The Sense of Embodiment in Augmented Reality

Inducing a Third Arm Illusion with Multimodal Feedback

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Abstract

In Augmented Reality (AR) people can interact with virtual objects, but there is a problem if these objects are too far away to reach. A solution could be to add a virtual hand, which can be used alongside the real hands, and can cover a larger distance. Ideally, this hand should be experienced like a real hand to make the interaction more natural. This experience is called the Sense of Embodiment (SoE). From the literature, we know that it is possible to induce the SoE in Virtual Reality (VR) over extended bodies, thus we can speculate that it should also be possible to induce the SoE in AR, where the real body is visible. Yet, there are fundamental differences between AR and VR, i.e. the visual presence of the real body in AR compared to a virtual body or no body in VR. Thus, we could not exactly copy the setups used in VR research to investigate our theory. Therefore we did three pilot studies to research visual-motor feedback, visual-tactile feedback and the visual presence of the real arm. We found two main factors to take into account, which are the visual appearance of the virtual hand and the congruency of the multimodal feedback. In a detailed experiment, we show that despite a significant effect of visual-tactile and visual-motor feedback, it is surprisingly not possible to induce ownership with our setup, due to the uncanny valley effect. We therefore conclude that, if at all, such ownership in AR may only appear if the virtual hand appears either very realistic or very abstract. Our results also show that the visual presence of the real hand does not affect the sense of agency, and it prevents a shift in sense of location, but caused some participants to experience that their left hand was in two locations simultaneously. This is promising as it may suggest that ones perception of location can be split, which could be the focus of a follow-up study.

Acknowledgements

I would first like to thank my daily supervisor Nina Rosa MSc, who provided me with much needed feedback and support throughout the entire master thesis. I also want to thank my first and second supervisors Dr. Wolfgang Hürst and Prof. Peter Werkhoven for their guidance and how they kept me engaged in this project due to their enthusiasm during the meetings. Also, I would like to thank my participants, who readily spent their time to help me with my experiments. Lastly, I want to thank my family, friends and especially my boyfriend, who stuck with me during this stressful period and encouraged me to make the most of it. This would not have been possible without them.

Contents

Preface

This thesis investigates how multi modal feedback affects the Sense of Embodiment, i.e. body ownership, agency and arm-location, towards a separate virtual arm in Augmented Reality (AR) when the real arms are visually present. To accomplish this, an initial goal was to find a setup which can be used for the experiments presented in this work, as the existing Virtual Reality (VR) setups do not take the visual presence of the real hands into account.

The major deliverables of this thesis are:

- An initial literature study identifying the state-of-the-art of the Sense of Embodiment in reality, VR and AR and the benefits it provides. Differences between the user experience in AR and VR are specified and the necessity of further investigation of this subject is discussed together with the necessity for a new setup in AR, where the real arms are visually present. This can be found in Chapter 1.
- A research proposal, as a result of the literature study, which concisely states the research question and discusses the goals and objectives of this study. These consist of the main goal of studying the Sense of Embodiment over an additional virtual hand in AR and an initial goal of finding a setup. It can be found in Chapter 2.
- A detailed report of the pilot studies conducted to find an appropriate experiment setup, which can be found in Chapter 3.
- A scientific paper discussing the performed experiment, which can be found in Chapter 4.

Further contributions and deliverables of this thesis include:

- Related source code and programs used in the scientific experiments.
- A video containing a description and the results of the experiment, targeted at a broad audience: *https://youtu.be/AUfVygYCS6I*

Chapter 1

A Literature Study of the Virtual Sense of Embodiment

1 Introduction

In our everyday lives we take for granted that we *have* a body and that it feels as *our* body. The question of what induces this feeling has occupied philosophers, psychologists and neuroscientists for some time. The experience of having a body is described by Kilteni et al. as the Sense of Embodiment (SoE) in [14], with the following definition:

> "SoE toward a body B is the sense that emerges when B's properties are processed as if they were the properties of one's own biological body."

We want to add to this definition, that one can also consciously take action with B as one would with one's own body. Three subcomponents of the SoE are body ownership, agency and self-location. Body ownership is defined as the feeling that the body is the source of experienced sensations [14] and it is often mentioned in the same context as agency [38, 5, 10] and self-localization [17]. Agency refers to the sense of having motor control over the body and self-localization represents the feeling of residing inside a body.

Since the use of Virtual Reality (VR) techniques in SoE research, this field has sparked the interest of computer scientists, as it could have benefits for various VR and Augmented Reality (AR) application areas. As a result of body ownership VR applications are an effective tool for rehabilitation and psychological treatment, such as phantom limb pain, eating disorders or burns [23, 13, 27]. Secondly, it has a positive influence on the effectiveness of immersive virtual simulation training [36, 42], due to a possible connection between body ownership and presence, where the latter is associated with how well a person's behavior in immersive VR matches real life behavior [32]. Finally, agency and ownership could increase a user's physical performance in VR applications. As agency is defined as the sense of motor control over the body, we could argue that a person, who experiences a higher level of control of the body, could have an increased physical task performance. Several experiments indicate a higher sense of agency when body ownership is present [10, 11, 35].

In contrast to VR, AR usually allaws us to see our real body and virtual objects are placed into our real environment. Sometimes, there is a desire to directly interact with these virtual objects. When these objects are out of reach of the user's hands, the addition of a virtual hand, which can cover a larger distance than the real hand, could be a solution. The SoE for this application is not only important for the user experience of the virtual hand, but it could also give the benefit of increased physical task performance when the virtual hand interacts with the virtual objects. Unfortunately we cannot directly transfer results from VR research to AR, nor can we copy a VR setup for AR research, because of the visual presence of the real hands in AR, and the mixed realities in AR compared to a completely virtual environment in VR. In the next sections we will look into the literature of the SoE in reality, VR and AR to find indications for the design of a setup that is needed to study the SoE in AR.

2 The Rubber Hand Illusion

The most famous illusion to investigate ownership is the Rubber Hand Illusion (RHI), first described by Botvinick and Cohen [1] and adapted by many others [39, 5, 11]. In the RHI the participant experiences ownership over a rubber hand. The real hand of the participant lays on a table behind a standing screen hidden from view of the participant. A life-sized rubber hand is then placed in front of the participant. The rubber hand and the real hand are then stroked simultaneously with a brush (Figure 1.1A). Experienced body ownership was measured by questionnaire and proprioceptive drift, which are now seen as standard measures.

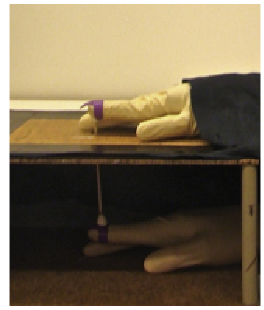
The RHI has been repeated many times, each time with a different focus. Haans et al. [5] investigated the effect of visual consistency on ownership of the rubber hand with different hand shapes and skin textures. They found that ownership is stronger in hand shaped objects and that different textures only had an effect when the object was hand shaped, where a natural skin texture increased the illusion. Tsakiris et al. were also interested in the effect of object shape. In [39] five objects were used that interpolated shape between a wooden block and a realistic prosthetic hand. They found that only the hand shaped object induced ownership.

Another interesting adaptation of the RHI is the addition of a visual-motor variable [10, 11]. Kalckert and Ehrsson used a setup with a wooden box where the rubber hand was placed on top (Figure 1.1B). The hand of the participant was placed into the box after which the index finger of the participant's hand was connected to the index finger of the rubber hand, allowing active movement of the rubber hand. They found that the illusion of ownership can be induced equally strong with visual-motor stimulus as with visual-tactile stimulus. Secondly, active movement also induced a sense of agency, whereas passive movement eliminated agency, but left ownership intact. Finally, they found a positive correlation between ownership and agency.

Not only the visual appearance of the virtual hand, visual-tactile, feedback and visual-motor feedback can affect the level of experienced ownership. The congruency of the visual-tactile stimulation, e.g. stroking in different directions [2], temperature [12] and perspective [20] were also found to have influence and it could be expected that more factors will be found in the future.

In the RHI the level of ownership is often measured with proprioceptive drift. However, proprioceptive drift is not a direct measure of ownership, but rather of hand location. It has been shown by both Rohde et al. and Holle et al. that a shift in hand location can occur without experiencing ownership [26, 8]. Maselli and Slater showed in [20] that self-location and ownership can be changed selectively, were the first was affected when having a third-person perspective of the body, and the latter with (partial) spacial overlap between the real and fake body. They also showed that ownership has a positive influence on change in the perceived self-location.

(A) The rubber hand (middle) and the real hand (left) are synchronously stroked with a brush. [3]



(B) The rubber hand (above) is moved via a stick connected to the real hand (below). [11]

Figure 1.1: The rubber hand illusion

3 Remote and extended bodies

While the previously discussed factors are variations of natural perception, there are also less natural occurrences which can trigger the ownership illusion. These can give indications of what is possible in AR. One such illusion is called the Body Transfer Illusion (the generalization of the RHI to the whole body), which has been conducted with mannequins and real bodies of the opposite sex [24], virtual bodies [31, 21] and even without a substitute body which induced an out-of-body experience [17, 3]. In these experiments the participant wears a head mounted display (HMD), which shows the image of two cameras mounted on, for example, a mannequin or a tripod. The experimenter strokes the abdomen or the back of the participant and the mannequin simultaneously with a rod.

As AR allows participants to see their own real body, having ownership of another body in first person perspective is not trivial, while the use of, for example, a limb or body outside of bodily borders could be a crucial addition to AR applications (e.g. interaction with out of reach objects). To realize a hand or arm outside of real bodily borders, the arm must be either very long or noncontinuous. Both cases were researched in VR by respectively Perez-Marcos et al. [22] and Kilteni et al. [15]. In [22] it is stated that body ownership is more easily evoked with a connected limb, but is not impossible to evoke over an unconnected limb, although the time to evoke the illusion is significantly longer, 140s compared to 90s. Kilteni et al. found that the ownership illusion declines when the arm length is increased [15]. With visual-tactile feedback the breaking point is four times the arm length. In a new AR experiment a remote arm should therefore not be further away than four times the arm length of the participant and the time of the experiment should be at least 140s to evoke the illusion.

Most research focuses on replacing a real limb with a virtual or fake one, but it is also possible to extend the body with extra limbs. Results of Steptoe et al. suggest that the participants could experience ownership over an avatar extended with a tail [35]. In [30, 29], Sikström et al. investigated the addition of wings to avatars and suggest that bodily movement, compared to the use of a controller, induces greater ownership over the wings. Finally, Guterstam et al. [4] showed that one can experience ownership over a right rubber hand while the real right hand is visually present. These studies indicate the illusion of ownership can be evoked for extra limbs and therefore we can argue that inducing ownership over a virtual limb in AR, where the real limbs are visually present, should be possible.

4 Comparing realities

Since the RHI in reality, VR and AR should require different setups, it is not clear whether the results are comparable, although many authors have shown that they in fact are. For example, Tsakaris et al. used a first person projection in [38] and their results were similar to other (not virtual) RHI studies. Slater et al. in [34] conducted an experiment where the participants looked at a screen with a back-projected image of an arm. The participants wore head tracked stereo glasses, thus seeing the virtual arm in 3D as it appeared to project from their shoulder. The experimenter used a tracked wand to stimulate the arm of the participant and a virtual ball simultaneously touched the virtual hand. This had a similar effect as the stroking with a brush in the original RHI. Raz, Weiss and Reiner used a VR Reach-In display [25] to study the effects of active and passive movement, haptic stimulation and self stimulation. Self stimulation induced a greater feeling of ownership, which was also found by Hara et al.[7]. The level of ownership was similar to non-virtual RHI studies, such as [41], but the sense of hand location of the touch-administrating hand differed. Hara et al. argue this difference could be caused by the difference in setup (virtual hand vs. rubber hand), duration of stimulation (30 s vs. 180 s) or the mode of measurement.

In an AR study, Suzuki et al. showed an AR version of the RHI also gives similar results to the original RHI [37]. The participant sat in front of a desk with his hand behind a standing screen and an HMD with a camera on his head. A Kinect captured the real hand and generated a model of the hand in real-time, which was projected on a marker in front of the participant. A cardio-visual feedback condition was added, where the color of the virtual hand changed from the captured skin color to red and back either synchronously or asynchronously with the participant's heartbeat. The results suggest that synchronous cardio-visual feedback increases the sensation of ownership. For the motion condition the participant could move his fingers and for the tactile condition the experimenter used a brush to stimulate the hand of the participant. The brush was also projected in real time.

The experiments mentioned assumed that the type of environment, i.e. real, virtual or mixed, does not have any effect on the Sense of Embodiment, but do not actually compare them in their studies. IJsselsteijn et al. looked into this by comparing the RHI in reality, virtual reality and augmented reality in [9]. In the VR condition a projected 2D image of a rubber hand including stimulation of a brush was used. This image was shown in front of the participant such that the participant could see the hand from a first person perspective. The VR condition resulted in a less vivid illusion compared to the classical RHI. They argue that the reason could be absence of a 3D shape. In the Augmented Reality (AR) condition a projection of a rubber hand was stimulated with a real brush. The AR condition showed a less vivid illusion compared to the VR condition. The difference in result was explained by inconsistency in shape, i.e. the hand was a 2D projection and the brush was 3D, and the results of the effect of the environment were inconclusive.

Most research in VR and AR report similar results to other RHI studies. It is therefore not expected that the SoE in AR deviates from the SoE in VR. However IJsselsteijn et al. show that small inconsistencies in setup have an effect on the level of ownership. Thus, it is important to more elaborately study the SoE in AR, so we can find out why these effects are present.

5 Conclusion

Related work has proven that the SoE has possible benefits for the development of VR applications. We argue that if we can induce the SoE in AR, AR applications may profit from similar benefits. Such applications could include a virtual hand to reach far away interactive objects. From the literature we can conclude that the SoE can be induced in AR, but it is not clear if the known VR setups are directly applicable to an AR environment.

Similar to VR, our following AR experiments should include extra limbs, limbs not connected to the real body and limbs that can cover a larger distance than the real limbs. The difference with VR is the visual presence of the real body. Motivated by related results in VR, we should take into account that the virtual hand should have a realistic shape and should not be further away than four times the arm length of the participant to make the induction of ownership possible. Both visual-tactile feedback and visual-motor feedback must be included to study ownership as well as agency and self-location.

Our next step is the implementation of a setup, taking into account the points mentioned above. With this setup, a series of pilot studies will be used to verify if this setup can induce the SoE, and if not to improve the setup. If the pilot studies prove successful and the SoE is induced, our main experiment will focus on investigating the effects of the SoE on AR applications and comparing them to VR in future research.

Chapter 2

Research Proposal

1 Description

We will investigate how Sense of Embodiment[14] (SoE) in AR is affected by multimodal feedback and interaction. SoE toward a body B is the sense that emerges when $B's$ properties are processed as if they were the properties of one's own body. The subcomponents of the SoE are the sense of body ownership, the sense of agency and the sense of self-location. There are indications that the SoE has benefits for Virtual Reality (VR) applications and it can be used for treatment [23, 13, 27] and training [36, 42]. If we can induce the SoE in Augmented Reality (AR), AR applications may also be used for this. The SoE might also have a positive impact for remote interaction in AR with a virtual hand. There are several differences between VR and AR, such as the visual presence of the real body and the mixed reality compared to a completely virtual reality and it cannot be assumed that the SoE is the same for VR and AR applications, and needs to be investigated.

2 Research question

How does multimodal feedback affect the SoE, i.e. body ownership, agency and arm-location, towards a separate virtual arm in AR when the real arms are visually present?

3 Goal and objectives

We cannot apply existing VR setups to an AR experiment, due to the differences mentioned above. Therefore our first goal is to design a setup for AR, with which we shall conduct a variation of the rubber hand illusion (RHI) [1], where a virtual hand will be used, which can reach a larger area than the real hand.

We will use the following independent variables:

- Visual-tactile feedback: {*synchronous, asynchronous*}
  A virtual ball bounces on the virtual wrist. Upon visual contact between the ball and wrist, a vibrotactile actuator on the wrist will vibrate either synchronously or asynchronously. This factor is traditionally tested in the RHI to evoke ownership over the rubber hand.

- Visual-motor feedback: {*none, passive synch, passive asynch, active synch, active asynch*}
  The real hand will be moved by actively or passively lifting the hand, and the virtual hand will move either synchronously or asynchronously. This factor is used to evoke ownership and agency. Passive movement generally does not induce agency, contrary to active movement. Results of Kalckert and Ehrsson [10] suggest that agency enhances body ownership.

- Arm: {*Only virtual arm visible, virtual and real arm visible*}
  The real hand will either be covered and out of sight or in the traditional position near the virtual hand. The visual presence of the real arm causes the virtual arm to be an extra limb instead of a replacement of the real arm, as is in the RHI. We suspect the visual presence of the real arm to negatively affect the strength of ownership over the virtual arm and to diminish the change in experienced location towards the virtual hand.

Body ownership, agency and arm-location will be rated using questionnaires with a 7-point Likert scale.

Chapter 3

Pilot Studies for the Design of the Virtual Hand Illusion in Augmented Reality

1 Introduction

Several studies have proven that it is possible to invoke the Sense of Embodiment (SoE), as stated in Chapter 1. The Virtual Reality (VR) setups mainly focus on body transfer or replacing real limbs with a virtual counterpart. Relatively few studies have been done in Augmented Reality (AR) and what has been done used a setup that replaced the real arm with a virtual arm [37]. Body transfer illusions pose a challenge in AR, because the real body generally cannot be replaced as it will always be visually present. On the other hand, instead of replacing the body, AR provides the opportunity to extend it with, for example, an extra arm. As we have seen in Chapter 1, there have been some studies in VR where ownership was induced over extended virtual bodies and unconnected limbs, but in AR it is uncertain what the effect is of the visual presence of the real hand. It is also unclear in what location the virtual hand can reach a larger area than the real hand, but will also be seen as an extension of the user.

