=1.982, p=0.173, η_p^2=0.079).

For the thoughts item of the questionnaire, a two-way repeated measures ANOVA showed a significant interaction between the avatar type and the embarrassment condition (F(1,23)=7.755, p=0.011, η_p^2=0.252). Simple main effects analysis showed that in the embarrassed condition, the score for the human actor was significantly higher than the score for the robot actor (F(1,23)=10.439, p=0.004, η_p^2=0.312). Furthermore, for the robot actor, the score in the non-embarrassed condition was significantly higher than the score in the embarrassed condition (F(1,23)=5.806, p=0.024, η_p^2=0.202). Main effects were not significant (Avatar type: F(1,23)=3.794, p=0.064, η_p^2=0.142; Embarrassment condition: F(1,23)=0.011, p=0.912, η_p^2=0.001).

For the auto real item of the questionnaire, two-way repeated measures ANOVA showed no significant interaction (F(1,23)=1.355, p=0.257, η_p^2=0.056) or main effects (avatar type: F(1,23)=0.388, p=0.540, η_p^2=0.017, embarrassment condition: F(1,23)=0.022, p=0.883, η_p^2=0.001).

For the actor real item of the questionnaire, a significant main effect on avatar type was observed with the score for the human actor being significantly higher than the score for the robot actor ($F(1,23)=4.626$, $p=0.042$, $\eta_p^2=0.167$). No significant main effect on embarrassment condition ($F(1,23)=0.001$, $p=0.970$, $\eta_p^2=0.000$), or significant interaction between was observed ($F(1,23)=2.135$, $p=0.158$, $\eta_p^2=0.085$).

For the emotion to actor item of the questionnaire, a significant interaction between the avatar type and the embarrassment condition was observed ($F(1,23)=4.548$, $p=0.044$, $\eta_p^2=0.165$). Simple main effects analysis did not show any significant difference, but in the embarrassed condition, the score for the human actor was marginally higher than the score for the robot actor ($F(1,23)=3.947$, $p=0.059$, $\eta_p^2=0.147$).

For the thoughts to actor item of the questionnaire, two-way repeated measures ANOVA did not show a significant interaction ($F(1,23)=2.589$, $p=0.121$, $\eta_p^2=0.101$) or main effects (avatar type: $F(1,23)=1.356$, $p=0.256$, $\eta_p^2=0.056$, embarrassment condition: $F(1,23)=0.460$, $p=0.504$, $\eta_p^2=0.019$).

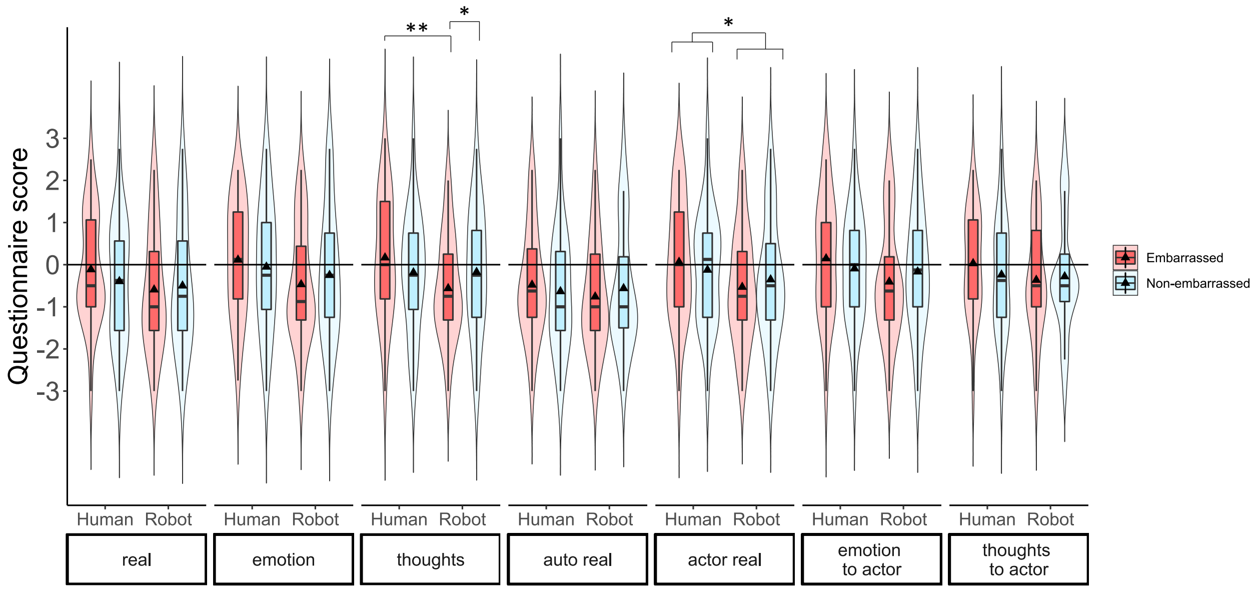

Figure 33: Results of the plausibility questionnaire

Overall Plausibility (average of all questions of the plausibility questionnaire)

Cronbach's alpha of the plausibility questionnaire was 0.983. Thus, we calculated the average of all items (Fig. 34). A two-way repeated measures ANOVA was conducted since the data did not deviate from normality according to the results of Shapiro-Wilk tests (embarrassed condition for human avatar: W=0.981, p=0.909, non-embarrassed condition for human avatar: W=0.980, p=0.890, embarrassed condition for robot avatar: W=0.976, p=0.820, non-embarrassed condition for robot avatar: W=0.971, p=0.698). A significant interaction between the avatar type and embarrassment condition were observed (F(1,23)=4.716, p=0.040, η_p^2=0.170). Simple main effects analysis showed that in the embarrassed condition, the score for the human actor was significantly higher than the score for the robot actor (F(1,23)=6.712, p=0.016, η_p^2=0.226).

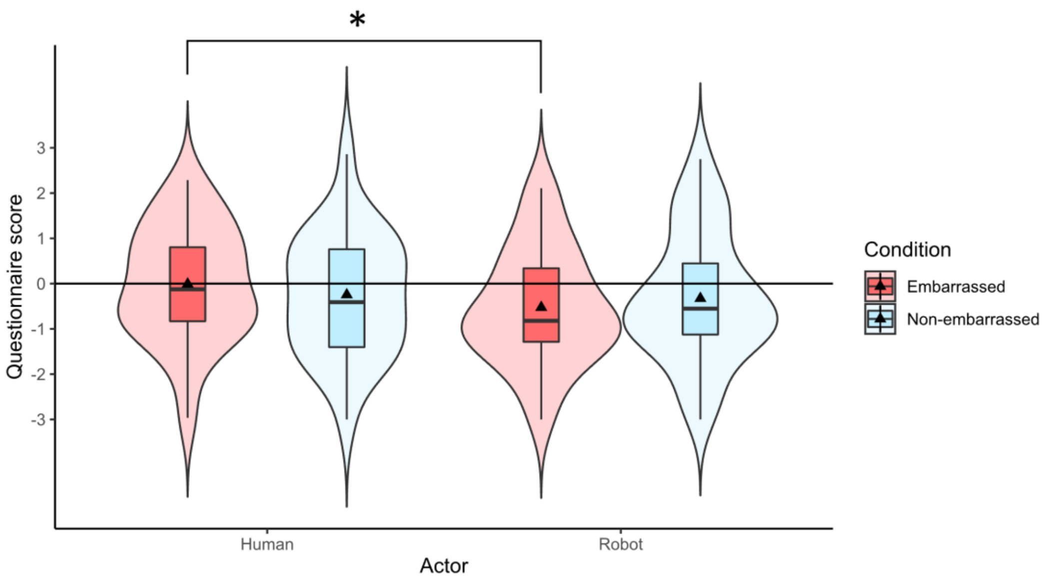

Figure 34: Averaged scores of all items of the plausibility questionnaire

8.4 Discussion

Summary of results

In Experiment 1, we investigated how humans feel empathic embarrassment and cognitive empathy (related to embarrassment) with robots compared to humans in four different virtual environments. Self-embarrassment showed no interaction between the actor type and embarrassment condition but showed significant main effects for both actor type and embarrassment condition with self-embarrassment being higher with the human actor than with the robot actor and higher in the embarrassed condition compared to the non-embarrassed condition. Actor-embarrassment showed a significant interaction between the actor type and embarrassment condition with significant simple main effects showing that the scores in the embarrassed condition were higher than the scores in the non-embarrassed condition for each actor (human and robot) and the score for the embarrassed condition was significantly higher with the human actor compared to that with the robot actor. Skin conductance showed a higher (but not significant) response with the human actor compared to that with the robot actor in the embarrassed condition.

In Experiment 2, we investigated the plausibility of the stimuli used in Experiment 1. The participants thought the situation was significantly more real in the embarrassed condition with the human avatar compared to the embarrassed condition with the robot avatar (thoughts item). They also thought the situation was more real in the non-embarrassed condition with the robot avatar compared to the embarrassed condition with the robot avatar (thoughts item). Furthermore, the human avatar was perceived to be more real compared to the robot avatar regardless of the embarrassed or non-embarrassed events that occurred in the scene (actor real item). The average scores of all items in the plausibility questionnaire also showed a significant difference between the embarrassed condition with the human avatar compared to the embarrassed condition with the robot avatar. Other items in the questionnaire (real, emotion, auto real, emotion to actor, and thoughts to actor items) did not show significant differences between experiment conditions.

Significant empathic embarrassment for both human and robot actors

Regardless of the avatar type of the actor, self-embarrassment and actor-embarrassment were both significantly higher when the actor faced an embarrassing incident (embarrassed condition) compared to when no embarrassing incident happened (non-embarrassed condition). This suggests that the situations chosen in this experiment in general were indeed considered as embarrassing events by the participants and the embarrassment was significantly higher than that in the non-embarrassed condition towards the robot actor as well as the human actor. Cronbach's alpha of two questionnaire items (self-embarrassment and acter-embarrassment) was 0.615. Thus, these two items have some consistency, but reflect different aspects of empathic embarrassment and cognitive empathy, respectively. The empathic embarrassment was not only cognitive inference, but also felt as self-embarrassment. Thus, humans can empathize with robots in embarrassing situations, suggesting that humans assume the robots can be aware of being witnessed and have some degree of self-consciousness based on self-reflection and self-evaluation.

However, the appearance of the robot may affect the empathic embarrassment because humans empathize more strongly with more human-looking robots and less with more mechanical-looking robots when they are mistreated by humans (Riek et al., 2009). Subjective ratings of empathic embarrassment for the human and the robot were not significantly different. It may be because we used a humanoid robot that had two arms, two legs, a head, and similar joints and proportions to humans. We should investigate the effect of robot appearance on empathic embarrassment in the future.

Lower actor-embarrassment with the robot actor compared to the human actor.

When we consider only the embarrassed condition, the inferred actor-embarrassment was significantly higher with the human avatar compared to that with the robot avatar. This suggests that cognitive empathy with regards to embarrassment is lower for robots compared to humans and this result is similar to previous studies that investigated empathy for robots during mistreatment (Riek et al., 2009) and pain (Suzuki et al., 2015). It may be due to naive knowledge that robots do not have a mind.

Humans are less concerned about abusing robots compared to abusing other humans (Bartneck & Hu, 2008) and children sometimes abuse social robots in public spaces (Nomura et al., 2015). The low cognitive empathy to robot embarrassment as well as the low cognitive empathy to robot pain16 may be related to these phenomena.

Skin conductance response

Skin conductance showed a higher (marginally significant) value towards the human actor compared to the robot actor in the embarrassed condition. Therefore overall, these results suggest that while we feel a certain level of empathic embarrassment and cognitive empathy towards robots, it is significantly less than that felt towards humans. However, the difference was not statistically significant. It may be caused by underpower. The data of 7 participants were removed out of 24 participants due to high noise ratios or technical errors during the experiment.

Plausibility of the experiment stimuli

The average plausibility in the embarrassed condition was significantly higher with the human avatar compared to the robot avatar. However, real, emotion, auto real, emotion to actor, and thoughts to actor items (see Fig. 33) were not significantly different among the experiment conditions. Therefore, part of the difference between human and robot avatars might be due to the difference of their plausibility, but it is not supposed that the empathic embarrassment, which is an emotion, was affected solely by the difference in plausibility of conditions.

Limitations

The study was limited to virtual environments and the actors were 3D avatars. Therefore, there is a possibility of participants feeling less empathy or emotion for them compared to real humans or physical robots. Furthermore, skin conductance responses showed only marginally significant results this time. The data loss of seven participants resulting a sample size of 17 for skin conductance data also may reduce the reliability of the results, which is a limitation of the current study. Furthermore, other measurements such as electroencephalography may provide better insights for physiological changes with regards to empathic emotions.

We measured embarrassment and pride in one scale in this experiment since embarrassment, and pride are both known to be members of a family of "self-conscious" emotions (Tangney, 1999) and we assumed pride to be the opposite emotion of embarrassment. Thus, we adopted a Likert scale from -3 (Extremely embarrassing) and + 3 (Extremely proud), while the previous studies used the scale from 1 (not at all) to 7 (very much embarrassing). In a pilot study, participants felt our scale was better than the previous one to evaluate the movie scenes. However, the relationship between embarrassment and pride should be further studied in future studies.

Dancing unskillfully in front of a crowd was considered embarrassing in this experiment compared to performing the same dance alone. However, one may argue that dancing in front of a crowd may instead show confidence and be perceived as a proud act instead of an embarrassing act. To check if the participants really found the dance scenes embarrassing or not, we analyzed the subjective ratings for self and actor-embarrassment only for the dance scenes of Experiment 1. Two-way repeated measures ANOVA with aligned rank transform (due to non-parametric data) showed that there was a significant main effect on the avatar type with the ratings for both self and actor-embarrassment for the human avatar showing a significantly higher embarrassment compared to the ratings for the robot avatar (Self-embarrassment: $F(1,23) = 8.832$, $p = 0.007$, $\eta_p^2 = 0.277$, Actor-embarrassment: $F(1,23) = 7.769$, $p = 0.010$, $\eta_p^2 = 0.253$). However, there was no significant main effect on Condition (embarrassing/non-embarrassing) and there was no significant interaction between the condition and avatar type for both self-embarrassment and actor-embarrassment. Therefore, choosing stimuli that differentiate embarrassing and non-embarrassing events better might be suited for future experiments related to embarrassment.

The overall score for the actor real item of the plausibility questionnaire was significantly higher towards the human avatar compared to the robot avatar, meaning that the human avatar was perceived more like a real human compared to the robot avatar being perceived as a real robot. This difference in actor realism could be due to the fact that we are not used to watching robots in real life as frequently as we see other humans. The difference in animations used for human, and robot avatars may also be another reason for this plausibility difference, and it is possible that the embarrassment scores were affected by this.

Chapter 9

General Discussion

9.1 Summary of Results

The first two studies of this dissertation (chapters 4, and 5) were based on virtual co-embodiment using the novel joint avatar. The first experiment reported in chapter 4 investigated how goal sharing, and knowing the intention behind limb movements of the partner affects the senses of body ownership, and agency towards that limb in a within-subjects design experiment. Additionally, we recorded skin conductance of participants when the two arms of the joint avatar were threatened with a knife stimulus as a physiological measure of body ownership. The results showed that both sense of body ownership and agency were higher towards the partner-controlled arm of the joint avatar when the two participants shared one goal, or when they could see the partner's target while having separate goals compared to when the partner's target was invisible while having separate goals. In any condition on target visibility, participants showed a higher sense of body ownership and agency towards the arm they controlled compared to the partner-controlled arm of the joint avatar. The increase in skin conductance levels also showed that the arousal when the controlled arm was stabbed with a virtual knife was significantly higher than that when the partner-controlled arm was stabbed with the virtual knife. However, between the target conditions, we did not observe significant differences in senses of body ownership or agency. Exploratory analysis of ownership tends to be higher towards the left arm of the joint avatar compared to the right arm only for the controlled arm. Such phenomenon was not observed with sense of agency or SCR. In the second experiment reported in chapter 5, we investigated how passive movements applied to the upper body of the participants affect the sense of body ownership and agency towards the arm controlled by the partner while using the joint avatar. In Experiment 2 we measured the change in body image and proprioceptive drift as behavioral measures of body ownership using three types of tests. The results showed that synchronized force feedback to the upper body of participants matching the movements of the partner-controlled arm causes a significant increase in the sense of body ownership as well as the sense of agency towards the partner-controlled virtual arm of the joint avatar. Out of the three behavioral tests, one showed a significant drift in proprioception of participants towards the partner-controlled arm of the virtual avatar only when the connection force feedback was present, and the proprioceptive drift was nearly significantly higher in the condition with connection force feedback compared to the condition without it. The other two tests did not show any significant changes in body image after using the joint avatar compared to before using it.

In the third experiment reported in chapter 6, we investigated how the movement speed of an autonomous prosthetic limb affects how it is perceived by the users. The autonomous prosthetic arm was programmed to move in a minimum jerk trajectory as a hinge joint elbow (rotating around only one axis) to make the movements more human like, and we measured the sense of body ownership, agency, usability, RoSAS (Competence, warmth and discomfort) of healthy participants in a within subject experiment. The results showed that sense of ownership, agency and usability changed with motion time (speed of the autonomous movement) in a similar pattern where fastest (motion time 125 ms) and slowest movements (motion time 4 s) showed lower ratings while moderate speed movements (motion time 1 s) showed significantly higher ratings. On the other hand, discomfort was the least when the embodiment and usability were the highest, showing a negative correlation with ownership, agency and usability.

In chapter 7, we investigated how biomechanically impossible movements are embodied by humans using an unnatural avatar that was capable of bending the arms from the elbow joints in the opposite direction of that of humans. Using this unnatural avatar in first person perspective, participants performed reaching tasks and we measured their sense of embodiment and skin conductance response to a threatening stimulus. Participants performed reaching tasks with the unnatural avatar with and without a 1 s delay between real and virtual movements. They also performed the same synchronous and asynchronous conditions in a normal avatar. Results showed that body ownership was significantly higher when there was no delay for both natural and unnatural avatars compared to when there was a delay. In the synchronous conditions, the natural avatar showed a significantly higher sense of body ownership than the unnatural avatar. Furthermore, the ownership for the unnatural avatar without a delay was significantly higher than the ownership towards the natural avatar with a 1 s delay. The sense of agency was in general significantly higher towards the natural avatar than towards the unnatural avatar, and significantly higher in the synchronous condition than in the asynchronous condition for both avatars. Significant differences in skin conductance responses were observed neither in avatar types nor in the synchronicity conditions.