In order to investigate this a suitable setup is required. In this chapter we explain the choices made in setup design, in the form of three pilot studies. In Pilot 1 the initial setup is based on the rubber hand illusion (RHI) [1] using visual-tactile feedback, followed by a setup with visual-motor feedback in Pilot 2 and a setup with combined feedback in Pilot 3. Each pilot setup is improved when needed through an iterative process, where each iteration is tested by one or more informed participants who are involved in the project. When making improvements, the experiment results of the participant and the remarks of the participant during the experiment are taken into account.

2 Pilot 1: Replicating the standard RHI

In the first pilot the focus lies on replicating the standard RHI in AR, i.e. we examine the virtual hand location in Iteration 1, the visual appearance of the virtual hand in Iteration 2 and the choice of suitable visual-tactile feedback in Iteration 3.

2.1 Material

- Meta Development Kit 1 head-mounted display (HMD)
- Elitac Tactile Display V3.1
- Meta marker
- A box to fit over the participants hand, which blocks it from view.
- The experiment application, developed in Unity v5.5.0f3

2.2 Setup

In AR the virtual hand needs to be able to cover a larger distance than the real hand. This is not possible if the the virtual hand lies in the same position as the real hand, such as in the original RHI. It was therefore decided to look at different hand positions further away from the body. The first position chosen was *in front of the participant*. This seemed like the optimal position for use in AR, because it makes it possible to reach in front of you. The other position chosen was *next to the participants arm*, in our case to the left of the left hand, as this position resembles the original position of the RHI the most.

In the setup (Figure 3.1) the participant is wearing a Meta DK1 HMD, through which a virtual hand can be seen. The virtual hand is a texture-less neutral hand. The virtual hand is placed at the position of a marker. The marker is placed 60 cm in front of the participant or 20 cm next to the participants left hand, where the participant needs to be able to see his own left hand, the virtual hand and the marker. The participant wears a wristband around the left arm with a vibro-tactile element attached to it. A box is placed on the table, where the participant's left hand can be placed in. During the experiment the participant will see a ball bouncing on the wrist of the virtual hand. The ball falls into view, bounces once on the wrist of the participant and disappears from view. The time between the bounces is a random number of seconds between 2.5 and 3.5. The vibro-tactile element will vibrate synchronously or asynchronously with the bounce of the ball, where asynchronous means with a delay of 300 ms.

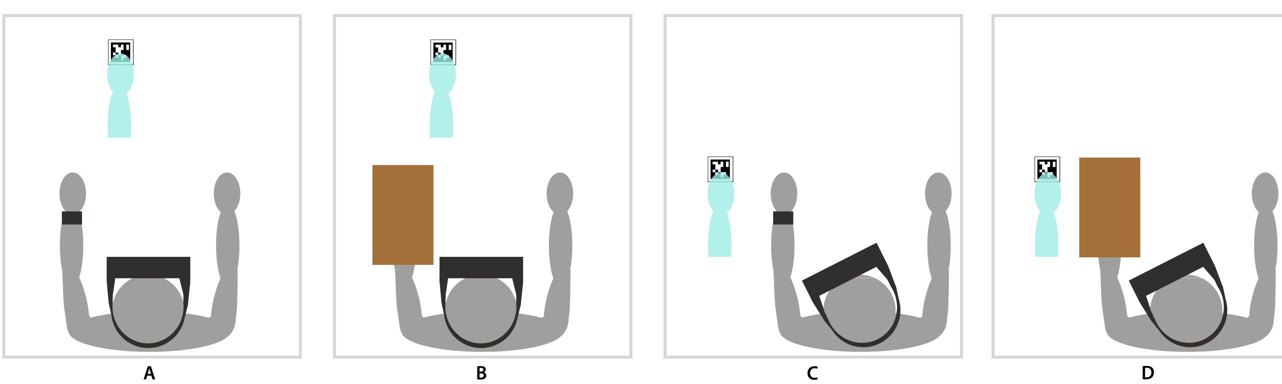


Figure 3.1: Setup of Pilot 1. **A)** The participant sees the virtual hand (blue) in front of him on the table through the Meta DK1 HMD. **B)** The left hand of the participant is blocked from view by a box. **C)** The virtual hand can be seen next to the left hand of the participant. The participant has to turn his/her head to see the virtual hand. **D)** the left hand of the participant is blocked from view by a box and the virtual hand can be seen next to the left hand of the participant.

2.3 Iteration 1: Hand position

Variables

The first iteration has the following within-subject independent variables:

- Arm: {*virtual, real and virtual*} The visual presence of the real and virtual arm (Figure 3.1 a) or only the virtual arm (Figure 3.1 b).
- Visual-tactile feedback: {*synchronous, asynchronous*} The vibro-tactile element will vibrate synchronously or asynchronously on the moment of contact of a virtual ball with the virtual hand.
- Virtual hand position: {*in front of the participant, next to participant's arm*} The virtual hand will be positioned at a larger distance than the real hands, as can be seen in Figure 3.1 a and c

The dependent variables are:

- Ownership: The level of ownership the participant experiences over the virtual hand.
- Location: Where the participant experiences the location of the left hand and the felt sensations.
- Agency: The level of agency the participant experiences of the virtual hand.

The dependent variables are rated by a questionnaire (Appendix 3.A.1) with a 7-point Likert scale corresponding to answers ranging from "strongly disagree" to "strongly agree". These questions are based on [10, 1, 18] and adapted to the current setup. For the results the questionnaire scores are displayed as a numerical range of -3 to 3, to make a clear distinction between a positive and negative answer and so it is possible to take the inverse of a result.

Procedure

The experimenter explains the experiment to the participant and the participant is told that he/she is allowed to stop the experiment at all times. The participant then puts the Meta DK1 on and the experimenter attaches the wristband with vibro-tactile element to the left wrist of the participant. The experimenter calibrates the Meta DK1 for head orientation and instructs the participant to keep his/her head still. The experimenter places the marker and the box in the correct positions. The session can then be started.

The participant experiences eight sessions, where the presentation of conditions is in a random order. During the session the participant sees a virtual ball bounce on the virtual hand. After two minutes the hand and ball disappear. The participant is then asked to answer the questionnaire and when he/she finishes there is a break of one minute. After four sessions the participant takes of the Meta DK1 and there is a break of five minutes. At the end of the experiment the participant is asked about his/her experience with the experiment and is thanked for his/her participation.

Results

The first iteration had one 23 years old male participant. The results are discussed through a visual analysis of Figure 3.2. The medians of the ownership questions are relatively close to each other in the different hand position conditions, never deferring more than two points. The response ranges for each question are also fairly similar. This coincides with the remarks of the participant, as the participant mentioned after the experiment that he experienced no noticeable difference in the strength of the illusion when the position of the virtual hand differed.

The participant had difficulty answering the questions regarding location after the first session, because the participant was not consciously aware of the felt location of the ball or the hands. This is confirmed by the large response ranges for location in Figure 3.2. This is not a big problem, because the main goal of this iteration was to research the effect of the virtual hand location on the strength of the ownership illusion and not on location or agency. However, it is necessary to make sure it does not happen again in the next iterations. The participant also mentioned that it seemed like the virtual hand was floating above the table instead of lying on it and that the marker was visible through the hand.

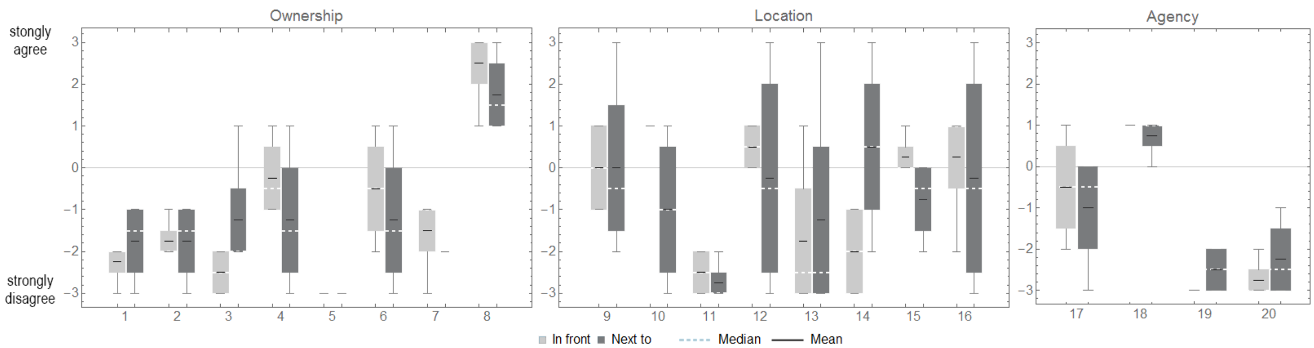


Figure 3.2: A boxplot of the questionnaire results of the questions arranged by the virtual hand position of the participant (*in front of the participant, next to the participants arm*). Each boxplot(i) shows the collection of the results of four sessions for the single participant for Q(i). A single line indicates that the participant gave the same score for each session. The numbers correspond to the questions Q(i) in Appendix 3.A.1. The participant did not feel confident in answering Q9-16 during the first session and this could have influenced the results.

Discussion

As was mentioned above there was no large difference in the results for the different virtual hand positions. It was decided to drop one of the cases to keep the number of test conditions low, namely the *next to participants arm* case, as the *in front of the participants* case has more potential for use in AR applications, since this position makes it possible to use the virtual hand to reach far away objects within the visual field of view.

The participant mentioned that the marker was visible through the virtual hand, which made the hand transparent, and that it seemed as though the hand was floating above the table instead of lying on it. This could emphasize the falseness of the virtual hand and this could negatively affect the strength of the illusion. As it is stated in [9, 5, 39], realism of the fake hand is an important factor in the illusion of ownership. Therefore the virtual hand should be placed next to the marker to make the hand appear more solid and lower in virtual space to make it appear closer to the table surface.

The participant did not feel confident while answering the questions regarding the perceived location of the virtual and real hand, as the participant was not consciously aware of the perceived locations of the hands and the ball. This could be solved by making the participant more aware of the hands in general during the experiment, by giving a verbal indication in advance, or by asking the questions while the virtual hand is still present. In the next iteration we will give a verbal indication.

2.4 Iteration 2: Realism of virtual hand and stimulus

Variables

The within-subjects independent variables and dependent variables of the second iteration are *Arm* and *Visual-tactile feedback* similar to in Iteration 1 (Section 2.3), except now the virtual hand position is always *in front of the participant.*

Procedure

The procedure is similar to the procedure of Iteration 1. The participant experienced four sessions of two minutes instead of eight sessions, where the conditions were presented in a random order. Also, before the start of the experiment, the participant was instructed to pay attention to how the virtual hand was perceived.

Results

The second iteration had one 23 years old female participant. If we compare the results of the first iteration with the second iteration, which are displayed in Figure 3.3, it can be seen that the results of the second iteration are slightly higher in most cases, except Q8.

The participant suggested that we should ask location related questions during the session. This coincides with the problems encountered in the first iteration, where the participant could not remember where he felt his hand to be. The participant also thought the ball fell rather fast and had no visible impact on the hand.

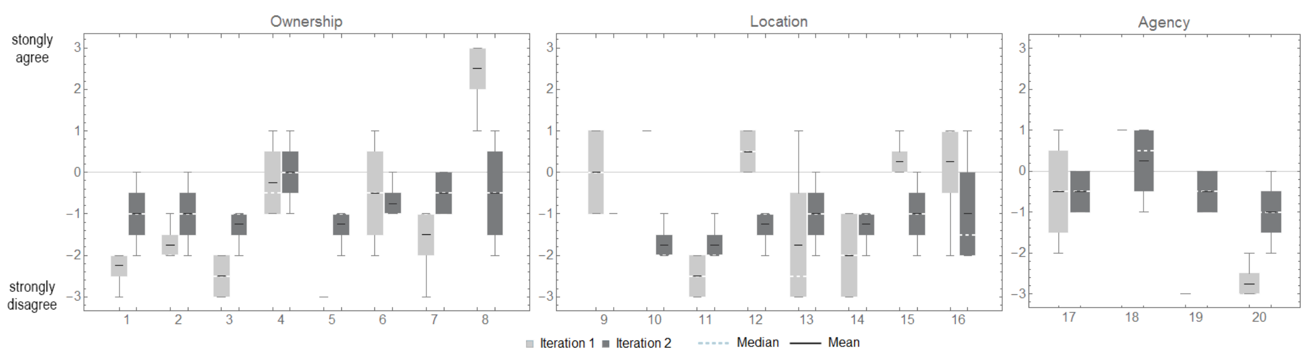


Figure 3.3: A boxplot of the questionnaire results of Iteration 1 with the virtual hand positioned *in front of the participant* compared to Iteration 2. Each boxplot(i) shows the collection of the results of 4 sessions for the single participant for Q(i). A single line indicates that the participant gave the same score for each session. The numbers correspond to the questions Q(i) in Appendix 3.A.1.

Discussion

From the results we can see that the illusion is still very weak. However it should be possible to increase the strength of the illusion. A simple option is to increase the illusion time. In [22] the average time until the illusion occurs for noncontinuous limbs is 140 seconds. For this reason the illusion time shall be changed to 2.5 minutes.

Another option is to improve the realism of the virtual hand further. For this a skin texture should be applied, as was shown in [5]. It is important to think about the realism of the tactile feedback. In most experiments with a rubber or virtual hand an identical stimulus, e.g a brush [1] or a wand with a ball [33], is used on the fake and the real hand. In the current setup a vibro-tactile element is used to simulate a ball touching the wrist and these sensations do not match. As we do not want the stimulus to be visually present on the real hand, a tactile display needs to be used. Therefore it is needed to find an object that matches the sensation of a vibro-tactile stimulus. This could be a smart watch that receives a notification.

The slightly higher results of Iteration 2 indicate an improvement in setup. However it should be taken into account that the participants react differently to the illusion. The result of Q8 can be explained by different interpretations of the question and a reformulation needs to be considered. Instead of “It seemed as though the touch I felt was caused by the ball touching the virtual hand.” for the next iteration the question was reformulated as “It felt as though the virtual hand was the reason I could perceive certain sensations”. To prevent further irregularities in future results it was decided to ask the location questions after 2.5 minutes during the illusion, while the illusion continues with a maximum duration of one minute.

2.5 Iteration 3: Smart watch

Remark: Pilot 2 (Section 3) was executed before Pilot 1, Iteration 3. Therefore several changes have been made to the procedure, questionnaire and result analyses that were based on the discussion of the iterations of Pilot 2. The changes made to the questionnaire can be seen in Appendix 3.A.3. The changes made in the procedure and the result analyses are discussed in the corresponding sections of this iteration.

To improve congruency it was decided to use a virtual smart watch as the source of the stimulus, as the sensation of a vibrating smart watch matches the sensation of the vibro-tactile element. The smart watch will vibrate visually and it will display a notification.

Setup

The setup is based on the setup of the previous iterations (Section 2.2). The differences are purely visual. Instead of a bouncing ball, the participant sees a virtual hand that is wearing a smart watch. The smart watch will visually vibrate and display a notification for 500 ms. The time between the vibrations is a random number of seconds between 2.5 and 3.5. The vibro-tactile element will vibrate synchronously or asynchronously with the visual vibration of the smart watch, where asynchronous means with a delay of 300 ms.

Variables

The within-subjects independent variables and dependent variables of the third iteration are similar to Iteration 1 (Section 2.3), where for the virtual hand position *in front of the participant* was chosen and the visual-tactile feedback (VT) is now represented with a smart watch receiving a notification in stead of a bouncing ball.

Procedure

The procedure is similar to the procedure of Iteration 2 (Section 2.4). Instead of a bouncing ball, the participant sees the virtual hand wearing a smart watch. The participant will experience four sessions of 2.5 minutes instead of 2 minutes, after which he/she will answer a questionnaire (Appendix 3.A.3).

Results

The third iteration had one 24 years old male participant. In Figures 3.4A and 3.4B the results of the questionnaire are shown comparing the *asynchronous* with the *synchronous* visual-tactile condition and comparing the *virtual and real* with the *virtual* arm condition, respectively. In Figure 3.4A can be seen that for ownership and agency the *synchronous* condition results in a higher mean for every question, except for Q12, Q13, Q20 and Q21, which was expected, as they have a reversed formulation. In Figure 3.4B no large differences can be observed, as the means do not differ more than 1 point.

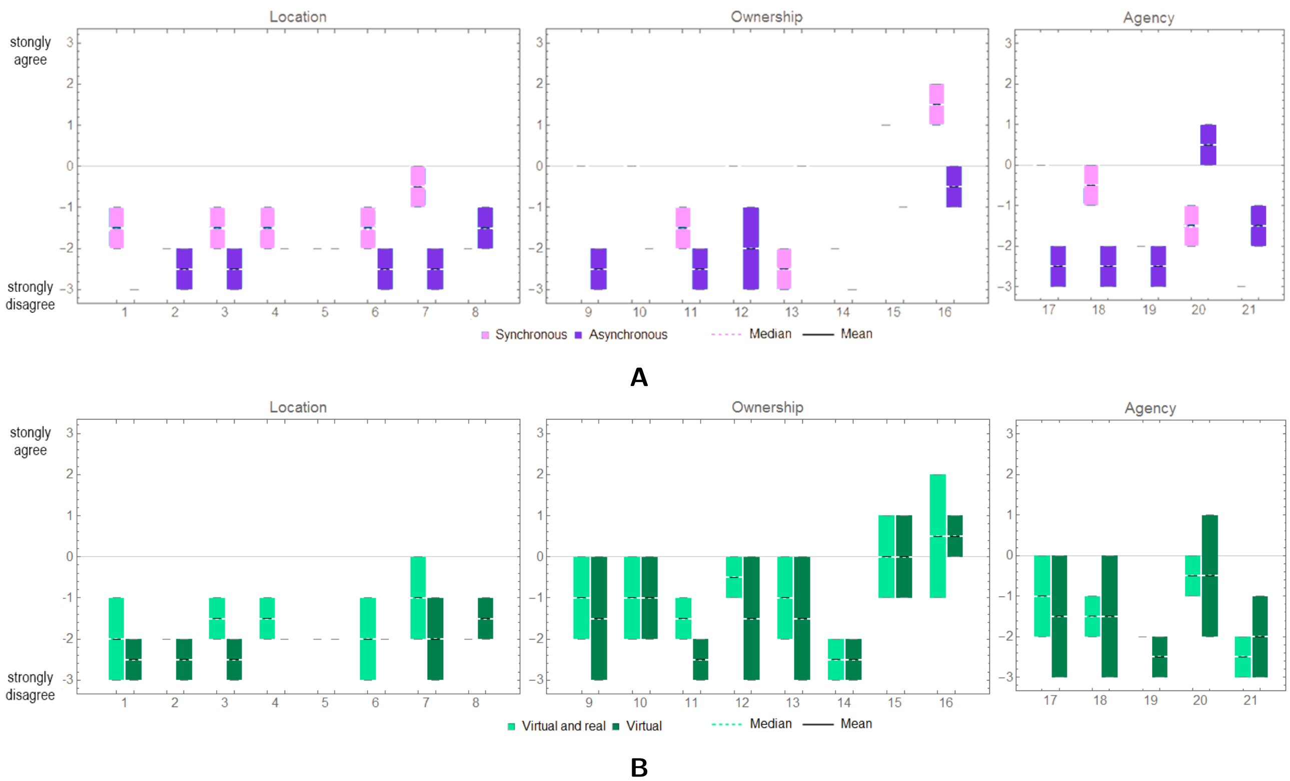


Figure 3.4: A boxplot of the questionnaire results of the individual questions Q(i) of Iteration 3, **A)** The *asynchronous visual-tactile* condition is compared to the *synchronous visual-tactile* condition. **B)** The condition with the *virtual and real arm* is compared to the condition with only the *virtual arm*. Each boxplot shows the collection of the results of two sessions for the single participant. A single line indicates that the participant gave the same score for each session. The numbers correspond to the questions Q(i) in Appendix 3.A.3.

For ownership and agency the individual questionnaire results are combined in Figure 3.5 to give a single distribution of ownership and agency. The ownership distribution is realized by combining the ownership questionnaire results, and omitting the control questions (Q10, Q14, Q15). Q11 is also omitted, because it does not give an indication of ownership itself, but an indication of the nature of the ownership. Of Q12 and Q13 the inverse is taken, because a high score for those questions indicates that no ownership

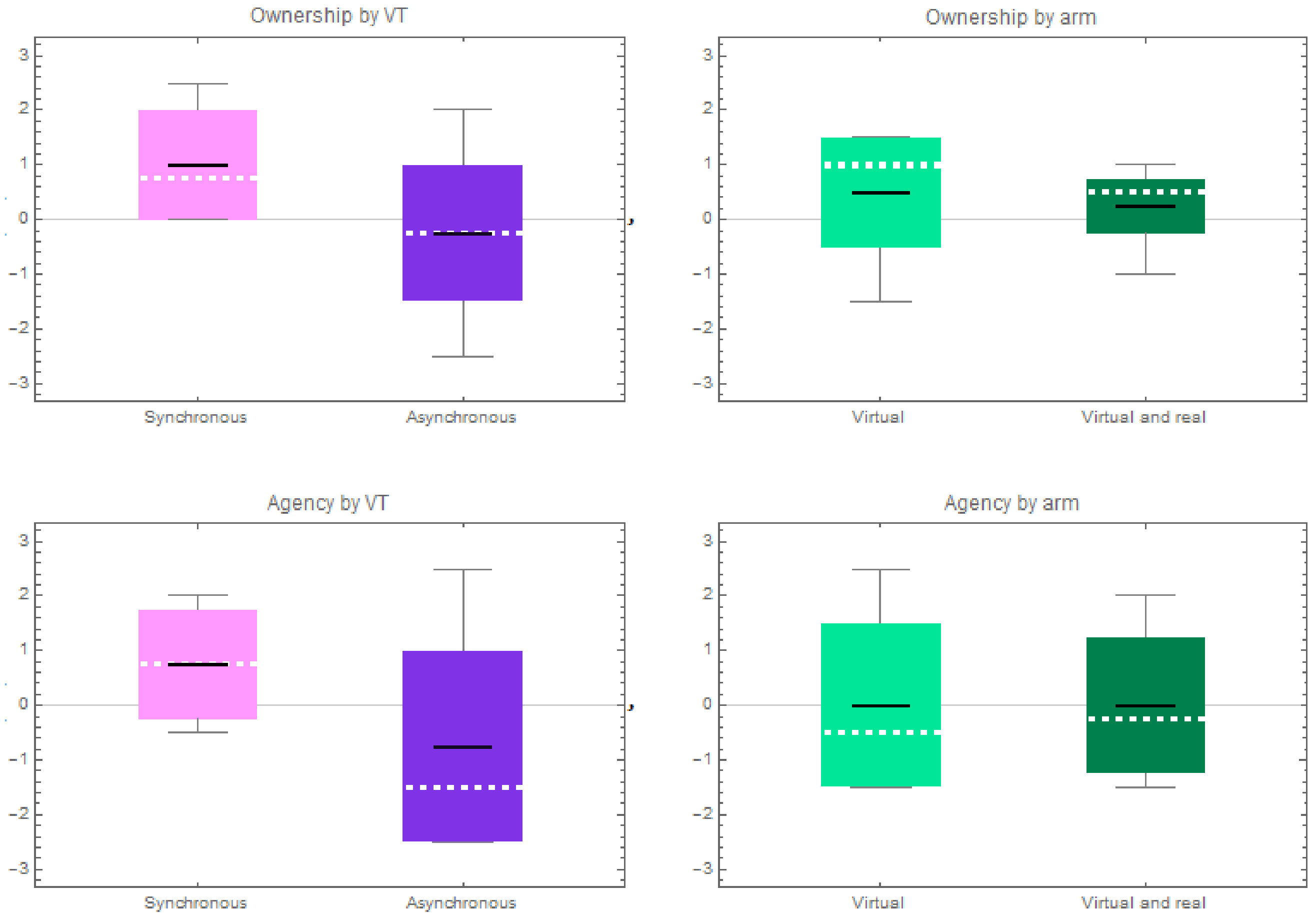


Figure 3.5: Boxplots of the questionnaire results of Pilot 1, Iteration 3 of ownership and agency where ownership is measured with Q9, the inverse of Q12, the inverse of Q13, and Q16. Q11 is omitted for this score, because it does not give an indication of ownership itself only an indication of the nature of the ownership. Agency is measured with Q17, 18, the inverse of Q19 and the inverse of Q20. The mean is indicated with a black line and the median is indicated with a dashed line. The individual question results can be seen in Figures 3.4A and 3.4B.

was experienced. The agency distribution is realized by combining the agency questionnaire results. The control question (Q21) is omitted from this equation. For Q19 and Q20 the inverse is taken, because these questions give an indication that no agency was experienced. The location questions are not combined, because it has no binary result.

It can be seen in Figure 3.5 that both arm conditions result in but positive ownership as well as the synchronous condition. The asynchronous condition for both ownership and agency have a relatively large response range. This corresponds to the results of 3.4, where for ownership Q9, Q12 and Q13 have low scores and Q16 has a high score, and for agency Q17, Q18 and Q19 have low scores and Q20 has a high score. This can be explained by the participant reporting that he came to expect the delayed vibration of the vibro-tactile element and this caused the participant to experience it as less asynchronous or even synchronous.

It can be seen that there is low but positive agency for the synchronous condition and that the plots of agency by arm are very similar for both arm conditions.

Discussion

The large response range of ownership for the asynchronous condition can be explained by the participant sometimes experiencing the asynchronous condition as synchronous and the large contrast between the high score of Q16 and the low scores of the other questions. As is stated in [28] it is possible that participants can experience delays under 600 ms as synchronous. It is also possible that participants will regard the delayed vibration as a property of the smart watch and will think it is synchronous. To avoid the participants getting used to the delayed vibrations, the delay of 300 ms should be replaced by a random delay or a random or predetermined pattern of vibrations.

The combined results show that the condition with the lowest level of ownership also has the lowest level of agency. This coincides with [10] where it is implied that ownership positively affects agency. It is interesting to see that the participant experienced a small sense of agency for the synchronous condition when there was no active motion involved in this pilot. It has however been reported in [6] that some people claim a sense of agency without receiving visual-motor feedback.

The positive ownership mean in the *virtual and real* arm condition suggests that it is possible to induce a sense of ownership over a virtual hand when the real hand is visually present. However, if we look at the individual responses of Q9 and Q16 it is interesting to see that although Q16 has a positive response, Q9 has not. Q9 asks directly if the virtual hand is seen as the participant's own hand and Q16 asks if the virtual hand was the reason the participant could perceive the sensations triggered by the smartwatch, which refers directly to the definition of ownership. This could mean that the participant subconsciously experiences the virtual hand as 'own', but consciously does not see it as such.

2.6 Conclusion

In this section we shall summarize the findings of Pilot 1. The goal of this pilot was to create a convincing experience of the visual-tactile feedback and to find out if the the location of the virtual hand has any effect on the strength of the illusion of ownership where the real hand is visually present. To do this, the results of an iteration were used to improve the setup in the next iteration. Two positions were chosen for the virtual hand to study the effect of the illusion. The first iteration proved that the different virtual hand positions did not trigger very different questionnaire scores and therefore the position of which we think it has the most potential for AR applications *(in front of the participant)* was chosen for the next iterations. We have argued that ownership over extended bodies should be possible, however the illusion is weakened by non-continuity and different proportions of the limb (e.g. a very long or distant arm). The results of the first pilot show that the combination of these weakening factors may have a strong effect. This makes other factors of which the impact is normally minor (e.g. realism of the virtual hand and the length of the illusion) more important, as is implied by the improved results of the next iterations. Not only the realism of the virtual hand is important, but also the realism of the feedback. This factor has been taken for granted, because the feedback was always exactly copied with a brush or wand. This is not possible in AR when the real hand is visually present, because the stimulus on the real hand should not be visible, as the sensation would then be associated with the real hand and not the virtual hand. The results of the pilot suggest that when the smaller factors as realism of the virtual hand, realism of the feedback and the length of the illusion are taken into account it is possible to induce ownership over a remote virtual hand while the real hand is visually present.

3 Pilot 2: Visual-motor feedback

Remark: The changes made in Pilot 1, Iteration 3 are not included in this section, because Pilot 1 Iteration 3 was executed after the pilot experiments discussed in this section. This means this iteration does not include asynchronous feedback with a random delay.

For Pilot 2 the focus lies on creating a convincing experience of the visual-motor feedback, which will consist of active and passive motion.

3.1 Material

- Meta Development Kit 1 head-mounted display (HMD)
- Meta Marker
- Arduino with the UnityConnector.ino script with an accelerometer attached
- A pivoting board to passively move the hand of the participant.
- A box to fit over the participants hand, which blocks it from view.
- The experiment application, developed in Unity v5.5.0f3

3.2 Setup

The setup is based on the setup of Pilot 1. When executing a passive motion, the left hand of the participant is placed on a pivoting board (Figure 3.6C), which can be moved up and down by the experimenter. A marker is placed 60 cm in front of the participant aligned with the right shoulder, so the virtual hand is positioned directly in front of the participant (Figure 3.6A). When executing a passive motion, the virtual hand also lies on a pivoting board to make the sensation of touching wood congruent with the visual feedback. Instead of a wristband with a vibro-tactile element, the participant wears an accelerometer on the middle finger of the left hand. During the experiment the participant moves his/her hand up and down or the hand is moved by the experimenter. The accelerometer measures the angle the hand makes with the table. The virtual hand synchronously or asynchronously copies the movement of the participant's hand, where asynchronous means with a delay of 300 ms.

3.3 Iteration 1: Active motion

Variables

The first iteration has the following within-subject independent variables:

- Arm: {*virtual, real and virtual*} The same as Pilot 1
- Visual-motor feedback: {*synchronous, asynchronous*} The virtual hand will move synchronously or asynchronously with the real hand.

A third variable could be added to this iteration, namely Motion: {*active, passive*}. However, the main focus was the correct movement of the virtual hand, therefore for the first iteration this variable was

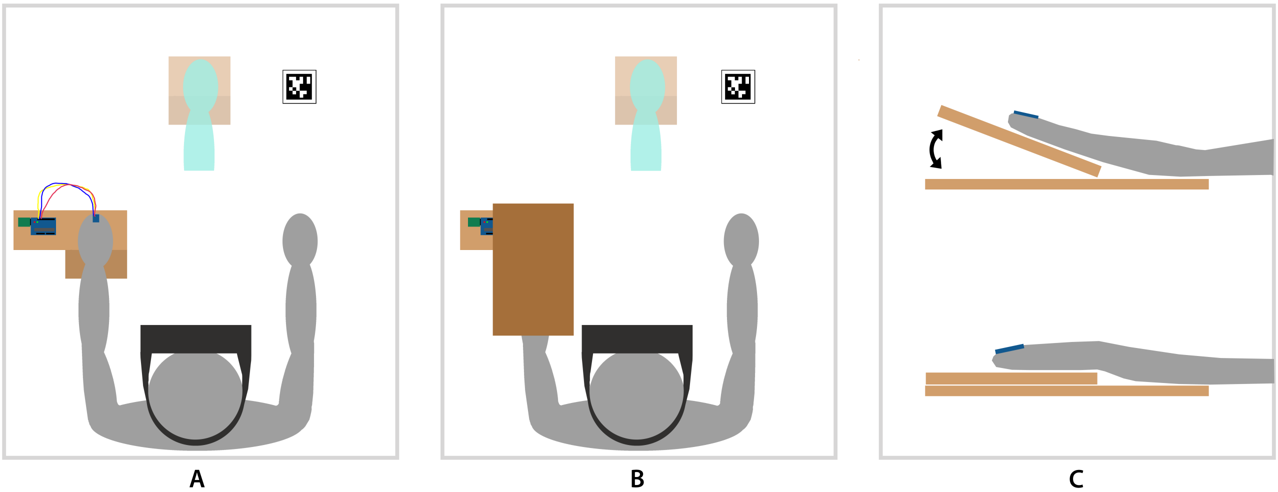


Figure 3.6: Setup of Pilot 2 with the pivoting board. For active motion the pivoting board is not used and the virtual hand does not lie on a board. **A)** The participant sees the virtual hand (blue) in front of him/her through the AR glasses. The accelerometer is placed on the middle finger of the left hand of the participant. **B)** The left hand of the participant is blocked from view by a box. **C)** The hand of the participant can be moved passively by the experimenter by use of the pivoting board.

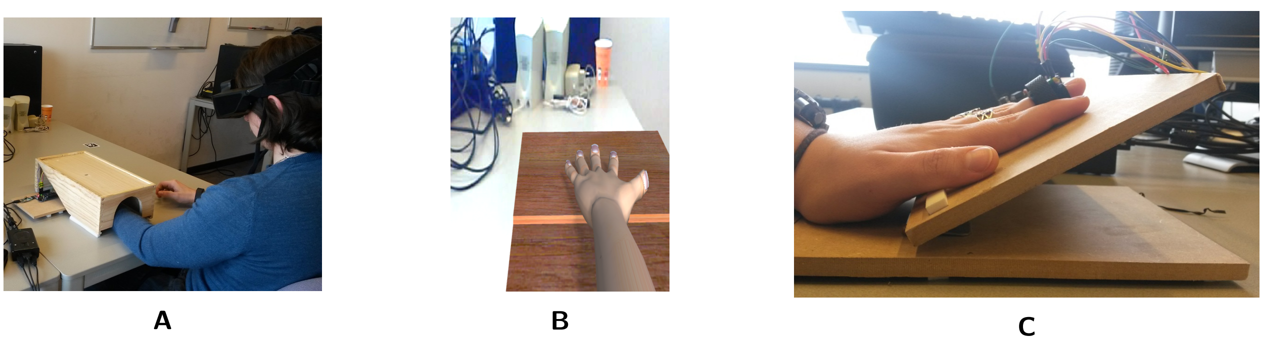


Figure 3.7: Setup of Pilot 2. **A)** The participant's hand is blocked from view by a box. **B)** The view of the participant through the Meta DK1. **C)** The participant wears an accelerometer on the middle finger and the hand is moved passively.

omitted. Only *active* motion was used in this iteration, and the Motion variable was included in Iteration 2.

The dependent variables are the same as the dependent variables of Pilot 1, see Section 2.3.

Procedure

The procedure is similar to the procedure of Pilot 1, Iteration 3 (Section 2.5). The differences are the following. The participant wears an accelerometer on the middle finger of the left hand. he/she experiences four sessions of a maximum of 4 minutes, during which the participant moves their hand, where after 2.5 minutes the participant is asked to answer a questionnaire (Appendix 3.A.2: During session). The illusion is then stopped and the participant is asked to answer a second questionnaire (Appendix 3.A.2: After session). During the session the participant sees a virtual hand on a plank. The participant moves his/her left hand up and down and the virtual hand moves accordingly.

Results

Remark: The combined distributions of ownership and agency are not shown, because these distributions were made for the questionnaire in Appendix 3.A.3, which was made after Pilot 2 Iteration 2.

Pilot 2, Iteration 1 had one 24 years old male participant, who also participated in Pilot 1, Iteration 3. When comparing the cases with and without the visual presence of the real hand (Figure 3.8), we see a great similarity of ownership, where each question has a difference of 1 point or less in the medians of the results, and no difference for the questions regarding agency, except for Q20, which has a small difference.