In chapter 8 we investigated how we feel empathic embarrassment for humans and robots in virtual environments. Participants observed a human avatar and a robot avatar go through a series of embarrassing situations (and non-embarrassing situations as a control condition) in virtual environments and rated their self-embarrassment and actor-embarrassment on a Lickert scale. Additionally, we measured their skin conductance response while they watched the human and robot avatars go through the embarrassing situations. In a follow-up experiment for the same study, we measured the plausibility of all the stimuli used to measure empathic embarrassment. Self-embarrassment was significantly higher with the human actor than with the robot actor and was significantly higher in the embarrassed condition compared to the non-embarrassed condition. Actor-embarrassment in the embarrassed condition was significantly higher than the that in the non-embarrassed condition for each actor (human and robot) and the score for the embarrassed condition was significantly higher with the human actor compared to that with the robot actor. Skin conductance showed a nearly significantly higher response with the human actor compared to that with the robot actor in the embarrassed condition. In a subsequent experiment, we assessed the plausibility of the stimuli used in Experiment 1. Participants perceived the situation as significantly more real in the embarrassed condition with the human avatar compared to the embarrassed condition with the robot avatar (thoughts item). They also found the situation to be more real in the non-embarrassed condition with the robot avatar than in the embarrassed condition with the robot avatar (thoughts item). Additionally, the human avatar was considered more real than the robot avatar regardless of whether the scene involved embarrassing events or not (actor real item). The average scores of all items on the plausibility questionnaire indicated a significant difference between the embarrassed condition with the human avatar and the embarrassed condition with the robot avatar. Other items on the questionnaire (real, emotion, auto real, emotion to actor, and thoughts to actor items) did not exhibit significant differences across experiment conditions.

9.2 Enhancing embodiment towards partner controlled and autonomous prosthetic limbs

The research presented in this dissertation provides new insights into the factors that enhance embodiment towards both partner-controlled and autonomous prosthetic limbs. By introducing the concept of the joint avatar and exploring the impact of goal sharing, intention visibility, force feedback, and movement speed, this work advances our understanding of how to foster a deeper sense of embodiment in novel body forms. These findings may have significant implications for the design of VR systems, wearable robotics, and prosthetics, ultimately contributing to the future integration of cyberspace and physical reality in the evolving metaverse and Society 5.0.

Future cyberspaces and virtual societies such as the metaverse, and society 5.0 are expected to weaken the concepts of race, gender, and physical disability (Duan et al., 2021). Virtual embodiment enables us to feel an illusory body ownership towards avatars in different skin color (Peck et al., 2013), gender (Lopez et al., 2019), and size (Tambone et al., 2021), bodies that are invisible or transparent (Guterstm et al., 2013; Guterstam et al., 2015; Martini et al., 2015, Kondo et al., 2018, Kondo et al., 2020), and non-human agents (Hoffmaan et al., 2018) and animals (Krekhov et al., 2019). We are interested in the idea of minimizing physical disabilities of users in the virtual worlds through specially designed virtual avatars (Inami et al., 2022). Human movement augmentation such as supernumerary limbs, body-parts remapping, and exoskeletons expands physical abilities both for impaired and unimpaired individuals (Eden et al., 2022; Saski et al., 2017; Umezawa et al., 2022; Kondo et al., 2020). Virtual co-embodiments like the shared body (Hgiwara et al., 2020; Fribourg et al., 2020) and our joint body could expand human collaborations as a co-embodied avatar by combining different persons' strengths and compensating weaknesses. In social VR platforms, with appropriate software developments and accurate body movement tracking, it would be possible for multiple users to embody one avatar and engage in various tasks together. This may allow disabled VR users to get support from others and increase work efficiency as well as user satisfaction in the future. Our results suggest that a person's goal or intention of the co-embodiment avatar must be conveyed to the partner in vision or other modalities to maintain the least sense of agency to the other's controlling limb.

To mention some possible real-world applications of our results outside VR, previous work has shown that upper limb amputees can be made to experience a rubber hand as a part of their own body by applying synchronous touches to the stump, which was out of view, and to the index finger of a rubber hand placed in full view (Ehrsson et al., 2008). Our findings in Experiment 1 may contribute to similarly inducing illusory senses of ownership and agency towards robotic or autonomous prosthetics of amputees through visual stimulation manipulation (possibly with AR glasses paired with autonomous prosthetics). For example, if the autonomous prosthesis system shows its target to be reached or grasped to the amputee user immediately before the action is performed, the user may feel a higher prosthesis embodiment which may improve usability and naturalness of such robotic/autonomous prosthetics.

Another critical aspect of enhancing embodiment for partner-controlled limbs is the use of synchronized force feedback. Our work shows that passive movements applied to the upper body of participants, synchronized with the movements of the partner-controlled arm, significantly increases the sense of embodiment. This was also evidenced by changes in proprioceptive drift with participants reporting a heightened sense of ownership and agency towards the partner-controlled arm when the synchronized force feedback to the upper body was present. These findings highlight the importance of multisensory integration in fostering a deeper sense of embodiment. In addition to this unique type of force-feedback, other haptic feedback may also contribute to enhancing embodiment towards partner-controlled or autonomous arms.

In addition to partner-controlled limbs, this dissertation also explores the embodiment of autonomous prosthetic limbs. The movement speed of these limbs was identified as a critical factor influencing embodiment, usability, and robotic social attributes. Results suggest that there could be an optimal speed range for autonomous prosthetic limbs that enhances their embodiment and usability. However, such optimal speeds could be task dependent, and further investigation on the effect of movement speeds and trajectories of autonomous arms is necessary.

9.3 Social attributes towards robots and prosthetic limbs

Understanding social attributes towards robots and prosthetic limbs is crucial for enhancing human-robot interaction and ensuring the acceptance and usability of these technologies. This dissertation investigates how different factors influence perceptions of competence, warmth, and discomfort in relation to robotic and prosthetic limbs, both autonomous and partner-controlled, and explores empathic embarrassment towards robots.

Robotic social attributes significantly impact the user's overall experience and acceptance of these systems. Our study showed that discomfort, a negative emotional response, was inversely related to the sense of embodiment and usability, with moderate-speed movements causing the least discomfort. In partner-controlled limbs, the novel joint avatar, controlled by two individuals simultaneously, provided a unique opportunity to study social dynamics in an embodied perspective. However, with regards to the joint avatar, our focus was on sense of embodiment. It would be insightful to investigate social attributes towards partners during collaborations in joint or shared avatars in future studies.

Utilizing technologies such as VR, wearable robotics, and autonomous prosthetic limbs can allow us to extend our range of motion beyond our biological bodies. Especially when it comes to prosthetics, usually amputees tend to replace lost body parts with prostheses that move with the same human biological constraints. However, if we can learn how to embody movements beyond such typical human movements, there may be a future where augmented bodies with biologically impossible movements would be frequently embodied by humans to get various tasks done efficiently. With such unique prostheses amputees may even be at a physical advantage over healthy individuals in the future.

Therefore, we believe that more research on embodying various types of biomechanically impossible avatars, robots, prostheses etc. should be encouraged.

The dissertation also explores empathic embarrassment, a complex social emotion providing insights into human empathy towards robots. Participants observed human and robot avatars in embarrassing and non-embarrassing situations and rated their levels of self-embarrassment and actor-embarrassment. Results indicated higher self-embarrassment and actor-embarrassment for human avatars, especially in embarrassing situations, with physiological responses supporting these findings. Follow-up experiments on the plausibility and realism of the stimuli showed that human avatars were perceived as more real and plausible, contributing to higher empathic embarrassment.

9.4 Limitations and future directions

In Experiment 1, the findings regarding the embodiment towards the non-controlled arm among the three main experiment conditions were not supported by SCR results in this study. Therefore, further investigation of other physiological measures such as proprioceptive drifts and changes in body schema/body image due to experiencing of the joint avatar, may be more appropriate for assessing embodiment in future work.

In Experiment 2, while we could observe clear cognitive differences in the feeling of ownership and agency due to the introduction of connection induced upper body movements (in the tied condition), the three tests we chose to measure behavioral differences were inconclusive. We did not conduct physiological tests like skin conductance variations in response to a threatening stimulus (Armel & Ramachandran, 2003), hand temperature (Moseley et al., 2008) and somatosensory evoked potentials (Heydrich et al., 2018) due to the presence of movements in our task, which significantly reduce the signal to noise ratio of these tests. But these and other new behavioral tests are needed in future studies to get a deeper understanding of embodiment.

In experiment 3, the autonomous prosthetic arm moved in six different speeds and with those six conditions, we experimentally concluded a relationship between motion time and perceptual attributes of participants. However, it is not possible to conclude why the participants feel higher embodiment, usability, and lower discomfort at moderate speeds. Further investigation has to be done comparing optimal movement speeds obtained in the experiment with real human arm speeds for the same task in the future. Doing so may provide insights on whether human-like arm movement speeds enhance embodiment and reduce discomfort for autonomous prosthetic limbs.