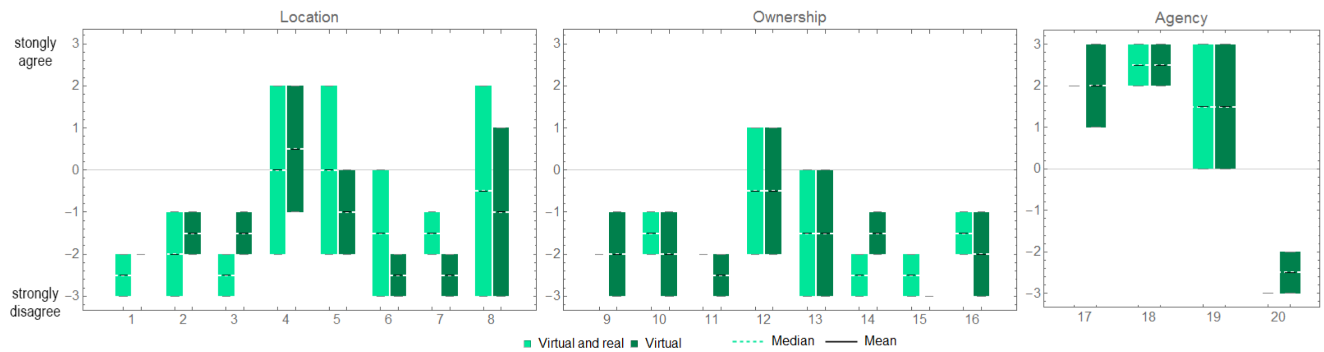


Figure 3.8: A boxplot of the questionnaire results of Pilot 2 Iteration 1, where the results *with the visual presence of the real hand* are compared with the results *without the visual presence of the real hand*. Each boxplot shows the collection of the results of two sessions. A single line indicates that the participant gave the same score for each session. The numbers correspond to the questions Q(i) in Appendix 3.A.2.

When comparing the synchronous cases with the asynchronous cases (Figure 3.9) it is notable that the synchronous cases have much higher results for location, ownership and agency, where Q4, Q5, Q8 and Q12 have a difference of 3 or more. At Q13 and Q19 a difference of 3 can be seen in favor of the asynchronous cases. Despite this difference, the overall results of the questions regarding ownership are still low. Q12 and Q13, which have higher scores, indicate the association of the virtual hand with someone else or that the virtual hand is a duplication of the real hand. This corresponds to the remarks of the participant, who reported not experiencing the illusion of ownership. He however did report a drift in the left hand. The participant also reported a noticeable delay in the movement of the virtual hand.

Discussion

The very low results for ownership suggest that the movement of the virtual hand is not accurate enough, since in other studies synchronous visual-motor feedback does induce ownership [10, 19, 11]. The participant also reported a noticeable delay in the movement of the virtual hand, which could have caused the absence of ownership. It is therefore important to minimize the visual delay of the visual-motor feedback. The visual presence of the real hand does not seem to affect the feeling of agency of the virtual hand, because the responses were very similar for both conditions. Synchronous movement appears to increase the feeling of agency, as expected, and asynchronous movement makes it appear as if the virtual hand copies the movement of the real hand instead of being controlled by the participant. The high results of Q4, Q5 and Q8 indicate a feeling of drift of the real and virtual hand towards a place between them. The participant also reported a feeling of drift. Often ownership is associated with an increase in drift [38, 9,

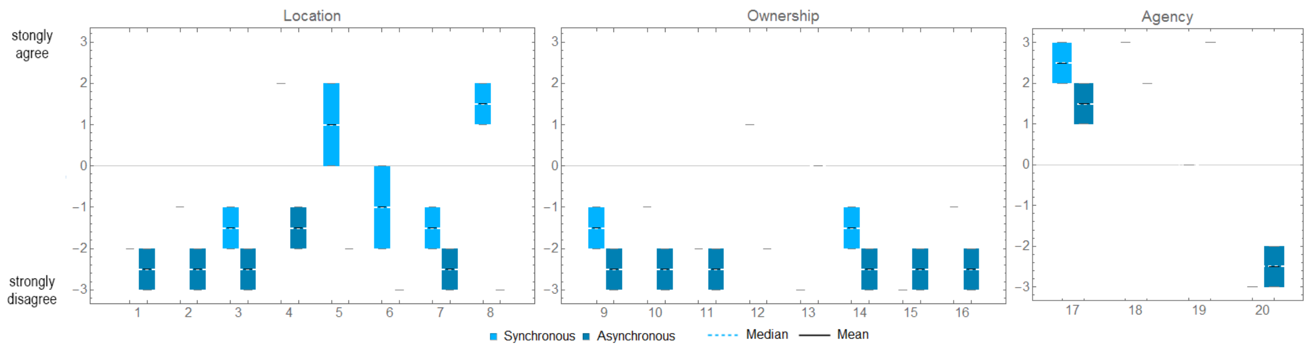


Figure 3.9: A boxplot of the questionnaire results of Iteration 1, where the results with *synchronous visual-motor* feedback are compared to the results with *asynchronous visual-motor* feedback. Each boxplot shows the collection of the results of two sessions. A single line indicates that the participant gave the same score for each session. The numbers correspond to the questions Q(i) in Appendix 3.A.2.

1], hence it is curious that the participant experienced drift without experiencing ownership. This could be explained by Rohde et al., who argue in [26] that proprioceptive drift is not caused by synchronous multimodal feedback, but that the asynchronous feedback lessens the already present drift towards the center of the body, which according to van Beers et al. [40] is always present when the hand is kept still.

3.4 Iteration 2: Active and passive motion

In this pilot the independent variable Motion (*active/passive*) is added. We shall focus on the improved motion of the virtual hand and the effect of different types of movement, including active and passive motion and synchronous and asynchronous visual-motor feedback.

Variables

Iteration 2 has the same variables as Iteration 1, with an added independent within-subjects variable Motion: {*active, passive*} The real hand will be moved actively by the participant or passively by the experimenter with the use of a pivoting board.

Procedure

The procedure was similar to the procedure of Iteration 1 (Section 3.3). The difference was that the participant experienced eight sessions in stead of four.

Results

For the second iteration there were two participants, one male, who participated in experiments before, and one female, both 24 years old. In Figure 3.10 the results of the cases with active movement and passive movement are compared. A large difference in agency can be seen, where the condition with passive movement has a much lower result. The results of the questions regarding ownership are also lower for the passive condition, but the differences in score is small (1 or less).

When comparing active motion results of Iteration 2 with Iteration 1 (Figure 3.11) a small increase in ownership can be seen. It should be noted that of Q12 and Q13 the inverse should be taken. It is also noticeable that the score of Q19 has changed with more than 2 points in favor of agency.

The participants reported a noticeable delay with the synchronous hand movement, this caused one of the participants to experience the asynchronous condition sometimes as more synchronous than the actual synchronous condition.

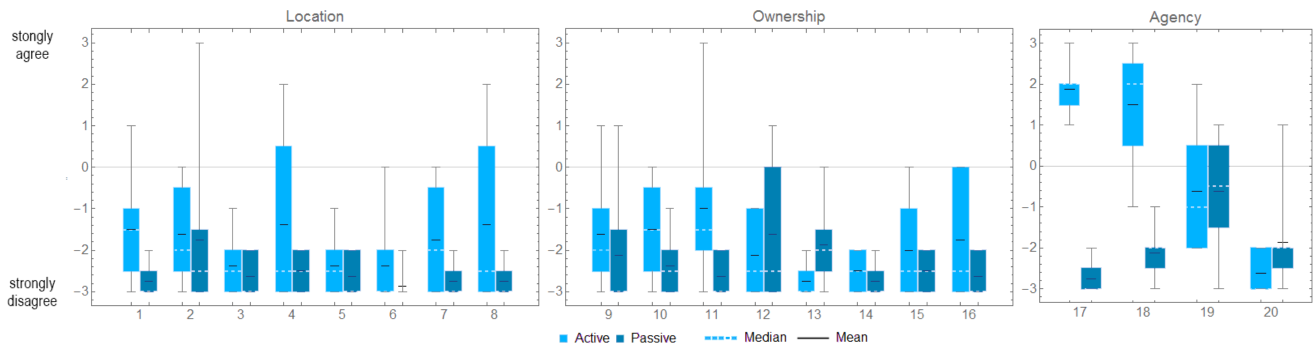


Figure 3.10: A boxplot of the questionnaire results of Iteration 2, where the results with *active movement* are compared to the results with *passive movement*. Each boxplot shows the collection of the results of four sessions. The numbers correspond to the questions Q(i) in Appendix 3.A.2.

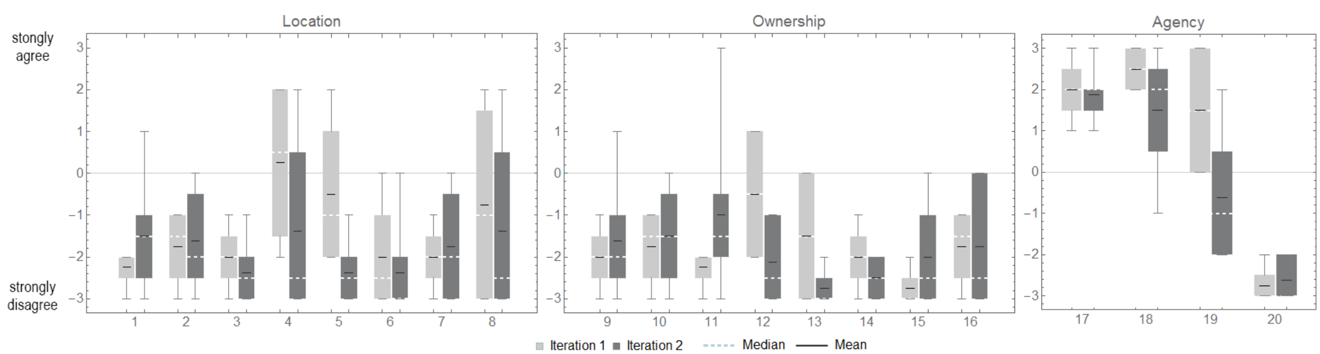


Figure 3.11: A boxplot of the questionnaire results of Iteration 1 compared to Iteration 2 with *active motion*. Each boxplot shows the collection of the results of four sessions. The numbers correspond to the questions Q(i) in Appendix 3.A.2.

Discussion

The effect of the passive motion on ownership is comparable with the results of [10, 19]. Passive motion weakens the sense of ownership, although it is stated that the difference in ownership could be caused by the difference in task demands, e.g. actively moving the hand is more demanding than relaxing the hand [10]. However in [19] it is suggested that active motion gives more proprioceptive and tactile impressions that can be linked to a synchronously moving virtual object, which would imply a stronger illusion of ownership. The passive motion negates agency when comparing it to active motion, as expected.

Although the sense of ownership has increased slightly compared to the previous iteration, the noticeable delay in the synchronous movement still causes problems and this could be a reason why the sense of ownership is not present, as a delay in feedback of 300 ms is said to break the illusion [28]. The communication with the Arduino is the bottleneck in the speed of the application, therefore another setup needs to be researched and implemented. In the next iteration, a setup with a webcam and color marker detection is used, which does not need an Arduino and causes substantially less delay.

3.5 Iteration 3: Hand tracking for active motion

In this iteration a different setup was used. The passive conditions were omitted in the experiment to focus on the effect of the new setup on ownership and agency.

Material

- Meta Development Kit 1 HMD
- Meta Marker
- A box to fit over the participant's hand, which blocks it from view
- Webcam with color feed
- Color marker
- The ColorTracker application to calibrate the tracking values.
- The experiment application, developed in Unity v5.5.0.f3

Setup

The setup is based on the original Pilot 2 setup. A webcam is placed 5 cm to the left of the left hand of the participant and a colored marker is placed on the middle finger of the left hand of the participant (Figure 3.12). During the experiment the participant will move his hand up and down. The webcam will track the colored marker. The virtual hand will synchronously copy the movement of the participant's hand or move with a prerecorded animation.

Variables

The third iteration has the same variables as the first iteration.

Procedure

The procedure of Iteration 3 is similar to the procedure of Iteration 1, Section 3.3. During a session the participant sees the virtual hand for 2.5 minutes, then the hand disappears and the participant is asked to answer the questionnaire.

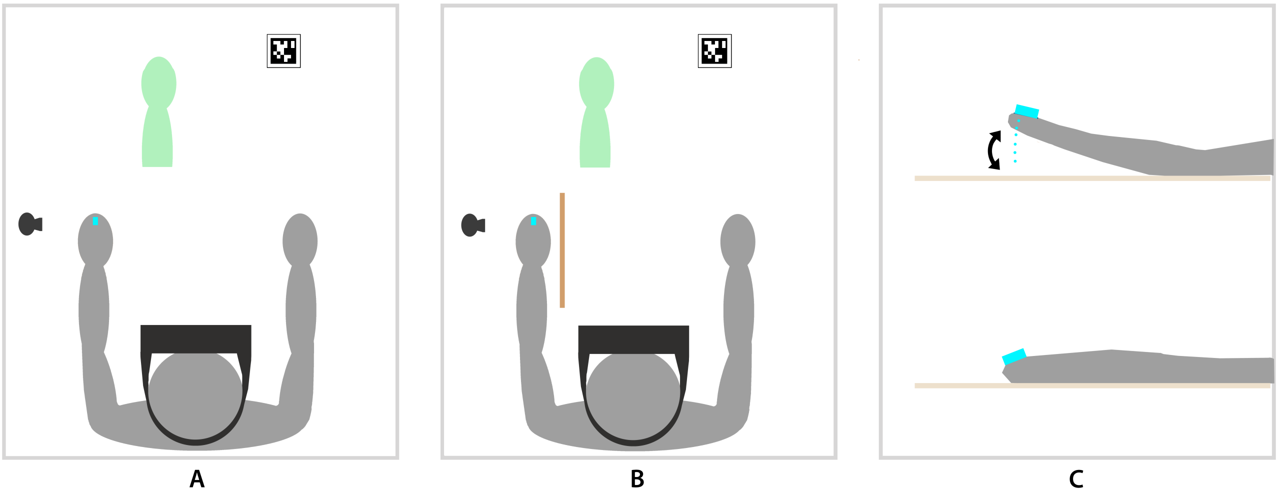


Figure 3.12: Setup of Pilot 2 Iteration 3. **A)** The participant sees the virtual hand (green) in front of him through the Meta DK1 HMD. The blue marker is in view of the webcam. **B)** The left hand of the participant is blocked from view by a screen. **C)** The webcam sees the blue marker on top the finger of the participant and tracks its movement.

Results

For the third iteration there was one female participant of age 24, who participated in earlier iterations. In Figure 3.14 the results are compared for the visual-motor conditions and the arm conditions. In Figure 3.15 the combined results for ownership and agency are shown, constructed in the same way as for Pilot 1 Iteration 2, see Section 2.5. For location only Q1, Q2 and Q7 resulted in scores above the minimum for the synchronous visual-motor condition and the virtual hand condition. It can be seen that the combined ownership is mainly positive for the synchronous condition, corresponding to the results of the individual questions. The largest differences between the synchronous and asynchronous conditions can be seen in Q9 and Q16, where the medians are 2.5 points higher for the synchronous condition. The asynchronous condition has a very large response range, because the individual questions all have very low scores. The combined ownership results for the hand conditions shows that the condition with only the virtual hand has a positive mean and the *virtual and real* condition has a very large response range, both results correlate with the individual question results. It is notable that agency has a higher result with the *virtual and real* condition.

During the condition with only the virtual hand and synchronous movement, the participant reported that she thought that she would feel it when something touched the virtual hand. During the condition with the virtual and the real hand and asynchronous movement the participant reported the feeling that the virtual hand controlled the movement of the real hand, because she wanted to make the movement of both hands match.

Discussion

The location questions with a slightly more positive result suggest that the participant sometimes experienced a shift in location towards the virtual hand. This shift is found in the literature as proprioceptive drift, but it is mostly used as an indication of ownership. The absence of an experienced shift for the virtual and real arm condition suggests that the presence of the real hand prevents a change in sense of

A **B**

Figure 3.13: Setup of Pilot 2 Iteration 3. **A)** The participant's hand has a marker attached to the middle finger and a camera is facing the hand. **B)** The marker lays on top of the finger and is therefore always visible for the camera.

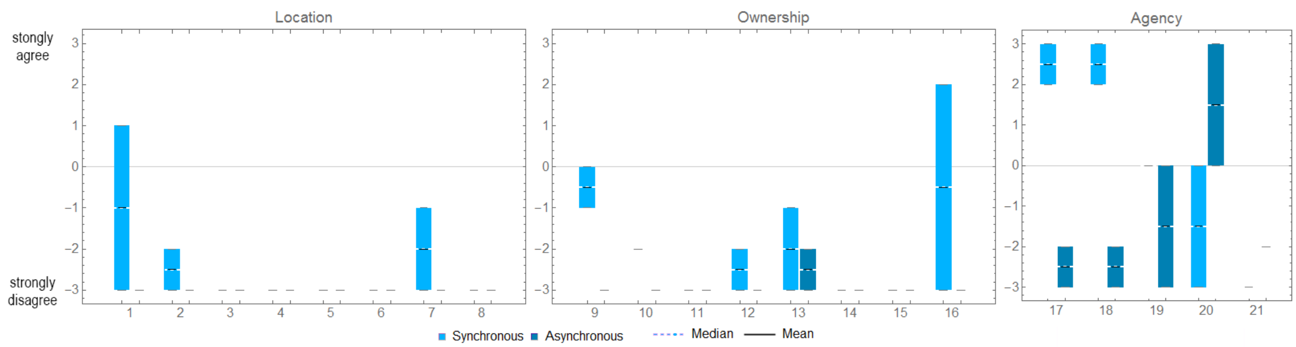
location.

The low scores of Q12 and Q13 for the asynchronous case can be explained by the tendency of the participant to make the movements of the real hand match the virtual hand. This could have caused the movement to be more synchronous and could have resulted in higher ownership. This could also explain the high score of agency for the *virtual and real* condition, as the matching can only happen when the real hand is visible. To make matching the movement harder, the virtual hand should move more randomly.

The participant did not only experience agency, but also expected to get tactile feedback from objects touching the virtual hand. If we define body ownership as the feeling that the body is the source of experienced sensations [14], this statement is a strong indication of the participant feeling ownership over the virtual hand. Although this feeling was only present when only the virtual hand was visually present, the positive ownership mean of the condition with the real and virtual hands indicate that it is possible to induce a sense of ownership over a virtual hand when the real hands are visually present.