In Experiment 4, we measured SCR as a countermeasure to get a physiological measure unaffected by demand characteristics of the participants associated with the questionnaire items on sense of agency and body ownership. However, from skin conductance data, as discussed previously, we did not get a result supporting the subjective ratings. Previous studies have shown that participants tend to respond in ways that confirmed the hypothesis, yet this tendency depends on attitudes toward the experiment or the experimenter and other individual differences (Nichols & Maner, 2008). Other recent studies also provide convincing evidence showing that participants can guess the aims of body illusion experiments (Lush, 2020; Lush et al., 2021; Reader, 2022). Therefore, the lack of action to minimize such demand characteristics is a limitation of the study.

An Asian male avatar was used in the first 4 experiments because most of the participants were Asian (Japanese) males. Appearance similarity between the participants and the virtual avatar affects embodiments; cartoon-like virtual avatar mimicking the outfit of the participant is better than the photorealistic avatar or dissimilar cartoon-like avatar (Jo et al., 2017). Thus, the similarity between the joint avatar and the individuals may possibly affect the results. This issue should be further investigated in the future.

With regards to age, gender and nationality, our results may have limitations. Majority of participants who participated in the experiments were Japanese male university students, causing a possible bias for male young adults in Japan. Gender and age can influence how individuals perceive and react to various situations and lack of diversity can introduce bias into the results (Brotto et al., 2021). Previous studies have shown an apparent gender effect associated with empathy, with a clear female superiority in empathic capability (Baron-Cohen & Wheelwright, 2004). It is also known that embarrassment is affected by cultures (Sueda & Wiseman, 1992; Imahori & Cupach, 1994). Familiarity and attitude to robots are affected by cultures as well (Haring et al., 2014; MacDorman et al., 2009). Therefore, further studies taking gender into account may be necessary to further understand the ability of humans to empathize with robots.

Chapter 10

Conclusions

This thesis explores the integration of virtual reality (VR) and robotics, inspired by the future vision of the metaverse and Society 5.0, where the convergence of physical and cyberspace aims to enhance human experience. Central to this research is the investigation of the sense of embodiment in novel bodies, including both virtual avatars and advanced prosthetics, and the emotional empathy experienced with virtual agents and autonomous robotic arms.

The first significant finding of this work is the introduction of the joint avatar, a novel concept of virtual co-embodiment where an avatar is controlled by two individuals simultaneously. This innovative approach allows for the study of embodiment towards partner-controlled limbs. The experiments showed that shared goals and visible partner intentions enhance the senses of body ownership and agency. However, participants consistently felt a stronger sense of ownership and agency towards the limbs they controlled, as evidenced by physiological measures such as skin conductance.

Another important aspect of this dissertation is the exploration of how passive upper body movements, synchronized with partner-controlled arm movements, affect embodiment. The findings revealed that force-feedback matching the partner's movements significantly increases both body ownership and agency, supported by changes in proprioceptive drift and body image. The research further investigated the perception of autonomous prosthetic limbs, demonstrating that movement speed significantly influences embodiment, usability, and robotic social attributes. Moderate-speed movements were found to be optimal for enhancing these attributes, while discomfort was inversely correlated with embodiment and usability.

A unique contribution of this dissertation is the study of biomechanically impossible movements and their embodiment in VR. Using an unnatural avatar with reverse-bending arms, the research showed that synchronous conditions significantly increase body ownership, even for non-human-like movements, although natural avatars generally received higher ratings.

Finally, the dissertation investigates empathic responses towards human and robotic avatars in embarrassing situations. The results indicated that humans elicit higher self-embarrassment and actor-embarrassment compared to robots, with physiological measures supporting these findings. The follow-up experiment on the plausibility of stimuli confirmed that human avatars were perceived as more real than robotic avatars, particularly in embarrassing contexts.

Overall, this dissertation provides experimental evidence on the factors affecting embodiment and empathy in virtual and robotic environments. The findings contribute to our understanding of human interaction in these contexts and offer insights that are crucial for the future development of integrated cyberspace and physical reality experiences. This work not only advances theoretical knowledge but also has practical implications for the design of VR systems, wearable robotics, and prosthetics, paving the way for enhanced human experiences in the evolving metaverse and Society 5.0.

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References

Armel, K. C., & Ramachandran, V. S. (2003). Projecting sensations to external objects: evidence from skin conductance response. Proceedings of the Royal Society of London. Series B: Biological Sciences, 270(1523), 1499-1506.

Aymerich-Franch, L., & Ganesh, G. (2016). The role of functionality in the body model for self-attribution. Neuroscience Research, 104, 31-37.

Aymerich-Franch, L., Petit, D., Ganesh, G., & Kheddar, A. (2015, June). Embodiment of a humanoid robot is preserved during partial and delayed control. In 2015 IEEE International Workshop on Advanced Robotics and its Social Impacts (ARSO) (pp. 1-5). IEEE.

Aymerich-Franch, L., Petit, D., Ganesh, G., & Kheddar, A. (2017). Object touch by a humanoid robot avatar induces haptic sensation in the real hand. Journal of Computer-Mediated Communication, 22(4), 215-230.

Aymerich-Franch, L., Petit, D., Ganesh, G., & Kheddar, A. (2016). The second me: Seeing the real body during humanoid robot embodiment produces an illusion of bi-location. Consciousness and Cognition, 46, 99-109.

Aymerich-Franch, L., Petit, D., Kheddar, A., & Ganesh, G. (2016). Forward modelling the rubber hand: illusion of ownership modifies motor-sensory predictions by the brain. Royal Society Open Science, 3(8), 160407.

Banakou, D., & Slater, M. (2014). Body ownership causes illusory self-attribution of speaking and influences subsequent real speaking. Proceedings of the National Academy of Sciences, 111(49), 17678-17683.

Banakou, D., Groten, R., & Slater, M. (2013). Illusory ownership of a virtual child body causes overestimation of object sizes and implicit attitude changes. Proceedings of the National Academy of Sciences, 110(31), 12846-12851.

Baron-Cohen, S., & Wheelwright, S. (2004). The empathy quotient: an investigation of adults with Asperger syndrome or high functioning autism, and normal sex differences. Journal of Autism and Developmental Disorders, 34, 163-175.

Bartneck, C., & Hu, J. (2008). Exploring the abuse of robots. Interaction Studies, 9(3), 415-433.

Batson, C. D., Batson, J. G., Slingsby, J. K., Harrell, K. L., Peekna, H. M., & Todd, R. M. (1991). Empathic joy and the empathy-altruism hypothesis. Journal of Personality and Social Psychology, 61(3), 413-426.

Batson, C. D., Early, S., & Salvarani, G. (1997). Perspective taking: Imagining how another feels versus imaging how you would feel. Personality and Social Psychology Bulletin, 23(7), 751-758.

Becklen, R., Wallach, H., & Nitzberg, R. (1984). A limitation of position constancy. Journal of Experimental Psychology: Human Perception and Performance, 10, 713–723.

Berger, C. C., Coppi, S., & Ehrsson, H. H. (2023). Synchronous motor imagery and visual feedback of finger movement elicit the moving rubber hand illusion, at least in illusion-susceptible individuals. Experimental Brain Research, 241(4), 1021-1039.

Bertoni, T., Mastria, G., Akulenko, N., Perrin, H., Zbinden, B., Bassolino, M., & Serino, A. (2023). The self and the Bayesian brain: testing probabilistic models of body ownership through a self-localization task. Cortex, 167, 247-272.

Blanke, O., & Metzinger, T. (2009). Full-body illusions and minimal phenomenal selfhood. Trends in Cognitive Sciences, 13(1), 7-13.

Botvinick, M., & Cohen, J. (1998). Rubber hands 'feel' touch that eyes see. Nature, 391(6669), 756-756.

Broadbent, E. (2017). Interactions with robots: The truths we reveal about ourselves. Annual Review of Psychology, 68(1), 627-652.

Brooke, J. (1996). SUS-A quick and dirty usability scale. Usability Evaluation in Industry, 189(194), 4-7.

Brotto, L. A., Chankasingh, K., Baaske, A., Albert, A., Booth, A., Kaida, A., ... & Galea, L. (2021). The influence of sex, gender, age, and ethnicity on psychosocial factors and substance use throughout phases of the COVID-19 pandemic. PLoS One, 16(11), e0259676.

Buss, A. H., Iscoe, I., & Buss, E. H. (1979). The development of embarrassment. Journal of Psychology, 103(2), 227-230.

Carpinella, C. M., Wyman, A. B., Perez, M. A., & Stroessner, S. J. (2017, March). The robotic social attributes scale (rosas) development and validation. In Proceedings of the 2017 ACM/IEEE International Conference on human-robot interaction (pp. 254-262).

Cheng, Y., Lin, C. P., Liu, H. L., Hsu, Y. Y., Lim, K. E., Hung, D., & Decety, J. (2007). Expertise modulates the perception of pain in others. Current Biology, 17(19), 1708-1713.

Costantini, M., & Haggard, P. (2007). The rubber hand illusion: sensitivity and reference frame for body ownership. Consciousness and Cognition, 16(2), 229-240.

Davis, M. H., Luce, C., & Kraus, S. J. (1994). The heritability of characteristics associated with dispositional empathy. Journal of Personality, 62(3), 369-391.