3.6 Conclusion

In this section we shall summarize the findings of Pilot 2. The goal of this pilot was to create a convincing experience of the visual-motor feedback. We used a similar approach as in Pilot 1. In Iteration 1 the focus was the active motion, where it was discovered that the motion of the real hand should precisely copy the real hand, and that the setup should be improved. The results also showed that the visual presence of the real hand did not affect the sense of agency of the virtual hand. In Iteration 2 passive motion was added and the results suggest that passive motion negatively affects ownership. It was also found that delay in the motion of the virtual hand had a negative effect on ownership. The positive ownership means of Iteration 3 show that visual delay is an important weakening factor for the illusion of ownership with visual-motor feedback, as it was not possible to invoke the illusion until the final iteration. It can be concluded that the setup of Iteration 3 is sufficient to induce ownership over a virtual noncontinuous hand. However the illusion is not vivid when the real hand is present. In a following pilot visual-motor and visual-tactile feedback shall be combined, which could positively influence the level of ownership, as was suggested by the results of [16].



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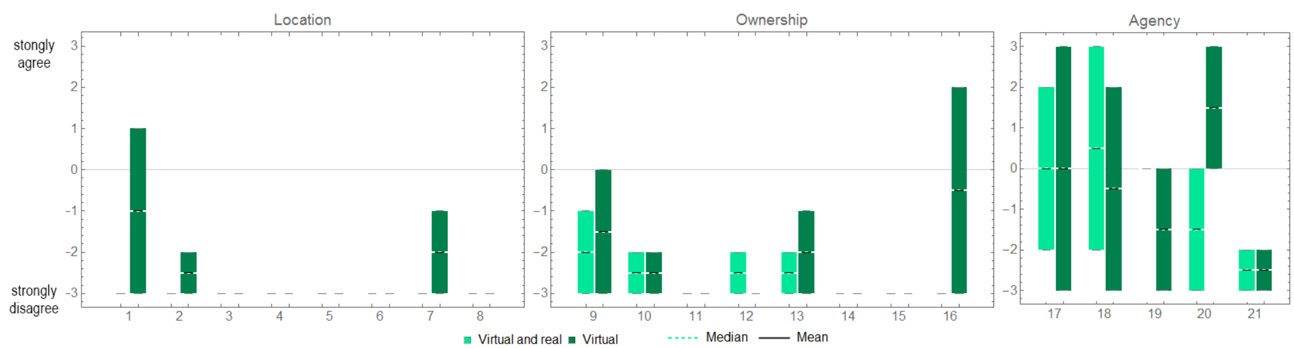


B

Figure 3.14: A boxplot of the questionnaire results of the individual questions of Pilot 2, Iteration 3, **A)** The *asynchronous visual-motor* condition is compared to the *synchronous visual-motor* condition. **B)** The condition with the *virtual and real arm* is compared to the condition with only the *virtual arm*. Each boxplot shows the collection of the results of two sessions for the single participant. A single line indicates that the participant gave the same score for each session. The numbers correspond to the questions Q(i) in Appendix 3.A.3.

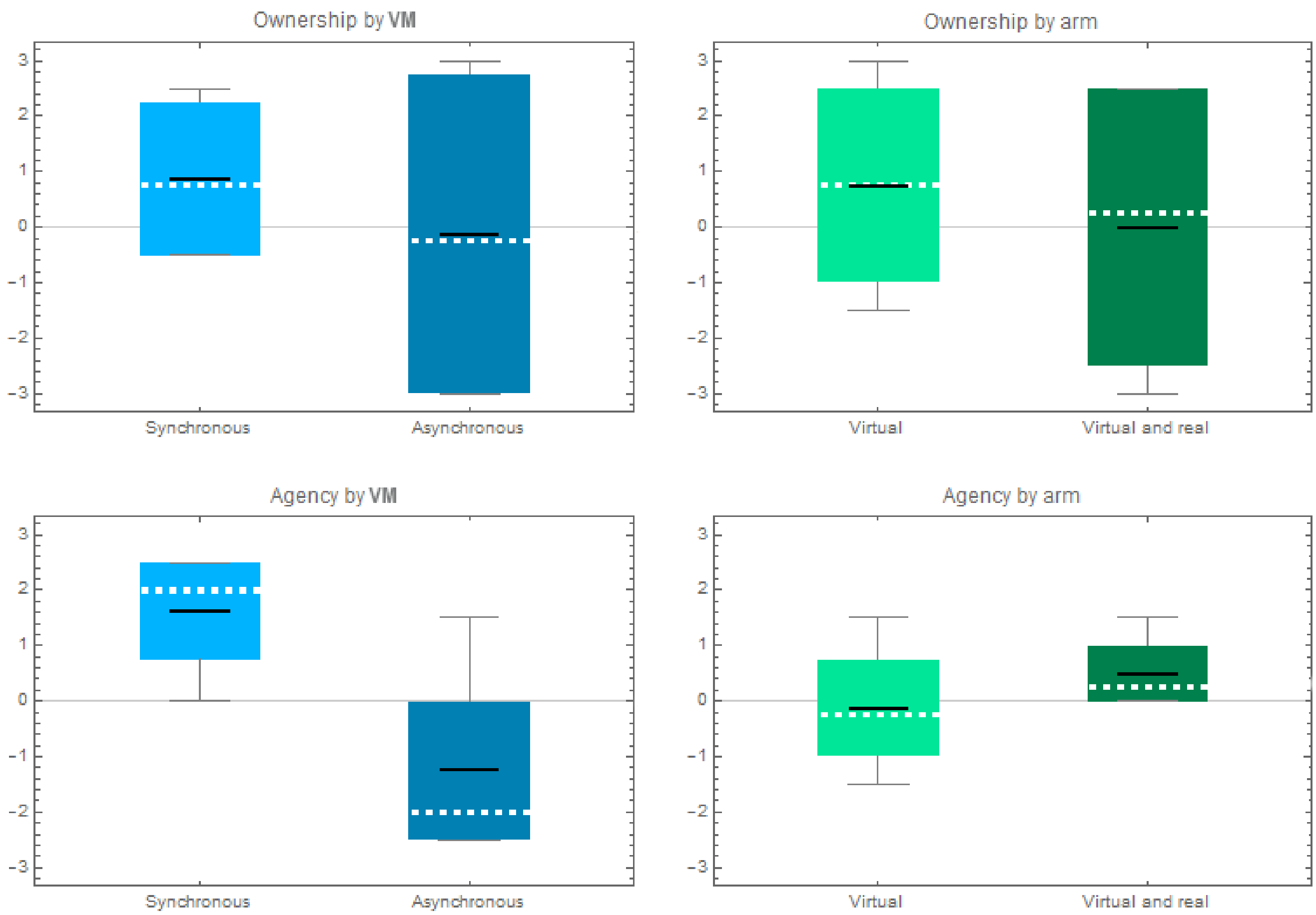


Figure 3.15: Boxplots of the combined questionnaire results of Pilot 2, Iteration 3 of ownership and agency where *synchronous* and *asynchronous visual-motor feedback* are compared and the visual presence of the *virtual hand* with the visual presence of the *virtual and real hand*. Ownership is measured with Q9, the inverse of Q12, the inverse of Q13, and Q16. Q11 is omitted for this score, because it does not give an indication of ownership itself only an indication of the nature of the ownership. Agency is measured with Q17, Q18, the inverse of Q19 and the inverse of Q20.

4 Pilot 3: Combining visual-tactile and visual-motor feedback

In this pilot the final setups of Pilot 1 and Pilot 2 are combined to investigate the effect of visual-tactile feedback (VT) in combination with visual-motor feedback (VM) on the strength of the illusion of ownership. This pilot has one iteration with active motion and synchronous VM and VT, where the effect of combined synchronous VT and VM is compared with either only synchronous VM or synchronous VT.

4.1 Material

- Meta Development Kit 1 HMD
- Meta marker
- Elitac Tactile Display V3.1
- Color marker
- Webcam with color feed
- A box to fit over the participants hand, which blocks it from view, but does not obstruct the webcam.
- The experiment application, developed in Unity v5.5.0f3
- The color tracker application

4.2 Setup

The setup is a combination of the setups of the final iterations of Pilot 1 and 2, combining the color tracking setup with visual-motor feedback and the smart watch setup with visual-tactile feedback.

4.3 Iteration 1

Variables

The first iteration uses the following independent within-subjects variables:

- Arm: {*virtual, real and virtual*} Identical to Pilot 1 and 2.
- Visual-tactile feedback: {*synchronous, none*} The vibro-tactile element will vibrate synchronously with the notification of the virtual smart watch, or there will be no vibrations.
- Visual-motor feedback: {*synchronous, none*} The virtual hand will move synchronously with the real hand, or will not move.

The dependent variables are identical to Pilot 1 and 2.

Procedure

The procedure is a combination of the procedures of the final iterations of Pilot 1 and 2, where the visual-tactile feedback and the visual-motor feedback are combined. The participant experiences 6 sessions of 2.5 minutes after which he/she will answer a questionnaire.

Results

Pilot 3 had one 24 years old female participant, who also participated in Pilot 2. In Figure 3.16 the results of the different combinations of feedback are compared. The results are noticeably low. To compare the results with the final iterations of Pilot 1 and Pilot 2, the individual question scores are combined in the same way as in Pilot 1 and 2, see Section 2.5. The comparison is shown in Figure 3.17. Here is shown that the response ranges of Pilot 3 are much larger than the response ranges of the previous pilots.

The participant reported that the motion of the virtual hand was jerky. She also reported that she thought that the smartwatch was the reason she felt the vibrations and not necessarily the virtual hand.

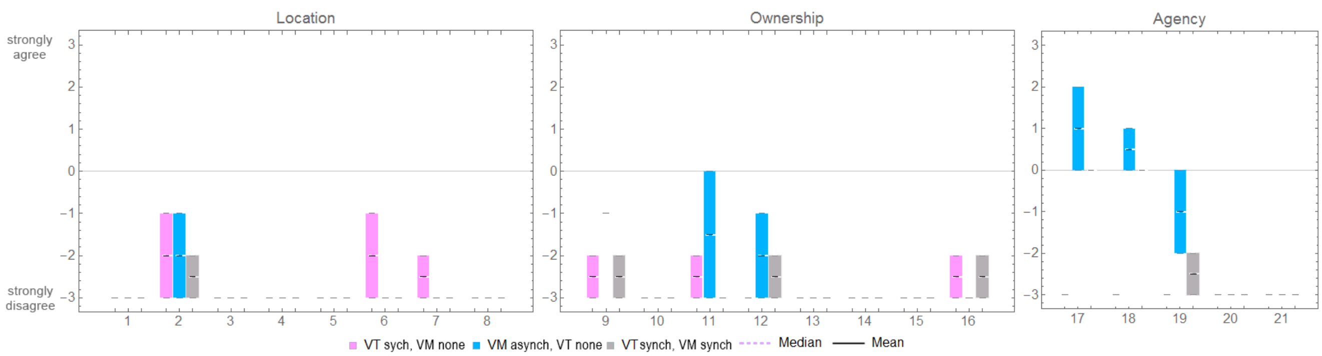


Figure 3.16: A boxplot of the questionnaire results of Pilot 3 where *synchronous visual-tactile feedback*, *synchronous visual-motor feedback* and a combination of VM and VT are compared. Each boxplot shows the collection of the results of two sessions. A vertical line means that the participant gave the same score in every session. The numbers correspond to the questions Q(i) in Appendix 3.A.3.

Discussion

The large response range of the results of Pilot 3 are surprising, because it was expected to find similar results to the final iterations of Pilot 1 and Pilot 2. The large response range of VM of Pilot 3 can be explained by the jerky motion of the virtual hand. This could have been caused by a bad lighting of the color marker, which caused the tracking to fail. A solution for this is to add a light to the setup to make the color of the marker more distinct and to use a different color marker.

The large response range of VT of Pilot 3 can be explained by the participant experiencing the smartwatch as the reason she felt the vibrations instead of the virtual hand, as the experience that a body part is the source of a sensation is a definition of ownership over that body part [14].

As the conditions with only VM or VT both resulted in a large response range, it is not surprising that the condition with both VM and VT resulted in a large response range as well. This condition was probably affected by the same factors as the conditions with only VM or VT. Unfortunately we cannot be certain about the effect of combined feedback on the illusion of ownership, but there are several possibilities. The

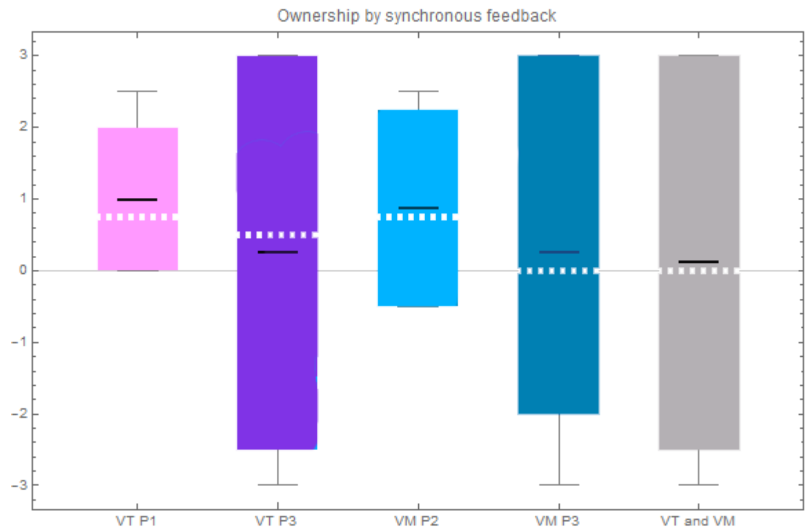


Figure 3.17: An overview of the ownership levels with synchronous feedback over all pilots, where *visual-tactile feedback* is compared with *visual-motor feedback* and a combination of *visual-tactile and visual-motor feedback*. The results of the final iterations of Pilot 1 and 2 for *synchronous feedback* are also displayed. Ownership is measured with Q9, the inverse of Q12, the inverse of Q13, and Q16. Q11 is omitted for this score, because it does not give an indication of ownership itself only an indication of the nature of the ownership.

first is that combined feedback does not increase the level of ownership, but that the level of ownership will be equal to the highest level achieved by either VM or VT. Secondly, asynchronous feedback could negatively affect other synchronous feedback. Finally combined feedback could indeed cause a higher level of ownership.

4.4 Conclusion

In this section we will summarize the findings of Pilot 3. The goal of this pilot was to investigate the effect of combined VM and VT on the illusion of ownership. Unfortunately due to an unstable tracking of the color marker, we cannot draw conclusions about the effect on the ownership illusion, but possible effects were described. We did however find a solution to make the color tracking more robust, by adding a light to the setup and using other color markers.

5 Summary and future prospects

In this chapter we explored the possibilities for a setup in AR to research the Sense of Embodiment over a virtual arm. We conducted three pilot studies that investigated visual-tactile feedback, visual-motor feedback and the combination of the two, in that order. In the first pilot we found that the appearance of the virtual hand and the congruency of the visual-tactile feedback with the visual stimulus are important factors. It was also found that participants could get used to delayed asynchronous feedback and experience it as synchronous. Therefore the delay was replaced by a random pattern. An increase in illusion time appeared to positively affect the level of ownership. In Pilot 2 we showed that the sense of agency is not affected by the visual presence of the real hand. It was also found that visual delay of the visual-motor feedback in the synchronous condition has a negative effect on the sense of ownership and we found a setup that minimizes the delay. In Pilot 3 we unfortunately encountered some problems with the motion tracking of the real hand and no conclusions could be drawn from the results. However a solution has been found to avoid such implementation related problems in the future. For a future setup we advise to use a smartwatch in combination with a vibro-tactile element for visual-tactile feedback and a color tracker for visual-motor feedback. We also suggest to set the illusion time to three minutes and to use a random pattern for asynchronous feedback. These observations from the pilots provide a solid basis for the design of the main experiment. This experiment and related results are the main contributions of this thesis. They are presented in Chapter 4 in the form of a scientific paper.

3.A Questionnaires

3.A.1 Pilot 1: Questionnaire

The questionnaire used for Pilot 1, Iteration 1 and Iteration 2. The questions are based on [1, 10, 18]. The categories are O: ownership, L: location and A: agency.

Category	**Nr.**	**Question**
O	1	It felt as if the virtual hand were the real hand.
O	2	It felt as if the virtual hand was part of my body.
O	3	It felt as if I had two left hands.
O	4	It felt like the virtual hand was a duplication of the real hand.
O	5	It felt like the virtual hand was somebody elses hand.
O (control)	6	It felt as if the real hand were becoming digital.
O (control)	7	The virtual hand began to visually resemble the real hand.
O	8	It seemed as though the touch I felt was caused by the ball touching the virtual hand.
L	9	It felt as if my left hand was at two different locations.
L	10	It felt as if the real hand was at the location of the virtual hand.
L	11	It felt as if the virtual hand was at the location of the real hand.
L	12	It felt as if the real hand were drifting towards the virtual hand.
L	13	It felt as if the virtual hand were drifting towards the real hand.
L	14	It seemed as if I were feeling the touch of the ball in the location where I saw the virtual hand touched.
L	15	It seemed as if the touch I was feeling came from somewhere between the real hand and the virtual hand.
L (control)	16	It felt like I could not really tell where my left hand was.
A	17	It felt like I was in control of the virtual hand.
A	18	It felt like I could move the virtual hand if I wanted to.
A	19	It felt as if the virtual hand copied what the real hand was doing.
A (control)	20	It seemed as if the virtual hand had a will of its own.

3.A.2 Pilot 2: Questionnaire

The questionnaire used for Pilot 2, Iteration 1 and Iteration 2. The questions are based on the questionnaire from Pilot 1 and adapted to fit the visual-motor feedback. The location questions were asked while the virtual hand was still visible and the ownership and agency questions were asked after the session. The categories are L: location, O: ownership and A: agency.

During session:

Category	**Nr.**	**Question**
L	1	It feels as if my left hand is at two different locations.
L	2	It feels as if the real hand is at the location of the virtual hand.
L	3	It feels as if the virtual hand is at the location of the real hand.
L	4	It feels as if the real hand is drifting towards the virtual hand.
L	5	It feels as if the virtual hand is drifting towards the real hand.
L (control)	6	It feels like I cannot really tell where my left hand is.
L	7	It seems as if I am sensing the hand movement in the location of the virtual hand.
L	8	It seems as if the movement I am feeling comes from somewhere between the real hand and the virtual hand.