Ding, M. (2018). "Society 5.0": The Way of Implementation of Japan's Super Smart Society. Contemporary Economy of Japan, 3, 1-14.

Duan, H., Li, J., Fan, S., Lin, Z., Wu, X., & Cai, W. (2021, October). Metaverse for social good: A university campus prototype. In Proceedings of the 29th ACM International Conference on Multimedia (pp. 153-161).

Dummer, T., Picot-Annand, A., Neal, T., & Moore, C. (2009). Movement and the rubber hand illusion. Perception, 38(2), 271-280.

Edelmann, R. J. (1987). The psychology of embarrassment. John Wiley & Sons.

Eden, J., Bräcklein, M., Ibáñez, J., Barsakcioglu, D. Y., Di Pino, G., Farina, D., ... & Mehring, C. (2022). Principles of human movement augmentation and the challenges in making it a reality. Nature Communications, 13(1), 1345.

Ehrsson, H. H., Spence, C., & Passingham, R. E. (2004). That's my hand! Activity in premotor cortex reflects feeling of ownership of a limb. Science, 305(5685), 875-877.

Ehrsson, H. H., Rosén, B., Stockselius, A., Ragnö, C., Köhler, P., & Lundborg, G. (2008). Upper limb amputees can be induced to experience a rubber hand as their own. Brain, 131(12), 3443-3452.

Eisenberg, N., & Miller, P. A. (1987). Empathy, sympathy, and altruism: Empirical and conceptual links. In N. Eisenberg & J. Strayer (Eds.), Empathy and its development (pp. 292–316). Cambridge University Press.

Eller, A., Koschate, M., & Gilson, K. M. (2011). Embarrassment: The ingroup–outgroup audience effect in faux pas situations. European Journal of Social Psychology, 41(4), 489-500.

Erro, R., Marotta, A., Tinazzi, M., Frera, E., & Fiorio, M. (2018). Judging the position of the artificial hand induces a "visual" drift towards the real one during the rubber hand illusion. Scientific Reports, 8(1), 2531.

Farne, A., Pavani, F., Meneghello, F., & Ladavas, E. (2000). Left tactile extinction following visual stimulation of a rubber hand. Brain, 123(11), 2350-2360.

Faul, F., Erdfelder, E., Buchner, A., & Lang, A. G. (2009). Statistical power analyses using G* Power 3.1: Tests for correlation and regression analyses. Behavior Research Methods, 41(4), 1149-1160.

Faul, F., Erdfelder, E., Lang, A. G., & Buchner, A. (2007). G* Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. Behavior Research Methods, 39(2), 175-191.

Feinberg, M., Willer, R., & Keltner, D. (2012). Flustered and faithful: Embarrassment as a signal of prosociality. Journal of Personality and Social Psychology, 102(1), 81-97.

Ferreira, C. M., & Serpa, S. (2018). Society 5.0 and social development. Management and Organizational Studies, 5(4), 26-31.

Finstad, K. (2010). Response interpolation and scale sensitivity: Evidence against 5-point scales. Journal of Usability Studies, 5(3), 104-110.

Flash, T., & Hogan, N. (1985). The coordination of arm movements: an experimentally confirmed mathematical model. Journal of Neuroscience, 5(7), 1688-1703.

Fribourg, R., Ogawa, N., Hoyet, L., Argelaguet, F., Narumi, T., Hirose, M., & Lécuyer, A. (2020). 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, 27(10), 4023-4038.

Frischen, A., & Tipper, S. P. (2004). Orienting attention via observed gaze shift evokes longer term inhibitory effects: implications for social interactions, attention, and memory. Journal of Experimental Psychology: General, 133(4), 516-533.

Fujii, T., Guo, T., & Kamoshida, A. (2018). A consideration of service strategy of Japanese electric manufacturers to realize super smart society (Society 5.0). In Knowledge Management in Organizations: 13th International Conference, KMO 2018, Žilina, Slovakia, August 6–10, 2018, Proceedings 13 (pp. 634-645). Springer International Publishing.

Fukuoka, M., Nakamura, F., Verhulst, A., Inami, M., Kitazaki, M., & Sugimoto, M. (2023). Sensory Attenuation with a Virtual Robotic Arm Controlled Using Facial Movements. IEEE Transactions on Visualization and Computer Graphics.

Gallagher, S. (2000). Philosophical conceptions of the self: implications for cognitive science. Trends in Cognitive Sciences, 4(1), 14-21.

Gallotti, M., & Frith, C. D. (2013). Social cognition in the we-mode. Trends in Cognitive Sciences, 17(4), 160-165.

García-Valle, G., Ferre, M., Breñosa, J., & Vargas, D. (2017). Evaluation of presence in virtual environments: haptic vest and user's haptic skills. IEEE Access, 6, 7224-7233.

Gonzalez-Franco, M., & Peck, T. C. (2018). Avatar embodiment. towards a standardized questionnaire. Frontiers in Robotics and AI, 5, 74.

Gonzalez-Franco, M., Perez-Marcos, D., Spanlang, B., & Slater, M. (2010, March). The contribution of real-time mirror reflections of motor actions on virtual body ownership in an immersive virtual environment. In 2010 IEEE Virtual Reality Conference (VR) (pp. 111-114). IEEE.

Government of Japan. 2016a. The 5th Science and Technology Basic Plan. Provisional translation. January 22.

Government of Japan. 2016b. Outline of the Fifth Science and Technology Basic Plan. Provisional Translation.

Gu, X., & Han, S. (2007). Attention and reality constraints on the neural processes of empathy for pain. Neuroimage, 36(1), 256-267.

Guterstam, A., Abdulkarim, Z., & Ehrsson, H. H. (2015). Illusory ownership of an invisible body reduces autonomic and subjective social anxiety responses. Scientific Reports, 5(1), 9831.

Guterstam, A., Gentile, G., & Ehrsson, H. H. (2013). The invisible hand illusion: multisensory integration leads to the embodiment of a discrete volume of empty space. Journal of Cognitive Neuroscience, 25(7), 1078-1099.

Haggard, P. (2005). Conscious intention and motor cognition. Trends in Cognitive Sciences, 9(6), 290-295. doi: 10.1016/j.tics.2005.04.012

Hagiwara, T., Ganesh, G., Sugimoto, M., Inami, M., & Kitazaki, M. (2020). Individuals prioritize the reach straightness and hand jerk of a shared avatar over their own. iScience, 23(12): 101732.

Hagiwara, T., Katagiri, T., Yukawa, H., Ogura, I., Tanada, R., Nishimura, T., ... & Minamizawa, K. (2021). Collaborative Avatar Platform for Collective Human Expertise. SIGGRAPH Asia 2021 Emerging Technologies, 1-2.

Hapuarachchi, H., & Kitazaki, M. (2022). Knowing the intention behind limb movements of a partner increases embodiment towards the limb of joint avatar. Scientific Reports, 12(1), 11453.

Hapuarachchi, H., and Kitazaki, M. (2022). Knowing the partner's objective increases embodiment towards a limb controlled by the partner, IEEE VR 2022 Conference, 12-16 March 2022, Poster. Proceedings of IEEE VR 2022, 802-803.

Hapuarachchi, H., Hagiwara, T., Ganesh, G., & Kitazaki, M. (2023). Effect of connection induced upper body movements on embodiment towards a limb controlled by another during virtual co-embodiment. PLoS one, 18(1), e0278022.

Hapuarachchi, H., Higashihata, K., Sugiura, M., Sato, A., Itakura, S., & Kitazaki, M. (2023). Empathic embarrassment towards non-human agents in virtual environments. Scientific Reports, 13(1), 13914.

Hapuarachchi, H., Inoue, Y., & Kitazaki, M. (2023). Exploring Embodiment and Usability of Autonomous Prosthetic Limbs through Virtual Reality. In SIGGRAPH Asia 2023 Posters (pp. 1-2).

Hapuarachchi, H., Ishimoto, H., Kitazaki, M., Sugimoto, M., & Inami, M. (2023). Temporal visuomotor synchrony induces embodiment towards an avatar with biomechanically impossible arm movements. i-Perception, 14(6), 20416695231211699.

Hapuarachchi, H., Ishimoto, H., Sugimoto, M., Inami, M., & Kitazaki, M. (2022, October). Embodiment of an Avatar with Unnatural Arm Movements. In 2022 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct) (pp. 772-773). IEEE.

Harayama, Y. (2017). Society 5.0: Aiming for a new human-centered society. Hitachi Review, 66(6), 8-13.

Haring, K. S., Silvera-Tawil, D., Matsumoto, Y., Velonaki, M., & Watanabe, K. (2014, October). Perception of an android robot in Japan and Australia: A cross-cultural comparison. In International conference on social robotics (pp. 166-175). Springer, Cham.

Held, R., & Hein, A. V. (1958). Adaptation of disarranged hand-eye coordination contingent upon re-afferent stimulation. Perceptual and Motor Skills, 8(3), 87-90.

Henschel, A., Hortensius, R., & Cross, E. S. (2020). Social cognition in the age of human–robot interaction. Trends in Neurosciences, 43(6), 373-384.

Heydrich, L., Aspell, J. E., Marillier, G., Lavanchy, T., Herbelin, B., & Blanke, O. (2018). Cardio-visual full body illusion alters bodily self-consciousness and tactile processing in somatosensory cortex. Scientific Reports, 8(1), 9230.