After session:

Category	**Nr.**	**Question**
O	9	It felt as if the virtual hand were the real hand.
O	10	It felt as if the virtual hand was part of my body.
O	11	It felt as if I had two left hands.
O	12	It felt like the virtual hand was a duplication of the real hand.
O	13	It felt like the virtual hand was somebody elses hand.
O (control)	14	It felt as if the real hand were becoming digital.
O (control)	15	The virtual hand began to visually resemble the real hand.
O	16	It seemed as though the movement I felt was caused by movement of the virtual hand.
A	17	It felt like I was in control of the virtual hand.
A	18	It felt like I could move the virtual hand if I wanted to.
A	19	It felt as if the virtual hand copied what the real hand was doing.
A (control)	20	It seemed as if the virtual hand had a will of its own.

3.A.3 Final questionnaire

This questionnaire was used for Pilot 1 Iteration 3, Pilot 2 Iteration 3 and Pilot 3. The questionnaires of appendix 3.A.1 and 3.A.2 were merged and adapted to encompass multiple types of multi-modal feedback, so the same questions can be used for visual-tactile feedback as for visual-motor feedback. It was decided to ask all questions after each session, as the split questionnaire of Pilot 2 did show any advantages. An open question was added to document the previous experiences of the participants with AR. The categories are L: location, O: ownership and A: agency.

Category	**Nr.**	**Question**
L	1	It felt as if my left hand was at two different locations.
L	2	It felt as if the real hand was at the location of the virtual hand.
L	3	It felt as if the virtual hand was at the location of the real hand.
L (control)	4	It felt as if the real hand was drifting towards the virtual hand.
L (control)	5	It felt as if the virtual hand was drifting towards the real hand.
L (control)	6	It felt like I could not really tell where my left hand was.
L	7	It felt as if the sensations occurred in the location of the virtual hand.
L	8	It felt as if the sensations occurred somewhere between the real hand and the virtual hand.
O	9	It felt as if the virtual hand were my hand.
O (control)	10	It felt as if the virtual hand was part of my body.
O	11	It felt as if I had two left hands.
O	12	It felt like the virtual hand was a duplication of the real hand.
O	13	It felt like the virtual hand was somebody else's hand.
O (control)	14	It felt as if the real hand were becoming digital.
O (control)	15	The virtual hand began to visually resemble the real hand.
O	16	It felt as though the virtual hand was the reason I could perceive certain sensations.
A	17	It felt like I was in control of the virtual hand.
A	18	It felt like I could move the virtual hand if I wanted to, as if it was obeying my will.
A	19	It felt as if the virtual hand copied what the real hand was doing.
A	20	It felt as if the virtual hand had a will of its own.
A (control)	21	It felt as if the virtual hand was controlling my will.
open	22	Do you have any remarks regarding the experience that were not covered by the questionnaire?

Chapter 4

The Sense of Embodiment in Augmented Reality: A Third Hand Illusion

Abstract

Augmented Reality creates the possibility for users to interact with virtual objects. A problem arises when the objects are out of reach of the real hands. A solution could be the addition of a third virtual hand, which can cover a larger distance than a real hand. To experience the virtual hand as a real hand, the user should experience a Sense of Embodiment over the virtual hand. It has been proven to be possible to invoke the Sense of Embodiment over a virtual hand in Virtual Reality, but it is uncertain if it can be done in Augmented Reality. We show that despite a significant effect of visual-tactile and visual-motor feedback, it is surprisingly not possible to induce ownership over a virtual hand with our setup, possibly due to the uncanny valley effect. We therefore conclude that, if at all, such ownership in AR may only appear if the virtual hand appears either very realistic or very abstract. Our results also show that the visual presence of the real hand does not affect the sense of agency, and it prevents a shift in sense of location, but caused some participants to experience that their left hand was in two locations simultaneously. This is promising as it may suggest that ones perception of location can be split, which could be the focus of a follow-up study.

Keywords: augmented reality, rubber hand illusion, third hand, sense of embodiment, body ownership, agency, self-location, multimodal feedback

1 Introduction

In Augmented Reality (AR) the real world is enhanced with virtual objects. If those objects are within reach, we could provide the possibility for users to directly manipulate them and interact with them. A problem arises when a user wants to interact with an object that is beyond the reach of a normal hand. This could be solved by adding a virtual hand which can cover a larger distance than a real hand. Extended bodies were researched in VR with a tail [27] and wings [23, 24], and in the real world with rubber hands [4]. To realize a larger reaching distance the arm should be either very long or unconnected. In VR and the real world ownership has been successfully induced over such arms [12, 19, 9]. The additional virtual hand should be experienced as a real hand, which is described by the *Sense of Embodiment* (SoE) [11] toward the virtual hand. Three subcomponents of the SoE are body ownership, agency and self-location, which all focus on another aspect of how a body is experienced.

Research in Virtual Reality (VR), which often uses multi-modal feedback to strengthen the SoE, suggests that experiencing SoE over virtual limbs creates benefits for virtual applications, such as increased credibility of the experience and increased user performance [7, 8, 27], and makes it possible for these applications to have a positive effect on the real world, as can be seen in the use of VR for psychological treatment [22, 10] and simulation training [28, 33]. Unfortunately we cannot assume that SoE in AR produces the same results as in VR, as there are crucial differences between the user experience in VR and AR: the visual presence of the real body, and the mixed reality compared to uniform reality (e.g. completely virtual or completely real). The visual presence of the real body makes it difficult to induce ownership over a different body, because the real body occupies the first person perspective, which is not crucial for, but can be a very strong cause of ownership [20, 25]. The visual presence of the real body also has a negative effect on the level of ownership over an extra body *part* [1]. The mixed reality may cause a larger distinction between the real body and the virtual body part, which could negatively influence the strength of the ownership illusion, similar to the use of no texture versus a skin texture [5]. Despite these differences, we argue that inducing ownership over a virtual limb in AR, where the real limbs are visually present, should be possible if all other necessary factors are performed correctly.

In this study we investigate how multi-modal feedback and interaction affect the Sense of Embodiment, i.e. body ownership, agency and arm-location, towards a separate virtual arm in AR when the real arms are visually present. To accomplish this we conducted an experiment based on the Rubber Hand Illusion (RHI), where visual-tactile feedback and visual-motor feedback are combined in an AR setup with a separate virtual hand: a third hand. We expect that, despite the negative effect of the presence of the real arms and the mixed reality, we will be able to induce a small level of ownership. Unfortunately, our results show that the majority of the participants did not experience ownership at all, even without the visual presence of the real arm, which should, according to the literature, result in an illusion of ownership. This suggests that the setup needs to be improved or that our intuitive assumption that AR behaves similarly to VR for the SoE is indeed incorrect. Our results suggest a stronger influence of realism as one would intuitively assume, thus indicating a high relevance of future research considering this aspect. We also show that participants experienced a strong sense of agency with active synchronous visual-motor feedback as expected and that agency was not affected by the presence of the real hand, which suggests that the motor-control of a virtual hand is not negatively affected by the presence of the real hand. Thirdly, active synchronous visual-motor feedback also caused some participants to experience that their left arm was in two locations at the same time indicating a relation between experienced agency and hand location. Based on the identified aspects relative to the unexpected negative ownership results, we propose possible improvements for the setup for further research in SoE in AR, and we name key issues for future research.

The structure of this paper is as follows. In Section 2 we discuss related topics, such as the Sense of Embodiment and the comparison of the SoE in different realities. In Section 3 and 4 the experiment is discussed, and Section 5 concludes the paper and gives directions for future research.

2 Related work

2.1 The Sense of Embodiment

Kilteni et al. define the *Sense of Embodiment* (SoE) [11], as follows: "The SoE toward a body(part) B is the sense that emerges when B's properties are processed as if they were the properties of one's own body." Three subcomponents of the SoE are body ownership, agency and self-location. Body ownership is defined as the feeling that the body(part) is the source of experienced sensations, and this is commonly researched using a setup based on the famous Rubber Hand Illusion (RHI), first described by Botvinick and Cohen [2], where the effect of congruent and incongruent visual-tactile feedback on ownership was investigated. The rubber hand and the real hand, which is out of sight, are congruently stroked by a brush to induce the illusion that the sense of being stroked originates from the rubber hand. The incongruent stroking, on the other hand, breaks the illusion causing no experienced ownership over the rubber hand. Ownership is also affected by other aspects, such as visual consistency between the rubber hand and the real hand, e.g. shape and texture [5, 31], and active and passive synchronous visual-motor feedback [7]. The possibility of experiencing ownership over multiple arms has also been investigated. Guterstam et al. [4] found that one can experience ownership over a real right hand and right-handed rubber hand simultaneously. On the other hand Folegatti et al. [3] showed that when presented with two right-handed rubber hands, one will only experience ownership over the closest one. The second concept, agency, refers to the sense of having motor control over the body(part). Kalckert et al. added visual-motor feedback to the illusion in [7, 8], where a finger of the rubber hand moved congruently with the real finger, which induced a sense of agency. Incongruent movement of the rubber hand eliminated the sense of agency. Their results suggested that ownership facilitates agency. Lastly, self-location represents the feeling of residing inside a body and to sense the relative position of the body parts. Lenggenhager et al. [14] demonstrate this by having participants mislocalize themselves towards a virtual body that is standing in front of them, due to congruent stroking of the back of the participant and the virtual body.

2.2 SoE in various realities

It was found that the SoE is affected similarly in VR as in reality, when the rubber hand is swapped for a virtual one, also known as the Virtual Hand Illusion (VHI) [19, 18, 30, 21, 26]. New discoveries were the effect of body continuity [19] and limb length [12] on ownership. The extension of the human body was also investigated further by the addition of tails [27] and wings [23]. Compared to VR and the real world, AR has seen very little research on the SoE. Suzuki et al. [29] and IJsselsteijn et al. [6] have executed a variation of the RHI in AR, with varying results. Suzuki et al. reported similar results to other non-AR studies, with the addition of cardio-visual feedback, which positively affected the level of ownership. IJsssselteijn et al., who investigated the difference between an unmediated RHI, a virtual RHI and an augmented RHI, found that the AR condition resulted in a significantly lower level of ownership than the VR and unmediated conditions. The difference was explained by the mixed reality of the AR condition, which made the difference between the real and virtual hands more obvious. Suzuki et al. did not mention this as problem, but the real hands were not visible in their experiment and the virtual hand was displayed as an exact copy of the hand of the user. It is clear that, although the SoE is thoroughly explored in reality and VR, in AR there are still questions to be answered. Therefore it is crucial that the SoE in AR is further investigated and the visual presence of the real body should be a key issue, as this is not regarded in earlier AR experiments.

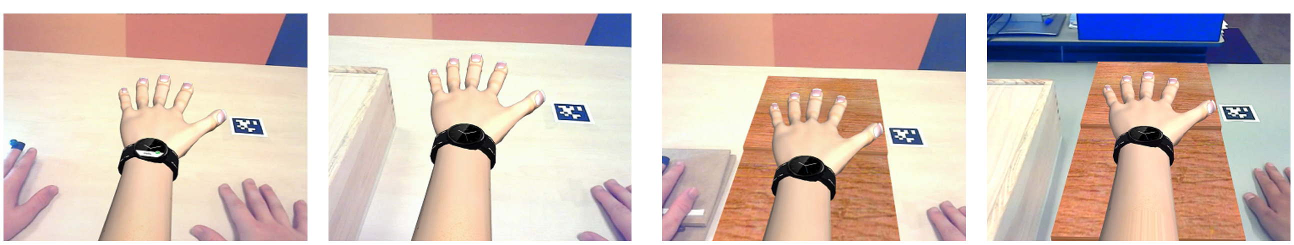
3 Third hand AR experiment

3.1 Material and setup

To create the AR, we used the the Meta DK1 HMD (head mounted display) with the Field of View (FoV) Expander Lens. The application was developed in Unity 5.5.0f3 using the Meta SDK 1.3.4.308 for Unity and EmguCV. The scripts were written in C# using Microsoft Visual Studio 2015. The participants saw a virtual hand wearing a smartwatch lying on the table in front of them. The virtual hand was positioned with a marker. A participant wore a wrist band with an Elitac Tactile Display V3.1 attached on the left wrist, which provided vibro-tactile feedback, and a color marker on the middle finger of the left hand. In case of passive motion, the virtual hand lay on a virtual pivoting board and the left hand of the participant lay on a real pivoting board. A camera was positioned to track the color marker on the left hand of the participant and a box was used to block the left hand from view. The box was open on the left side as to not block the line of sight of the camera. A lamp focused on the color marker to make the color more distinct. The color tracking had a delay of 60ms, during synchronous movement. During head movement of a participant, the delay of repositioning the virtual hand was less than 200ms. The setup can be seen in Figure 4.1 and the view of the participants can be seen in Figure 4.2.

A B C D

Figure 4.1: Setup of the experiment. The participant wears a wrist band with a vibro-tactile element on the left wrist and a blue color marker on the middle finger. **A)** The participant's hand is visible. **B)** The participant's hand is blocked from view by a box. **C)** The participant's hand is visible and lies on a pivoting board. **D)** The participant's hand lies on a pivoting board and is blocked from view by a box.



A B C D

Figure 4.2: View of the participant. The virtual hand wears a smartwatch. **A)** The participant's hand is visible and the smartwatch receives a notification. **B)** The participant's hand is blocked from view by a box. **C)** The virtual hand lies on a pivoting board, just like the real hand. **D)** The virtual hand lies on a pivoting board and the participant's hand is blocked from view by a box.

3.2 Method and Procedure

The experiment consists of the independent variables seen in Table 4.1. VM and VT were chosen, as both types of feedback are proven to induce a level of ownership in the RHI and VHI, and VM induces agency as well. The dependent variables are the levels of ownership, agency, and location the participant experienced over the virtual hand. These were measured with a 7-point Likert scale questionnaire referring to three aspects of the SoE: ownership, agency and location, seen in Table 4.3, after Section 5. The questions are based on [7, 2, 15]. The medical ethics committee of the UMC Utrecht did not raise objections to the execution of this experiment.

Independent Variable	**Level**	**Description**
real and virtual hands (hand, w)	v-hand	*Only* the virtual hand is visible in front of the participant; the real hand is out of sight in a box.
	vr-hand	*Both* virtual and real hands are visible.
visual vibro-tactile stimulation (VT, w)	synch-VT	The vibro-tactile element on the participant's wrist vibrates *synchronously* with a virtual smartwatch worn by the virtual hand.
	asynch-VT	The vibro-tactile element on the participant's wrist vibrates *asynchronously* with a virtual smartwatch worn by the virtual hand.
	no-VT	The virtual smartwatch does not vibrate and there is *no* vibration of the vibro-tactile element.
visual-motor stimulation (VM, b)	a-synch-VM	The participant *actively* moves the real hand and sees the virtual hand move *synchronously*.
	a-asynch-VM	The participant *actively* moves the real hand and sees the virtual hand move *asynchronously*.
	p-synch-VM	The real hand is moved *passively* by the experimenter and the participant sees the virtual hand move *synchronously*.
	p-asynch-VM	The real hand is moved *passively* by the experimenter and the participant sees the virtual hand move *asynchronously*.
	no-VM	The real hand does *not* move, nor does the virtual hand.

Table 4.1: The independent variables, within subjects (w) and between subjects (b)

Each participant received a letter with information about the experiment at least a week in advance. Before the experiment started each participant was seated in a neutral room, was given a summary of the information letter and was allowed to ask any questions they had regarding this information. They received more detailed information about the experiment, signed a consent form and filled out a general information form.

At the start of the experiment the Meta HMD was calibrated for each participant. The participants were divided in five groups, where each group experienced a different kind of visual-motor feedback (*VM*). Each participant tested six conditions with three variances of visual-tactile feedback (*VT*) and two for visual presence of the real hand (*hand*) (Table 4.1). The conditions were presented in a random order. During the testing of a condition, for each group except the *no-VM* group, the experimenter calibrated the color tracker. Then the virtual hand appeared and the condition started. This consisted of three minutes looking at the virtual hand with a specific form of *VT* and/or *VM* stimulation. After these three minutes the participants answered a questionnaire and had a break of another three minutes before the next condition was tested.

After the experiment, the participant was explained the purpose of the experiment and the purpose of the different conditions. Altogether, the experiment took about an hour. To assure there were no lasting effects of the experiment, the participant was asked a few safety questions directly after the experiment and one week later. The safety questions were the same is those used by Kilteni et al. [12].

3.3 Participants

For this experiment there were 29 participants: 19 male, 10 female, 18-26 years old (mean 22). Twenty-two were right handed and one participant was ambidextrous. Twelve participants have had earlier experiences with AR, of which two participated in other AR experiments and one develops AR applications. As the experiment consists of simple tasks, we do not expect these differences to influence the results, also we did not observe any indications of this during the experiment. Data of two participants were omitted from the results: one due to incorrect settings of the HMD, and the other due to incorrect hand positioning, meaning data of 27 participants was used for analyses. Post-experiment questions revealed no lasting effects of the experiment for all participants.

3.4 Results

The data was analyzed using a repeated measures MANOVA, with factors *hand* (two levels), *VT* (three levels) and between-subjects *VM* (five levels). For post hoc comparisons of *hand* and *VT* the Bonferroni correction is used and for *VM* the Tukey's test is used. When Levene's test failed, Games-Howell was used for post hoc comparisons. All post hoc comparisons can be seen in the corresponding figures. Results are discussed below and illustrated in Figures 4.4, 4.5 and 4.6. The interactions are compared in Figure 4.3. The results are also shown in Table 4.2.