Hoffman, M. L. (2001). Toward a comprehensive empathy-based theory of prosocial moral development. A.C. Bohart, D.J. Stipek (Eds.), Constructive & destructive behavior: Implications for family, school, & society, American Psychological Association, Washington, DC (2001), pp. 61-86.

Hoffmann, L., Bock, N., & vd Pütten, A. M. R. (2018, March). The peculiarities of robot embodiment (EmCorp-Scale): development, validation and initial test of the embodiment and corporeality of artificial agents scale. In 2018 13th ACM/IEEE International Conference on Human-Robot Interaction (HRI) (pp. 370-378). IEEE.

Hoffmann, L., Krämer, N. C., Lam-Chi, A., & Kopp, S. (2009). Media equation revisited: do users show polite reactions towards an embodied agent?. In Intelligent Virtual Agents: 9th International Conference, IVA 2009 Amsterdam, The Netherlands, September 14-16, 2009 Proceedings 9 (pp. 159-165). Springer Berlin Heidelberg.

Honma, M., Koyama, S., & Osada, Y. (2009). Double tactile sensations evoked by a single visual stimulus on a rubber hand. Neuroscience Research, 65(3), 307-311.

Hortensius, R., Hekele, F., & Cross, E. S. (2018). The perception of emotion in artificial agents. IEEE Transactions on Cognitive and Developmental Systems, 10(4), 852-864.

Imahori, T. T., & Cupach, W. R. (1994). A cross-cultural comparison of the interpretation and management of face: US American and Japanese responses to embarrassing predicaments. International Journal of Intercultural Relations, 18(2), 193-219.

Inami, M., Uriu, D., Kashino, Z., Yoshida, S., Saito, H., Maekawa, A., and Kitazaki, M. (2022). Cyborgs, Human Augmentation, Cybernetics, and JIZAI Body, In Proceedings of Augmented Humans 2022.

Inoue, Y., & Kitazaki, M. (2010). Effects of biomechanical constraint on view-dependency and the inversion effect in human-posture recognition. Shinrigaku Kenkyu: The Japanese Journal of Psychology, 81(2), 105-113.

Inoue, Y., & Kitazaki, M. (2021). Virtual mirror and beyond: The psychological basis for avatar embodiment via a mirror. Journal of Robotics and Mechatronics, 33(5), 1004-1012.

Iwano, K., Kimura, Y., Takashima, Y., Bannai, S., & Yamada, N. (2017). Future services & societal systems in society 5.0. In Workshop Report. Center for Research and Development Strategy Japan Science and Technology Agency.

Iwasaki, Y., Navarro, B., Iwata, H., & Ganesh, G. (2022). Embodiment modifies attention allotment for the benefit of dual task performance. Communications Biology, 5(1), 701.

Jackson, P. L., Meltzoff, A. N., & Decety, J. (2005). How do we perceive the pain of others? A window into the neural processes involved in empathy. Neuroimage, 24(3), 771-779.

Jo, D., Kim, K., Welch, G. F., Jeon, W., Kim, Y., Kim, K. H., & Kim, G. J. (2017, November). The impact of avatar-owner visual similarity on body ownership in immersive virtual reality. In Proceedings of the 23rd ACM Symposium on Virtual Reality Software and Technology (pp. 1-2).

Joshi, A., Kale, S., Chandel, S., & Pal, D. K. (2015). Likert scale: Explored and explained. British Journal of Applied Science & Technology, 7(4), 396-403.

Kalckert, A., & Ehrsson, H. H. (2012). Moving a rubber hand that feels like your own: a dissociation of ownership and agency. Frontiers in Human Neuroscience, 6, 40.

Kalckert, A., & Ehrsson, H. H. (2014). The moving rubber hand illusion revisited: Comparing movements and visuotactile stimulation to induce illusory ownership. Consciousness and Cognition, 26, 117-132.

Katsumata, Y., Inoue, Y., Toriumi, S., Ishimoto, H., Hapuarachchi, H., & Kitazaki, M. (2023). Shared Avatar for Hand Movement Imitation: Subjective and Behavioral Analyses. IEEE Access.

Kilteni, K., Normand, J. M., Sanchez-Vives, M. V., & Slater, M. (2012). Extending body space in immersive virtual reality: a very long arm illusion. PLoS one, 7(7), e40867.

Kilteni, K., Groten, R., & Slater, M. (2012). The Sense of Embodiment in Virtual Reality. Presence: Teleoperators and Virtual Environments, 21(4), 373-387.

Kitazaki, M. (2013), Effects of retinal position on visuo-motor adaptation of visual stability in a virtual environment, i-Perception, 4(4), 242–252.s

Kodama, D., Mizuho, T., Hatada, Y., Narumi, T., & Hirose, M. (2023). Effects of collaborative training using virtual co-embodiment on motor skill learning. IEEE Transactions on Visualization and Computer Graphics, 29(5), 2304-2314.

Koilias, A., Mousas, C., & Anagnostopoulos, C. N. (2019). The effects of motion artifacts on self-avatar agency. Informatics, 6(2):18s

Kokkinara, E., & Slater, M. (2014). Measuring the effects through time of the influence of visuomotor and visuotactile synchronous stimulation on a virtual body ownership illusion. Perception, 43(1), 43-58.

Kondo, R., Sugimoto, M., Minamizawa, K., Hoshi, T., Inami, M., & Kitazaki, M. (2018). Illusory body ownership of an invisible body interpolated between virtual hands and feet via visual-motor synchronicity. Scientific Reports, 8: 7541.

Kondo, R., Tani, Y., Sugimoto, M., Inami, M., and Kitazaki, M. (2020a). Scrambled body differentiates body part ownership from the full body illusion. Scientific Reports, 10(1), 5274.

Kondo, R., Tani, Y., Sugimoto, M., Minamizawa, K., Inami, M., and Kitazaki, M. (2020b). Re-association of Body Parts: Illusory Ownership of a Virtual Arm Associated with the Contralateral Real Finger by Visuo-motor Synchrony. Frontiers in Robotics and AI: Virtual Environments, 7:26.

Krakauer, J. W. (2009). Motor learning and consolidation: the case of visuomotor rotation. In Progress in Motor Control: A Multidisciplinary Perspective, Sternad, D. (ed), pp.405-421, Springer New York, NY.

Krebs, D. (1975). Empathy and altruism. Journal of Personality and Social Psychology, 32(6), 1134-1146.

Kreimeier, J., & Götzelmann, T. (2019, May). First steps towards walk-in-place locomotion and haptic feedback in virtual reality for visually impaired. In Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems (pp. 1-6).

Krekhov, A., Cmentowski, S., & Krüger, J. (2019, August). The illusion of animal body ownership and its potential for virtual reality games. In 2019 IEEE Conference on Games (CoG) (pp. 1-8). IEEE.

Krekhov, A., Cmentowski, S., Emmerich, K., & Krüger, J. (2019, October). Beyond human: Animals as an escape from stereotype avatars in virtual reality games. In Proceedings of the Annual Symposium on Computer-Human Interaction in Play (pp. 439-451).

Krogmeier, C., Mousas, C., & Whittinghill, D. (2019). Human–virtual character interaction: Toward understanding the influence of haptic feedback. Computer Animation and Virtual Worlds, 30(3-4), e1883.

Lamm, C., Nusbaum, H. C., Meltzoff, A. N., & Decety, J. (2007). What are you feeling? Using functional magnetic resonance imaging to assess the modulation of sensory and affective responses during empathy for pain. PloS one, 2(12), e1292.

Lemole Jr, G. M., Banerjee, P. P., Luciano, C., Neckrysh, S., & Charbel, F. T. (2007). Virtual reality in neurosurgical education: part-task ventriculostomy simulation with dynamic visual and haptic feedback. Neurosurgery, 61(1), 142-149.

Lenggenhager, B., Mouthon, M., & Blanke, O. (2009). Spatial aspects of bodily self-consciousness. Consciousness and Cognition, 18(1), 110-117.

Lewis, M., Sullivan, M. W., Stanger, C., & Weiss, M. (1989). Self development and self-conscious emotions. Child Development, 146-156.

Lopez, S., Yang, Y., Beltran, K., Kim, S. J., Cruz Hernandez, J., Simran, C., ... & Yuksel, B. F. (2019, May). Investigating implicit gender bias and embodiment of white males in virtual reality with full body visuomotor synchrony. In Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (pp. 1-12).

Lush, P. (2020). Demand characteristics confound the rubber hand illusion. Collabra: Psychology, 6(1), 22.

Lush, P., Seth, A. K., & Dienes, Z. (2021). Hypothesis awareness confounds asynchronous control conditions in indirect measures of the rubber hand illusion. Royal Society Open Science, 8(11), 210911.

MacDorman, K. F., Green, R. D., Ho, C. C., & Koch, C. T. (2009). Too real for comfort? Uncanny responses to computer generated faces. Computers in Human Behavior, 25(3), 695-710.

Martini, M., Kilteni, K., Maselli, A., & Sanchez-Vives, M. V. (2015). The body fades away: investigating the effects of transparency of an embodied virtual body on pain threshold and body ownership. Scientific Reports, 5(1), 13948.

Matamala-Gomez, M., Malighetti, C., Cipresso, P., Pedroli, E., Realdon, O., Mantovani, F., & Riva, G. (2020). Changing body representation through full body ownership illusions might foster motor rehabilitation outcome in patients with stroke. Frontiers in Psychology, 11, 1962.

Metzinger, T. (2007). Empirical perspectives from the self-model theory of subjectivity: a brief summary with examples. Progress in Brain Research, 168, 215-278.

Miller, R. S. (1987). Empathic embarrassment: Situational and personal determinants of reactions to the embarrassment of another. Journal of Personality and social Psychology, 53(6), 1061-1069.

Miller, R. S., & Tangney, J. P. (1994). Differentiating embarrassment and shame. Journal of Social and Clinical Psychology, 13(3), 273-287.

Montada, L., & Schneider, A. (1989). Justice and emotional reactions to the disadvantaged. Social Justice Research, 3(4), 313-344.

Morita, T., Slaughter, V., Katayama, N., Kitazaki, M., Kakigi, R., & Itakura, S. (2012). Infant and adult perceptions of possible and impossible body movements: An eye-tracking study. Journal of Experimental Child Psychology, 113(3), 401-414.

Moseley, G. L., Olthof, N., Venema, A., Don, S., Wijers, M., Gallace, A., & Spence, C. (2008). Psychologically induced cooling of a specific body part caused by the illusory ownership of an artificial counterpart. Proceedings of the National Academy of Sciences, 105(35), 13169-13173.

Nass, C., Moon, Y., & Green, N. (1997). Are machines gender neutral? Gender-stereotypic responses to computers with voices. Journal of Applied Social Psychology, 27(10), 864-876.

Neyret, S., Navarro, X., Beacco, A., Oliva, R., Bourdin, P., Valenzuela, J., ... & Slater, M. (2020). An embodied perspective as a victim of sexual harassment in virtual reality reduces action conformity in a later milgram obedience scenario. Scientific Reports, 10(1), 6207.

Nichols, A. L., & Maner, J. K. (2008). The good-subject effect: Investigating participant demand characteristics. The Journal of General Psychology, 135(2), 151-166.

Nishio, S., Watanabe, T., Ogawa, K., & Ishiguro, H. (2012, October). Body ownership transfer to teleoperated android robot. In International conference on social robotics (pp. 398-407). Berlin, Heidelberg: Springer Berlin Heidelberg.

Nomura, T., Uratani, T., Kanda, T., Matsumoto, K., Kidokoro, H., Suehiro, Y., & Yamada, S. (2015, March). Why do children abuse robots?. In Proceedings of the Tenth Annual ACM/IEEE International Conference on Human-robot Interaction Extended Abstracts (pp. 63-64).

Ocklenburg, S., Rüther, N., Peterburs, J., Pinnow, M., & Güntürkün, O. (2011). Laterality in the rubber hand illusion. Laterality, 16(2), 174-187.

Pan, M. K., Knoop, E., Bächer, M., & Niemeyer, G. (2019, November). Fast handovers with a robot character: Small sensorimotor delays improve perceived qualities. In 2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) (pp. 6735-6741). IEEE.

Peck, T. C., & Gonzalez-Franco, M. (2021). Avatar embodiment. a standardized questionnaire. Frontiers in Virtual Reality, 1, 44.

Peck, T. C., Seinfeld, S., Aglioti, S. M., & Slater, M. (2013). Putting yourself in the skin of a black avatar reduces implicit racial bias. Consciousness and Cognition, 22(3), 779-787.

Peck, T. C., Sockol, L. E., & Hancock, S. M. (2020). Mind the gap: The underrepresentation of female participants and authors in virtual reality research. IEEE Transactions on Visualization and Computer Graphics, 26(5), 1945-1954.

Petit, L., & Harris, I. (2005). Anatomical limitations in mental transformations of body parts. Visual Cognition, 12(5), 737-758.

Petkova, V. I., & Ehrsson, H. H. (2008). If I were you: perceptual illusion of body swapping. PLoS one, 3(12), e3832.

Petkova, V. I., Khoshnevis, M., & Ehrsson, H. H. (2011). The perspective matters! Multisensory integration in ego-centric reference frames determines full-body ownership. Frontiers in Psychology, 2, 35.

Pinardi, M., Ferrari, F., D'alonzo, M., Clemente, F., Raiano, L., Cipriani, C., & Di Pino, G. (2020). Doublecheck: a sensory confirmation is required to own a robotic hand, sending a command to feel in charge of it. Cognitive Neuroscience, 11(4), 216-228.

Prasetyo, Y. A., & Arman, A. A. (2017, October). Group management system design for supporting society 5.0 in smart society platform. In 2017 International Conference on Information Technology Systems and Innovation (ICITSI) (pp. 398-404). IEEE.

Preston, C., & Ehrsson, H. H. (2014). Illusory changes in body size modulate body satisfaction in a way that is related to non-clinical eating disorder psychopathology. PloS one, 9(1), e85773.

Reader, A. T. (2022). What do participants expect to experience in the rubber hand illusion? A conceptual replication of Lush (2020). Collabra: Psychology, 8(1), 35743.

Redding, G. M., & Wallace, B. (1993). Adaptive coordination and alignment of eye and hand. Journal of Motor Behavior, 25(2), 75-88.

Redding, G. M., Rossetti, Y., & Wallace, B. (2005). Applications of prism adaptation: a tutorial in theory and method. Neuroscience & Biobehavioral Reviews, 29(3), 431-444.

Reed, C. L., Stone, V. E., Bozova, S., & Tanaka, J. (2003). The body-inversion effect. Psychological Science, 14(4), 302-308.

Reeves, B., & Nass, C. (1996). The media equation: How people treat computers, television, and new media like real people. Cambridge, UK, 10, 236605.

Richard, G., Pietrzak, T., Argelaguet, F., Lécuyer, A., & Casiez, G. (2021). Studying the role of haptic feedback on virtual embodiment in a drawing task. Frontiers in Virtual Reality, 1, 573167.

Riek, L. D., Rabinowitch, T. C., Chakrabarti, B., & Robinson, P. (2009, March). How anthropomorphism affects empathy toward robots. In Proceedings of the 4th ACM/IEEE international conference on Human robot interaction (pp. 245-246).

Rorden, C., Heutink, J., Greenfield, E., & Robertson, I. H. (1999). When a rubber hand 'feels' what the real hand cannot. Neuroreport, 10(1), 135-138.

Rosenthal-von der Pütten, A. M., Krämer, N. C., Hoffmann, L., Sobieraj, S., & Eimler, S. C. (2013). An experimental study on emotional reactions towards a robot. International Journal of Social Robotics, 5(1), 17-34.

Rosenthal-Von Der Pütten, A. M., Schulte, F. P., Eimler, S. C., Sobieraj, S., Hoffmann, L., Maderwald, S., … & Krämer, N. C. (2014). Investigations on empathy towards humans and robots using fMRI. Computers in Human Behavior, 33, 201-212.

Sakurada, K., Kondo, R., Nakamura, F., Kitazaki, M., & Sugimoto, M. (2023). Investigating the perceptual attribution of a virtual robotic limb synchronizing with hand and foot simultaneously. Frontiers in Virtual Reality, 4, 1210303.

Sanchez-Vives, M. V., Spanlang, B., Frisoli, A., Bergamasco, M., & Slater, M. (2010). Virtual hand illusion induced by visuomotor correlations. PLoS one, 5(4), e10381.

Sasaki, T., Saraiji, M. Y., Fernando, C. L., Minamizawa, K., & Inami, M. (2017). MetaLimbs: Multiple arms interaction metamorphism. In ACM SIGGRAPH 2017 Emerging Technologies (pp. 1-2).

Schaal, S. (2007). The new robotics—towards human-centered machines. HFSP journal, 1(2), 115-126.

Sebanz, N., Bekkering, H., & Knoblich, G. (2006). Joint action: bodies and minds moving together. Trends in Cognitive Sciences, 10(2), 70-76.

Shibata, M., Ohtsuka, Y., Okamoto, K., & Takahashi, M. (2017, July). Toward an efficient search method to capture the future MOT curriculum based on the society 5.0. In 2017 Portland International Conference on Management of Engineering and Technology (PICMET) (pp. 1-7). IEEE.

Slater, M. (2009). Place illusion and plausibility can lead to realistic behaviour in immersive virtual environments. Philosophical Transactions of the Royal Society B: Biological Sciences, 364(1535), 3549-3557.

Slater, M., Banakou, D., Beacco, A., Gallego, J., Macia-Varela, F., & Oliva, R. (2022). A separate reality: an update on place illusion and plausibility in virtual reality. Frontiers in Virtual Reality, 3, 81.

Slater, M., Spanlang, B., Sanchez-Vives, M. V., & Blanke, O. (2010). First person experience of body transfer in virtual reality. PLoS one, 5(5), e10564.

Smith, K. D., Keating, J. P., & Stotland, E. (1989). Altruism reconsidered: The effect of denying feedback on a victim's status to empathic witnesses. Journal of Personality and Social Psychology, 57(4), 641-650.

Spanlang, B., Normand, J. M., Borland, D., Kilteni, K., Giannopoulos, E., Pomés, A., ... & Slater, M. (2014). How to build an embodiment lab: achieving body representation illusions in virtual reality. Frontiers in Robotics and AI, 1, 9.