Ownership questions

The effect of the *hand* was significant for O1 ($F(1, 22) = 11.554, p < 0.01$), O2 ($F(1, 22) = 5.676, p < 0.05$) and O6 ($F(1, 22) = 5.519$, $p < 0.05$). The effect of *VT* was significant for O1 ($F(2, 44) = 11.593$, $p < 0.001$), O2 ($F(2, 44) = 11.177$, $p < 0.001$), O4 ($F(2, 44) = 5.667$, $p < 0.01$), O5 ($F(2, 44) = 4.116$, $p < 0.05$) and O8 ($F(2, 44) = 10.239$, $p < 0.001$). The effect of *VM* was significant for O3 ($F(4, 22) = 8.085$, $p < 0.001$), O4 ($F(4, 22) = 9.184$, $p < 0.001$) and O5 ($F(4, 22) = 3.980$, $p < 0.05$). The interaction between *hand* and *VT* was significant for O5 ($F(2, 44) = 5.739, p < 0.01$). There were no other significant interactions. In spite of the significant differences, the results for ownership were mainly negative.

Agency questions

The effect of the *hand* was not significant for any of the questions. The effect of *VT* was significant for A1 ($F(2, 44) = 4.297$, $p < 0.05$). The effect of *VM* was significant for A1 ($F(4, 22) = 16.482$, $p < 0.001$), A2 ($F(4, 22) = 18.158$, $p < 0.001$), A3 ($F(4, 22) = 14.326$, $p < 0.001$) and A4 ($F(4, 22) = 21.564$, $p < 0.001$). The interaction between *VT* and *VM* was significant for A3 ($F(8, 44) = 3.751$, $p < 0.01$), and there were no other significant interactions.

Location questions

The effect of the *hand* was significant for all questions except L1. L2 ($F(1,22) = 10.754$, $p < 0.01$), L3 ($F(1,22) = 16.873$, $p < 0.001$), L4 ($F(1,22) = 8.152$, $p < 0.01$), L5 ($F(1,22) = 5.563$, $p < 0.05$), L6 ($F(1,22) = 10.071$, $p < 0.01$), L7 ($F(1,22) = 9.823$, $p < 0.01$) and L8 ($F(1,22) = 5.730$, $p < 0.05$). The effect of VT was significant for L2 ($F(1.406,44) = 7.026$, $p < 0.01$) with Greenhouse-Geisser correction, L3 ($F(2,44) = 4.178$, $p < 0.05$), L6 ($F(2,44) = 4.438$, $p < 0.05$), L7 ($F(2,44) = 9.083$, $p < 0.001$) and L8 ($F(2,44) = 3.823$, $p < 0.05$). The effect of VM was only significant for L1 ($F(4,22) = 7.952$, $p < 0.001$). The interaction between *hand*, VT and VM was significant for L1 ($F(8,44) = 2.282$, $p < 0.05$), and the interaction between VT and VM was significant for L3 ($F(8,44) = 3.078$, $p < 0.01$). There were no other significant interactions.

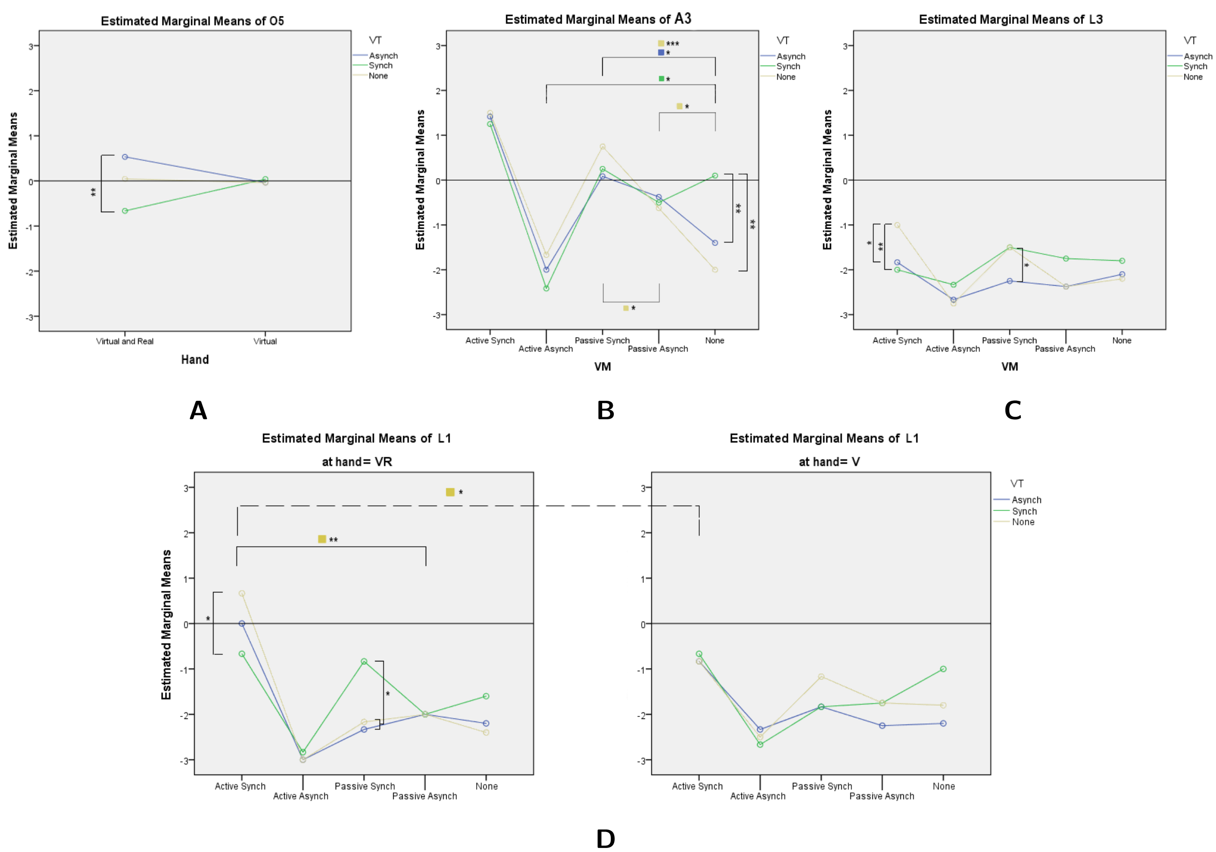


Figure 4.3: A line plot of the estimated marginal means of the significant interactions. Significance is indicated with *** ($p < 0.001$), ** ($p < 0.01$) and * ($p < 0.05$). **A)** Results of O5, where the interaction of *hand* and *VT* is shown **B)** Results of A3, where the interaction of the different *VM* groups with *VT* is shown. **C)** Results of L3, where the interaction of *VT* and *VM* is shown. **D)** Results of L1, where the interaction of *hand*, *VT* and *VM* is shown.

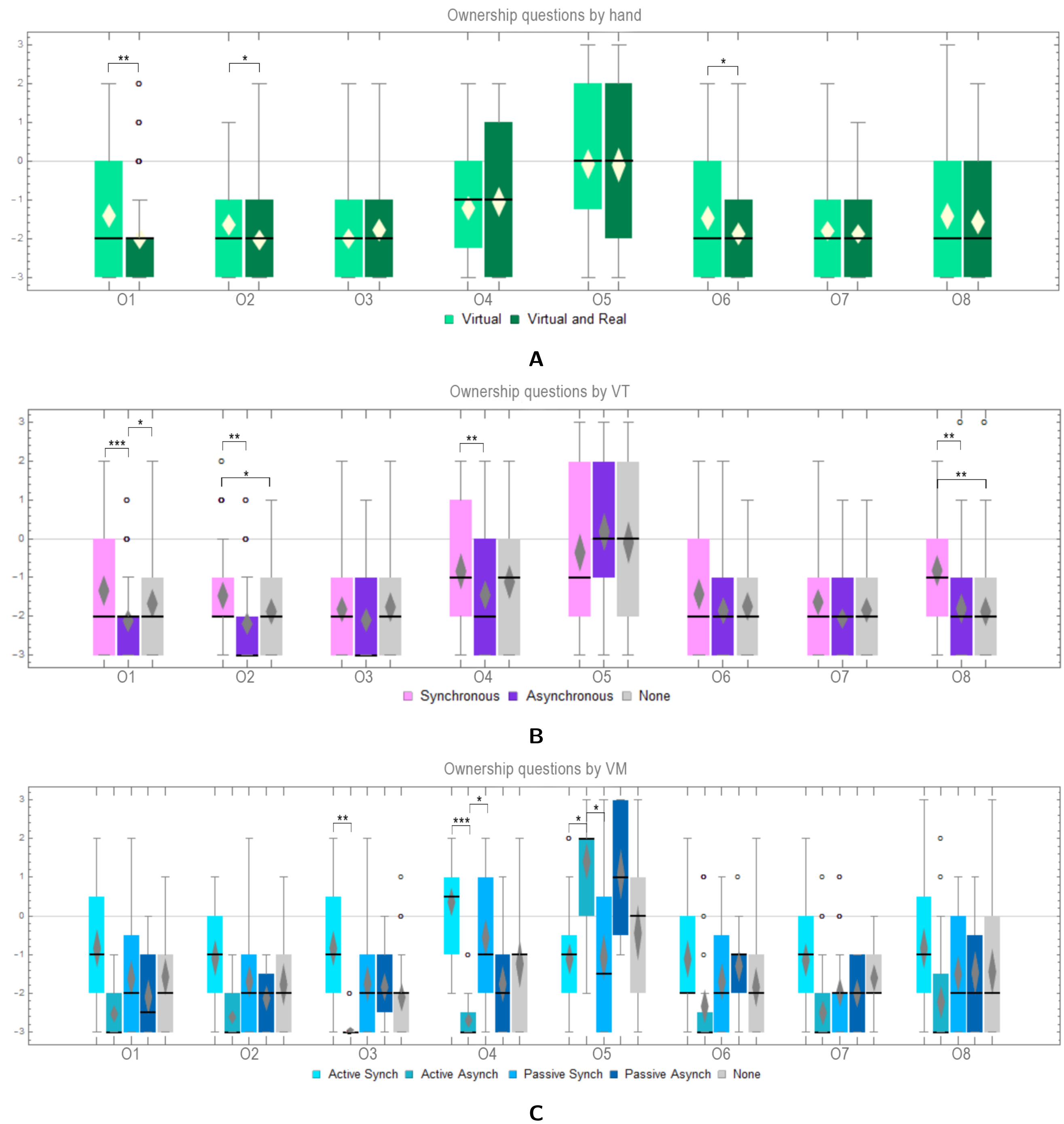
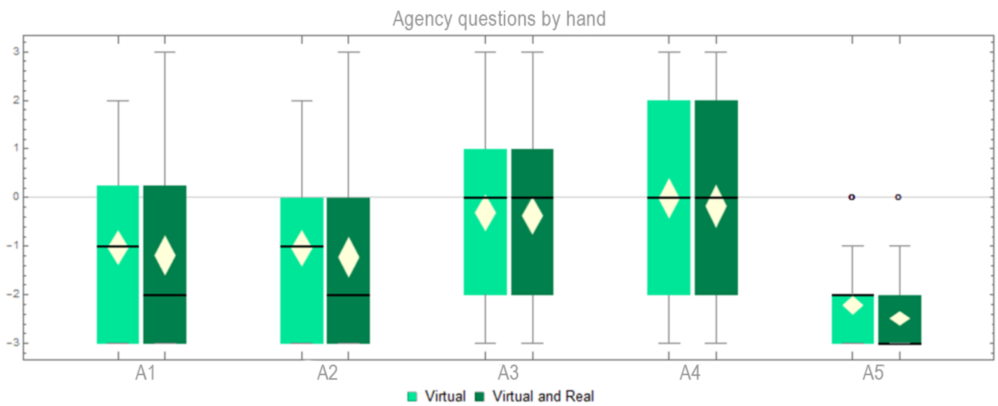


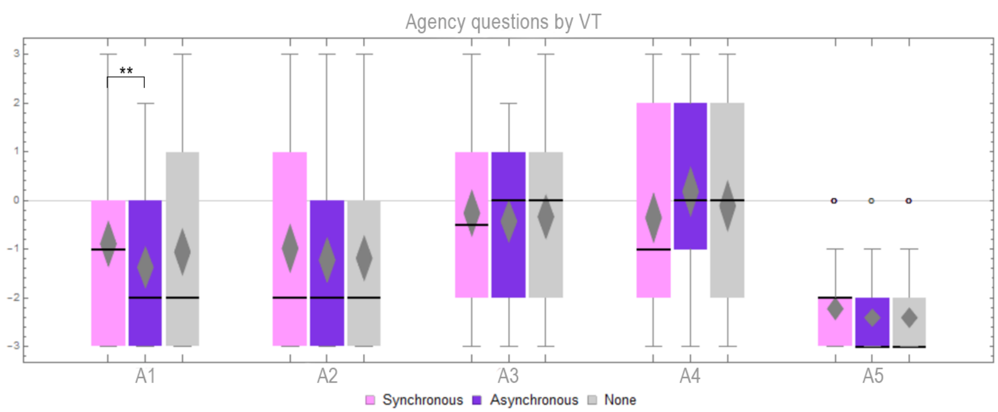
Figure 4.4: A boxplot of the questionnaire results of O1-O8. The black line represents the median and the diamond represents the mean and the 95% confidence interval. The numbers correspond to the questions in Table 4.3. Post hoc comparisons are indicated with *** ($p < 0.001$), ** ($p < 0.01$) and * ($p < 0.05$). **A)** The results of *v-hand* are compared with the results of *vr-hand*. Each boxplot shows the collection of the results of three sessions of all participants. **B)** The results of *synch-VT* are compared with the results of *asynch-VT* and *no-VT*. Each boxplot shows the collection of the results of two sessions of all participants. **C)** The results of the *VM* groups are compared. Each boxplot shows the collection of the results of all sessions of the participants of one *VM* group.

Ind. Variable	**Factor**	**Question**	Significance	
Ownership	*hand*	O1	$F(1,22) = 11.554$	$p < 0.01$
		O2	$F(1,22) = 5.676$	$p < 0.05$
		O6	$F(1,22) = 5.519$	$p < 0.05$
	VT	O1	$F(2,44) = 11.593$	$p < 0.001$
		O2	$F(2,44) = 11.177$	$p < 0.001$
		O4	$F(2,44) = 5.667$	$p < 0.01$
		O5	$F(2,44) = 4.116$	$p < 0.05$
		O8	$F(2,44) = 10.239$	$p < 0.001$
	VM	O3	$F(4,22) = 8.085$	$p < 0.001$
		O4	$F(4,22) = 9.184$	$p < 0.001$
		O5	$F(4,22) = 3.980$	$p < 0.05$
	*hand*VT*	O5	$F(2,44) = 5.739$	$p < 0.01$
Agency	*VT*	A1	$F(2,44) = 4.297$	$p < 0.05$
	VM	A1	$F(4,22) = 16.482$	$p < 0.001$
		A2	$F(4,22) = 18.158$	$p < 0.001$
		A3	$F(4,22) = 14.326$	$p < 0.001$
		A4	$F(4,22) = 21.564$	$p < 0.001$
	*VT*VM*	A3	$F(8,44) = 3.751$	$p < 0.01$
Location	*hand*	L2	$F(1,22) = 10.754$	$p < 0.01$
		L3	$F(1,22) = 16.873$	$p < 0.001$
		L4	$F(1,22) = 8.152$	$p < 0.01$
		L5	$F(1,22) = 5.563$	$p < 0.05$
		L6	$F(1,22) = 10.071$	$p < 0.01$
		L7	$F(1,22) = 9.823$	$p < 0.01$
		L8	$F(1,22) = 5.730$	$p < 0.05$
	VT	L2	$F(1.406,44) = 7.026$	$p < 0.01^G$
		L3	$F(2,44) = 4.178$	$p < 0.05$
		L6	$F(2,44) = 4.438$	$p < 0.05$
		L7	$F(2,44) = 9.083$	$p < 0.001$
		L8	$F(2,44) = 3.823$	$p < 0.05$
	VM	L1	$F(4,22) = 7.952$	$p < 0.001$
	*hand*VT*VM*	L1	$F(8,44) = 2.282$	$p < 0.05$
	*VT*VM*	L3	$F(8,44) = 3.078$	$p < 0.01$

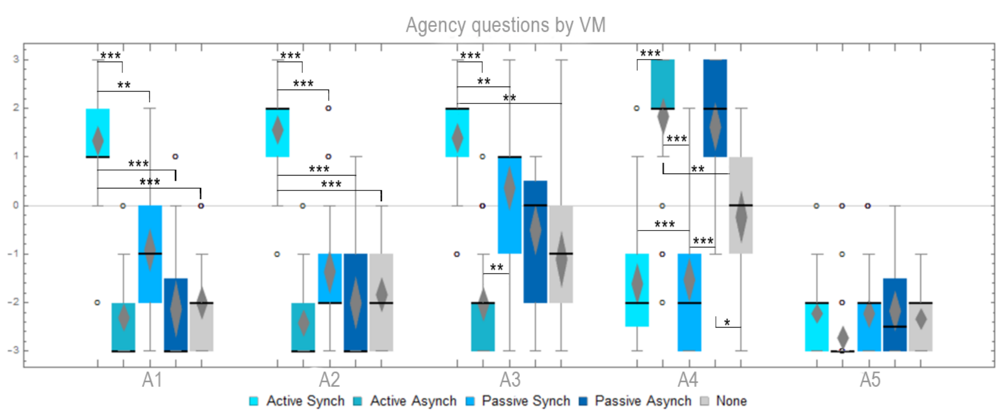
Table 4.2: The significant results displayed per independent variable, for each factor and interaction. G indicates the Greenhouse-Geisser correction.