Stocks, E. L., Lishner, D. A., Waits, B. L., & Downum, E. M. (2011). I'm embarrassed for you: The effect of valuing and perspective taking on empathic embarrassment and empathic concern. Journal of Applied Social Psychology, 41(1), 1-26.

Stratton, G. M. (1896). Some preliminary experiments on vision without inversion of the retinal image. Psychological Review, 3, 611–617.

Sueda, K., & Wiseman, R. L. (1992). Embarrassment remediation in Japan and the United States. International Journal of Intercultural Relations, 16(2), 159-173.

Sugiura, M., Higashihata, K., Sato, A., Itakura, S., and Kitazaki, M. (2020). Empathy with Human's and Robot's Embarrassments in Virtual Environments, ICAT-EGVE 2020. Poster

Suzuki, Y., Galli, L., Ikeda, A., Itakura, S., & Kitazaki, M. (2015). Measuring empathy for human and robot hand pain using electroencephalography. Scientific Reports, 5(1), 15924.

Synofzik, M., Thier, P., & Lindner, A. (2006). Internalizing agency of self-action: perception of one's own hand movements depends on an adaptable prediction about the sensory action outcome. Journal of Neurophysiology, 96(3), 1592-1601.

Synofzik, M., Vosgerau, G., & Newen, A. (2008). Beyond the comparator model: a multifactorial two-step account of agency. Consciousness and Cognition, 17(1), 219-239.

Tai, W., He, L., Zhang, X., Pu, J., Voronin, D., Jiang, S., ... & Du, L. (2020). Characterization of the receptor-binding domain (RBD) of 2019 novel coronavirus: implication for development of RBD protein as a viral attachment inhibitor and vaccine. Cellular & Molecular Immunology, 17(6), 613-620.

Tajadura-Jiménez, A., Banakou, D., Bianchi-Berthouze, N., & Slater, M. (2017). Embodiment in a child-like talking virtual body influences object size perception, self-identification, and subsequent real speaking. Scientific Reports, 7(1), 9637.

Tambone, R., Poggio, G., Pyasik, M., Burin, D., Dal Monte, O., Schintu, S., ... & Pia, L. (2021). Changing your body changes your eating attitudes: embodiment of a slim virtual avatar induces avoidance of high-calorie food. Heliyon, 7(7), e07515.

Tangney, J. P. (1999). The self-conscious emotions: Shame, guilt, embarrassment and pride. In T. Dalgleish & M. J. Power (Eds.), Handbook of cognition and emotion (pp. 541–568). John Wiley & Sons Ltd.

Tollefsen, D. (2005). Let's pretend! Children and joint action. Philosophy of the Social Sciences, 35(1), 75-97.

Toothman, N., & Neff, M. (2019, March). The impact of avatar tracking errors on user experience in VR. In 2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR) (pp. 756-766). IEEE.

Tosi, G., Mentesana, B., & Romano, D. (2023). The correlation between proprioceptive drift and subjective embodiment during the rubber hand illusion: A meta-analytic approach. Quarterly Journal of Experimental Psychology, 17470218231156849.

Tsakiris, M., & Haggard, P. (2005). The rubber hand illusion revisited: visuotactile integration and self-attribution. Journal of Experimental Psychology: Human Perception and Performance, 31(1), 80-91.

Tsakiris, M., Hesse, M. D., Boy, C., Haggard, P., & Fink, G. R. (2007). Neural signatures of body ownership: A sensory network for bodily self-consciousness. Cerebral Cortex, 17(10), 2235-2244.

Tsakiris, M., Prabhu, G., & Haggard, P. (2006). Having a body versus moving your body: How agency structures body-ownership. Consciousness and Cognition, 15(2), 423-432.

Tsuji, T., Yamakawa, H., Yamashita, A., Takakusaki, K., Maeda, T., Kato, M., ... & Asama, H. (2013, November). Analysis of electromyography and skin conductance response during rubber hand illusion. In 2013 IEEE Workshop on Advanced Robotics and its Social Impacts (pp. 88-93). IEEE.

Umezawa, K., Suzuki, Y., Ganesh, G., & Miyawaki, Y. (2022). Bodily ownership of an independent supernumerary limb: an exploratory study. Scientific Reports, 12(1), 2339.

Van Der Hoort, B., & Ehrsson, H. H. (2016). Illusions of having small or large invisible bodies influence visual perception of object size. Scientific Reports, 6(1), 34530.

Van Der Hoort, B., Guterstam, A., & Ehrsson, H. H. (2011). Being Barbie: the size of one's own body determines the perceived size of the world. PloS one, 6(5), e20195.

Vesper, C., Abramova, E., Bütepage, J., Ciardo, F., Crossey, B., Effenberg, A., ... & Wahn, B. (2017). Joint action: mental representations, shared information and general mechanisms for coordinating with others. Frontiers in Psychology, 7, 2039.

Vitaglione, G. D., & Barnett, M. A. (2003). Assessing a new dimension of empathy: Empathic anger as a predictor of helping and punishing desires. Motivation and Emotion, 27(4), 301-325.

Von der Pütten, A. M., Krämer, N. C., Gratch, J., & Kang, S. H. (2010). "It doesn't matter what you are!" Explaining social effects of agents and avatars. Computers in Human Behavior, 26(6), 1641-1650.

Wallach, H. (1987). Perceiving a stable environment when one moves. Annual Review of Psychology, 38, 1–27.

Walsh, L. D., Moseley, G. L., Taylor, J. L., & Gandevia, S. C. (2011). Proprioceptive signals contribute to the sense of body ownership. The Journal of physiology, 589(12), 3009-3021.

Wegner, D. M., & Wheatley, T. (1999). Apparent mental causation: Sources of the experience of will. American Psychologist, 54(7), 480-492.

Wegner, D. M., Sparrow, B., & Winerman, L. (2004). Vicarious agency: experiencing control over the movements of others. Journal of Personality and Social Psychology, 86(6), 838-848.

Weijs, M. L., Macartney, E., Daum, M. M., & Lenggenhager, B. (2021). Development of the bodily self: Effects of visuomotor synchrony and visual appearance on virtual embodiment in children and adults. Journal of Experimental Child Psychology, 210, 105200.

Welch, R. B. (1969). Adaptation to prism-distorted vision: The importance of target-pointing. Perception & Psychophysics, 5, 305–309.

Wen, W., Muramatsu, K., Hamasaki, S., An, Q., Yamakawa, H., Tamura, Y., ... & Asama, H. (2016). Goal-directed movement enhances body representation updating. Frontiers in Human Neuroscience, 10, 329.

Wen, W. (2019). Does delay in feedback diminish sense of agency? A review. Consciousness and Cognition, 73, 102759.

Wiese, E., Metta, G., & Wykowska, A. (2017). Robots as intentional agents: using neuroscientific methods to make robots appear more social. Frontiers in Psychology, 8, 1663.

Wobbrock, J. O., Findlater, L., Gergle, D., & Higgins, J. J. (2011, May). The aligned rank transform for nonparametric factorial analyses using only anova procedures. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (pp. 143-146).

Yuan, Y., & Steed, A. (2010, March). Is the rubber hand illusion induced by immersive virtual reality?. In 2010 IEEE Virtual Reality Conference (VR) (pp. 95-102). IEEE.

Publication list

Journal papers

Hapuarachchi, H., & Kitazaki, M. (2022). Knowing the intention behind limb movements of a partner increases embodiment towards the limb of joint avatar. Scientific Reports, 12(1), 11453.

Hapuarachchi, H., Hagiwara, T., Ganesh, G., & Kitazaki, M. (2023). Effect of connection induced upper body movements on embodiment towards a limb controlled by another during virtual co-embodiment. PLoS one, 18(1), e0278022.

Hapuarachchi, H., Higashihata, K., Sugiura, M., Sato, A., Itakura, S., & Kitazaki, M. (2023). Empathic embarrassment towards non-human agents in virtual environments. Scientific Reports, 13(1), 13914.

Hapuarachchi, H., Ishimoto, H., Kitazaki, M., Sugimoto, M., & Inami, M. (2023). Temporal visuomotor synchrony induces embodiment towards an avatar with biomechanically impossible arm movements. i-Perception, 14(6), 20416695231211699.

Conference proceedings

Hapuarachchi, H., & Kitazaki, M. (2022, March). Knowing the partner's objective increases embodiment towards a limb controlled by the partner. In 2022 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW) (pp. 802-803). IEEE.

Hapuarachchi, H., Ishimoto, H., Sugimoto, M., Inami, M., & Kitazaki, M. (2022, October). Embodiment of an avatar with unnatural arm movements. In 2022 IEEE international symposium on mixed and augmented reality adjunct (ISMAR-adjunct) (pp. 772-773). IEEE.

Hapuarachchi, H., Ishimoto, H., Kato, Y., and Kitazaki, M. (2023, March). Embodiment of an Unnatural Avatar studied in VRChat Laboratory. 2023 the 7th International Conference on Virtual and Augmented Reality Simulations (ICVARS 2023) and 16th the International Conference on Computer and Automation Engineering (ICCAE), 1 page.

Hapuarachchi, H., Inoue, Y., & Kitazaki, M. (2023). Exploring Embodiment and Usability of Autonomous Prosthetic Limbs through Virtual Reality. In SIGGRAPH Asia 2023 Posters (pp. 1-2).