A

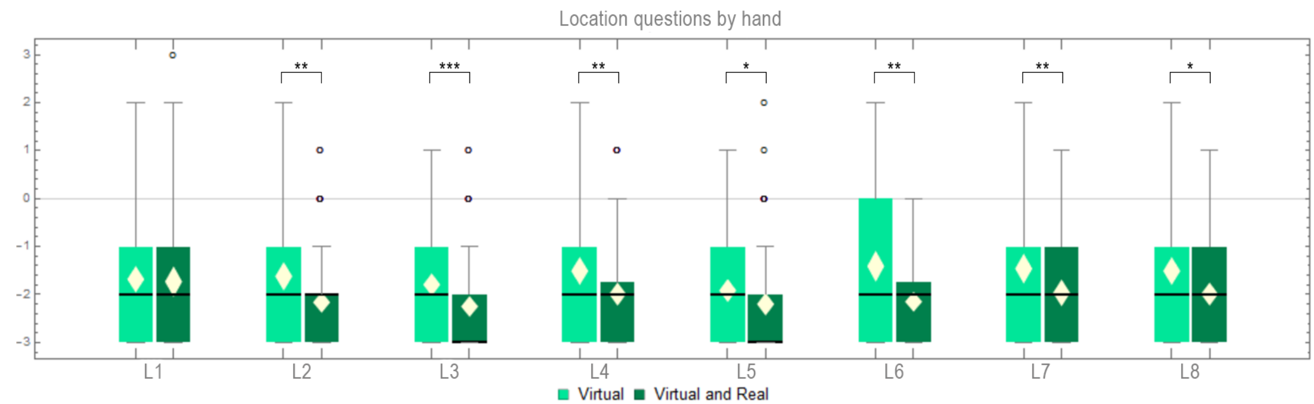


B

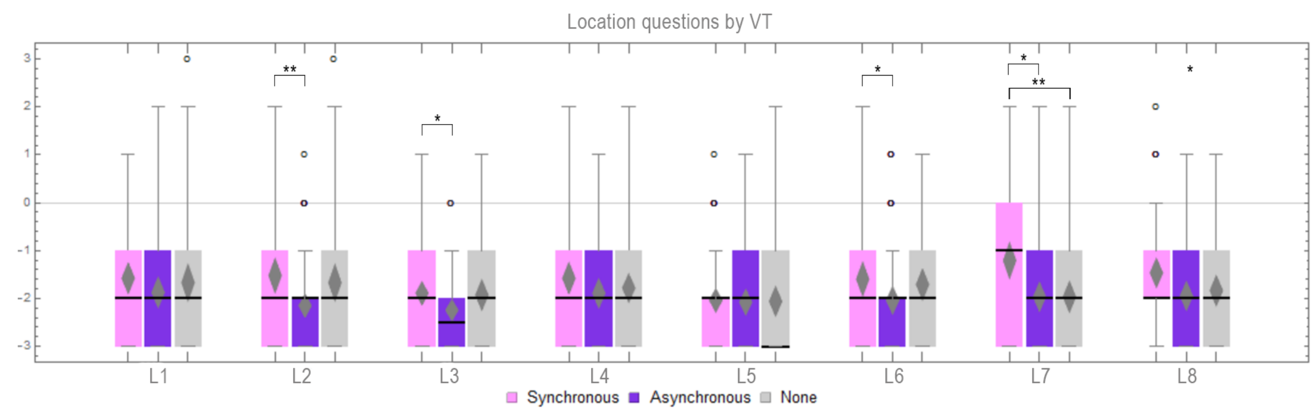


C

Figure 4.5: A boxplot of the questionnaire results of A1-A5. The black line represents the median and the diamond represents the mean and the 95% confidence interval. The numbers correspond to the questions in Table 4.3. Post hoc comparisons are indicated with *** ($p < 0.001$), ** ($p < 0.01$) and * ($p < 0.05$). **A)** The results of *v-hand* are compared with the results of *vr-hand*. Each boxplot shows the collection of the results of three sessions of all participants. **B)** The results of *synch-VT* are compared with the results of *asynch-VT* and *no-VT*. Each boxplot shows the collection of the results of two sessions of all participants. **C)** The results of the different *VM* groups are compared. Each boxplot shows the collection of the results of all sessions of the participants of one *VM* group.



A



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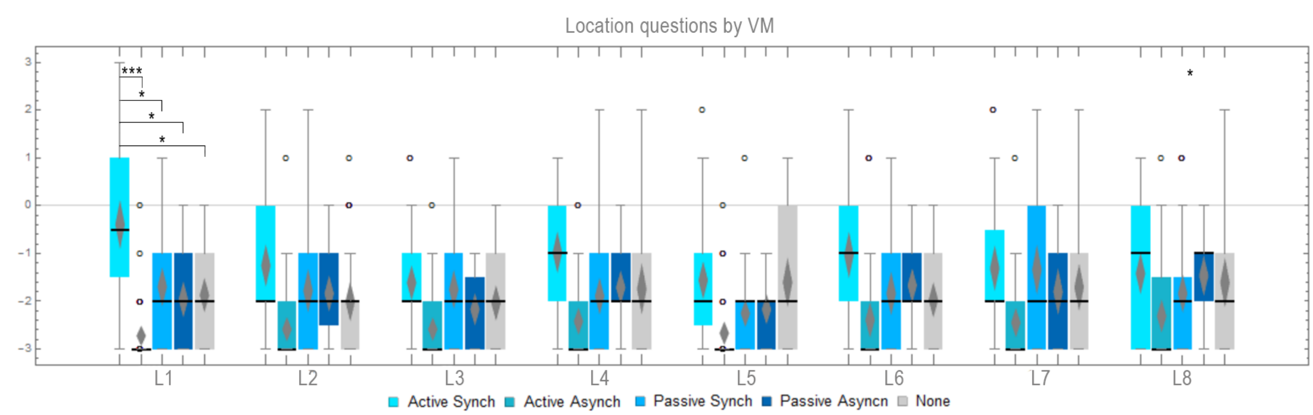

C

Figure 4.6: A boxplot of the questionnaire results of L1-L8. The black line represents the median and the diamond represents the mean and the 95% confidence interval. The numbers correspond to the questions in Table 4.3. Post hoc comparisons are indicated with *** ($p < 0.001$), ** ($p < 0.01$) and * ($p < 0.05$). **A)** The results of *v-hand* are compared with the results of *vr-hand*. Each boxplot shows the collection of the results of three sessions of all participants. **B)** The results of *synch-VT* are compared with the results of *asynch-VT* and *no-VT*. Each boxplot shows the collection of the results of two sessions of all participants. **C)** The results of the different *VM* groups are compared. Each boxplot shows the collection of the results of all sessions of the participants of one *VM* group.

4 Discussion

Ownership

We expected that it is possible to invoke at least a small level of ownership over the virtual hand, while the real hand is visually present, but unfortunately the results do not support this. However, the significant differences for all factors show there is an effect on ownership. Our results identified the possibility to experience ownership over a third virtual hand, as more than 25% of the participants experienced that they had three hands in the *a-synch-VM* condition and this was a significant difference with the *a-asynch-VM* condition, where none of the participants experienced this. It was shown earlier by Guterstam et al. [4] that one can experience ownership over a third rubber hand in the real world. It is interesting that the *hand* had no significant effect on this phenomenon (O3), which suggests that someone can experience the virtual hand as an *extra* hand without seeing the real hand as well as while seeing the three hands.

The results show a significantly higher ownership level for the *v-hand* condition compared to the *vr-hand* condition, but the ownership level was mainly negative for both conditions and not similar to the results of other RHI experiments, such as [2, 7, 21, 26], as expected. We suspect that the inability to induce the illusion was caused by various choices in the setup. This is supported by the results of O1 and O5 which, considering they concern whether the virtual hand belonged to the participant or someone else, should have opposite results, but this was not the case for the *as-VM* and *ps-VM* conditions. We suspect that the appearance of the virtual hand had a large influence, as six participants mentioned that the virtual hand did not look like their own hand and some even described detailed differences like the finger nails. This, together with the obvious differences between real and virtual, could have amplified the sense that the virtual hand was not their own. This phenomenon was also addressed by IJsselsteijn et al. in [6]. Lugrin et al. found in [16] that two humanoid avatars induced a lower level of ownership than the robot avatar and cartoon avatar, because the participants noticed details to a higher extent in the humanoid avatars. This effect was explained by the uncanny valley. Our experiment seems to be affected more strongly by the uncanny valley, as our results show a mainly negative level of ownership, while the virtual hand appears similar to virtual hands in VHI studies with positive ownership. It could be possible that the curve has a lower maximum for AR, see Figure 4.7. To avoid the uncanny valley we propose to either make an exact copy of the hand of the participant as in [29], or to give the virtual hand a less human appearance, like a wire frame or a robot hand.

A few remarks must be made regarding the control questions. As the virtual hand is not connected to the real body, it was expected that O2, which asks the participant if the virtual hand is part of the body, was answered negatively for every condition, but this is not the case. This question was used in [7], but no individual question responses were shown and it was not seen as a control question, as the hand used in the experiment was connected to the body. In [19] unconnectedness of the hand is addressed, but this question was not used. O6, 'it felt as if the real hand were becoming digital', showed a significant difference between the *hand* conditions, where the *v-hand* condition had a higher mean. This seems intuitive, since one can see that the real hand is not digital in the *vr-hand* condition. This question was similar to the 'hand appears rubbery' question in [6, 2], and the results were similar to the results of the *v-hand* condition.

Agency

Our results show that the *hand* variable did not have a significant effect and *VM* and *VT* did, as expected. This shows that one of the two main differences between AR and VR has no effect on agency. The other

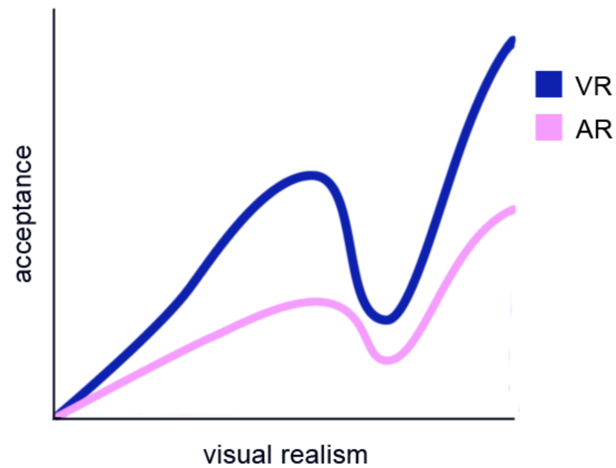

Figure 4.7: The suspected shape of the acceptance-realism curve for VR and AR, where the acceptance of the reality of an object is a precondition for ownership, as a consequence of visual realism.

difference is the dissimilarity between virtual and real objects, caused by the mixed reality. In [17] it is shown that agency is not affected by human-likeness of the controlled object, as agency is induced over non-corporeal objects. This implies that the mixed reality also has no effect on agency. We therefore argue that agency in AR is similar to agency in VR and the real world. This claim is supported by the results of the experiment presented in this paper. Participants did not experience agency over the third hand when it was moved passively, in contrasts to the *a-synch-VM* condition. This is shown by the comparison of the results of A1 and A4, and by the results of A2 where there is not only a significant difference between *a-synch-VM* and *a-asynch-VM*, but also between *a-synch-VM* and *p-synch-VM*, where passive movement results in a mainly negative response range. This effect was also shown in [30, 7]. The results of A3, where the response range for *p-asynch-VM* is partially positive, contradict this, but can be explained by the asynchronous movement sometimes being experienced as synchronous, due to the random movements of the virtual hand that were sometimes temporarily congruent with the movement of the real hand. An interaction was found between *VM* and *VT* for A3. This suggests that *VM* has a larger influence on the copy sensation than *VT*, as the difference in agency level for the *VT* conditions was only visible without the influence of *VM*. This seems intuitive as agency is generally not associated with *VT*. It should however be taken into account that the response range of *no-VM* and all three *VT* conditions was large.

Our results show that the visual presence of the real hand does not affect the level of agency experienced over the virtual hand by the participant, and a user in an AR application will be able to experience motor control over an additional virtual hand. However, if ownership over the virtual hand cannot be induced, the participant could experience a lower level of agency than possible, as it was shown that ownership positively affects agency [7]. We can argue that someone who experiences a higher level of motor-control, also has a higher level of physical task-performance. As a consequence a virtual hand might not be used as effectively as the real hands. Since our results only show that a virtual hand can be controlled, but not how effective it can be in its use, additional research is needed to see if a user will be able to perform tasks in AR as well with the addition of the virtual hand in comparison to only the use of the real hands. There is also the possibility that the addition of the virtual hand increases the task performance of the user, as was the case in [34].

Location

We expected that the visual presence of the real hand would negatively affect the shift in sense of location. The results show that the visual presence of the real not only negatively affects the shift, but entirely prevents a shift in sense of location of the left hand. Interestingly it does not prevent an additional location from being experienced. The prevention in change of location can be seen from L2, L3, L4, L5 and L6 where there is a significant difference between the two *hand* conditions, where the *vr-hand* condition shows completely negative response ranges, minus a few outliers. This shows that participants experienced no change in location or a sense of drift and that the participants were very confident about were their hand was. According to L7 and L8 almost all participants also felt the sensations at the location of the real hand in the *vr-hand* condition. Some participants experienced that their left hand was in two locations at once. This only occurred for synchronous *VM*. Of the participants that experienced this, 69% also reported a feeling of having two left hands. It has been reported earlier in [13] that the sense of limb location, in this case of the legs, can be affected by *VM*. The location of the legs was measured with a questionnaire question, asking if the real legs were located where the virtual legs were seen. The question received significantly higher results for the synchronous *VM* condition, which suggests that synchronous movement shifts the sense of location towards the seen movement, or in our case creates a sense of two locations. This is very interesting as it suggest that one's perception of limb-location can be split and it raises the question if this is possible for complete bodies as well. If this is the case, in a non-VR game setting a user could localize themselves not only in the position of their own body, but also in the position of the controlled avatar, which could improve the gaming experience of the user. This for the reason that spatial presence is shown to enhance the enjoyment of players [32] and we can argue that, since self-location towards and avatar in a virtual environment, places the self in the virtual environment, self-location could positively affect the sense of presence.

Some results of the control questions need to be addressed. The questions L4,L5 and L6 all had mainly negative response ranges as expected, but showed a significant difference between the *hand* conditions. L4 and L5 were also seen in [26, 2] and gave similar results, which had no significant differences between synchronous and asynchronous multimodal feedback as is the case here. L6 was used in [15], but no results were given for this question. Unfortunately the significant difference for the *hand* conditions cannot be compared with earlier research as no research has been done with a visually present real arm. A possibility for this result could be that participants were less certain of the location of their hand compared to the *vr-hand* condition, where the real hand is visible, and answered accordingly.

5 Conclusion and Future work

In this study, we investigated the effect of visual-tactile feedback and visual-motor feedback on the SoE over a virtual third hand in AR, while the real hands were visually present, and a number of key results were identified. Firstly, we have shown that in the current setup, despite the significant effect of both visual-tactile and visual-motor feedback, the ownership illusion could not be induced for neither the condition with the real left hand visually present nor the condition with only the virtual left hand. This overall negative ownership result contradicts earlier research, which indicates issues with the experiment setup, that could highlight the importance of realism in AR. Secondly, we have shown that the sense of agency is not affected by the visual presence of the real hands and we found similar effects of the visual-motor feedback as in previous RHI research. Finally, our results suggest that the visual presence of the real hand prevents a shift in the sense of location of the hand, but that it is possible to simultaneously experience the left hand in two positions.

The main issue identified in this experiment was the appearance of the virtual hand. The participants mentioned that the virtual hand did not look like their own, mentioning even small details, such as the finger nails. Possibly the contrast between the virtual third hand and the real hands amplified this feeling, which can be explained as the uncanny valley effect. We therefore propose to either exactly copy the hands of the participants, to make the difference as small as possible, or to not make it similar at all by using a robot hand.

Our experiment made the first step in investigating the effect of the visual presence of the real hands on the SoE in AR. Although the ownership illusion was not induced, the significant differences found for all factors point out that firstly, it is worth investigating in future research what the underlying effect of those factors on the SoE is. Secondly, the uncanny valley seems to affect the level of ownership more strongly in AR than in VR and to fully understand the difference it is crucial to determine the shape of the curve that represents the uncanny valley, for both AR and VR. Thirdly, as the sense of agency was not impeded by the presence of the real hands, a next step could be to research if a virtual hand can be used in combination with real hands to complete tasks in AR, where it would be interesting to see if a user can use them simultaneously, and do tasks equally efficient with both hands. Finally it is curious that it is possible to experience that your hand is in two locations at the same time and it would be interesting to see if this is also possible for complete bodies, which could in turn lead to improved user experience for games when a user senses to be in both the location of the real body and the location of the avatar. A setup to investigate such bi-location could use different perspectives, where one body could have a first-person perspective and the other a third-person perspective, or two bodies with a third-person perspective or even two bodies with both a first-person perspective.

Nr.	Question
O1	It felt as if the virtual hand were my hand.
O2 (C)	It felt as if the virtual hand was part of my body.
O3	It felt as if I had two left hands.
O4	It felt like the virtual hand was a duplication of the real hand.
O5	It felt like the virtual hand was somebody else's hand.
O6 (C)	It felt as if the real hand were becoming digital.
O7 (C)	The virtual hand began to visually resemble the real hand.
O8	It felt as though the virtual hand was the reason I could perceive certain sensations.
A1	It felt like I was in control of the virtual hand.
A2	It felt like I could move the virtual hand if I wanted to, as if it was obeying my will.
A3	It felt as if the virtual hand copied what the real hand was doing.
A4	It felt as if the virtual hand had a will of its own.
A5 (C)	It felt as if the virtual hand was controlling my will.
L1	It felt as if my left hand was at two different locations.
L2	It felt as if the real hand was at the location of the virtual hand.
L3	It felt as if the virtual hand was at the location of the real hand.
L4 (C)	It felt as if the real hand was drifting towards the virtual hand.
L5 (C)	It felt as if the virtual hand was drifting towards the real hand.
L6 (C)	It felt like I could not really tell where my left hand was.
L7	It felt as if the sensations occurred in the location of the virtual hand.
L8	It felt as if the sensations occurred somewhere between the real hand and the virtual hand.
open	Do you have any remarks regarding the experience that were not covered by the questionnaire?

Table 4.3: Questionnaire used during the experiment, with categories Location (L), Ownership (O) and Agency (A) where a C indicates a control question. The questions were answered with a 7-point Likert scale with values ranging from "strongly disagree" to "strongly agree".

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