Revisiting the Rubber Hand Illusion: Do virtual hands 'feel' touch eyes see, using minimal parameters?

Abstract

The mechanisms behind the cognitive processes relating to our sense of body ownership and self-attribution are still not fully understood. This study reproduces and builds upon the Rubber Hand Illusion (RHI), where subjects report the curious sensation of feeling an artificial hand as being their own. Two experiments are conducted. The first investigates if the results of the original RHI can be successfully reproduced using the same experimental design. The second investigates the constraints of the phenomenon, using a virtual hand with a resolution of 55%, whilst applying an optical delay of 300ms. The results of the first experiment support the findings of the original RHI. Subjects in the experimental group exhibited a noticeable drift of 40mm toward the rubber hand, when asked to point to their own left hand; $p = .007$. Participant statements regarding ownership of the rubber hand also proved significant; $p < 0.05$. A delay of 300ms in haptic feedback was shown to be sufficient to break the illusion in the second experiment, where there was also a noticeable drift of -10mm away from the virtual hand for the control group, and a 29mm drift toward the virtual hand for the experimental group; $p < .001$. In addition, a resolution of 55% was sufficient to create the illusion using an anatomically correct virtual hand. In the second experiment both the experimental (8 out 15 subjects), and the control group (9 out 15 subjects) felt the virtual hand was their own. Suggesting avatar bodily representations that are anatomically correct/similar elicit a sense of ownership.

Keywords: body ownership, rubber hand, illusion, virtual reality, haptic, cognition.

Terms of Reference

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1. Introduction

Our ability to adopt foreign body parts, as being part of our own body whether physical or virtual is a curious phenomenon, like many aspects of self-consciousness. We instinctively understand our hands as belonging to our own body, but the mechanisms behind the cognitive processes relating to this sense of body ownership and self-attribution are still not fully understood. This study reproduces and builds upon the 'Rubber Hand Illusion' (Botvinick & Cohen, 1998), where subjects report the curious sensation of feeling an artificial rubber hand as being their own, when watching the rubber hand being stroked with a paintbrush at the same time as their own hidden hand.

The results reported in the original Rubber Hand Illusion (RHI) indicate that intermodal matching (visual and haptic stimulation) is sufficient for the self-attribution of body parts. Additionally, introducing a slight delay between the stroking of the subject's own hand and the rubber hand is sufficient to break the illusion. In better quantifying the subjective experience of body ownership the RHI has created a paradigm for many studies of body ownership (Kilteni, et al., 2015). The same design as the original RHI is used to investigate whether the results can be successfully reproduced. The hypothesis being the illusion can be reproduced using the same experimental design. In the original RHI the control group reported low prevalence of the illusion (mean 7% of the exposure period compared to 42% for the experimental group; $P < 0.01$). Further the control group failed to display a reach displacement toward the rubber hand (mean displacement 13 mm away from the rubber hand, compared with 23 mm towards it in the experimental group; $P < .04$).

Many studies (1280 as at 04 February 2017) have built upon the findings from the original RHI making it important to corroborate the findings (Casadevall & Fang, 2010). In addition, constraints of the phenomenon are investigated using an anatomically correct virtual hand. The hypothesis being that the illusion will also occur using a virtual hand when specific minimal parameters are applied. Without further investigating human responses to multisensory stimulation during VR experiences, we may never fully understand the constituent parts required to develop effective VR applications, related to areas such as training, collaboration and remote working.

Previous studies such as (Ide, 2013) and (Kalckert & Ehrsson, 2012) indicate that anatomical plausibility of a false limb is important in creating the illusion. Therefore, the parameter for the resolution of the virtual hand is used as one constraint. In addition, (Shimada, et al., 2009) suggests that delays of less than 300ms are critical for multi-sensory integration processes. However, others (Zoulias, et al., 2016) suggest further exploration in delays of 300ms or less, as no significant difference in the perception could be found. So, the temporal delay was chosen as a second constraint.

2. Method

2.1. Participants

In experiment one, 32 healthy subjects, and in experiment two, a different group of 30 healthy subjects took part. The age of the subjects ranged from 18 to 54 years. All subjects participating were attendees at Edinburgh Napier University and were told the procedure, but were naïve to the hypotheses for the experiments. No incentives were offered in return for taking part in either experiment. Different subjects were tested in each experiment. All subjects volunteered and provided informed consent prior to participation. The study was approved by the Edinburgh Napier University Ethics Committee.

2.2. Procedure

During both experiments subjects sat upright, in front of a table, with a tape measure affixed to the nearside edge. The drift measures were recorded using the affixed tape measure before a condition was applied. During the condition subjects observed a 'false' hand located in front of them for a period of five minutes, while their own 'real' left hand which was situated pronated (palm face down) on the table and hidden from view. During this period, the subject's real hand was stoked with a paintbrush, at the same time as they observed the false hand being stroked with an identical paintbrush - either synchronously or asynchronously depending on the chosen condition. After five minutes had elapsed the drift measures were recorded once more, before subjects answered open questions about their experience. Lastly subjects completed a questionnaire. Two experiments were conducted as follows.

2.3. Design

A between-groups experimental design was used for both experiments. The independent variable of stroking, asynchronously (out of time) and synchronously (in time) was used to compare the control and experimental groups respectively. The dependant variables were the same for both experiments, and are discussed in detail under section '2.5. Measures'.

2.3.1. Experiment 1

To explore whether the results from the original RHI could be reproduced, the subject had their own left hand obscured by a screen and a rubber hand placed in front of them on the table. The rubber hand was observed being stroked at the same time as the subject's real hand using two paintbrushes, under these conditions:

1. Condition 1: The stroking was applied at the same time and in the same location on the rubber hand and on the subject's real left hand, creating synchronous stroking.
2. Condition 2: A slight, but noticeable delay was introduced. Creating asynchronous stroking, so that the stroking was applied in the same location, but slightly later to the rubber hand, to that of the subject's real left hand.

Condition two was used as the control, as in the original RHI experiment, where a delay was introduced between the stroking of the hands to break the illusion.

2.3.2. Experiment 2

To explore whether the RHI exists using a virtual hand, subjects used a head mounted display to view a virtual environment, where a virtual hand was observed. The subject was unable to view their real left hand while wearing the headset. The digital hand was observed being stroked in the same locations as the subject's real hand using the same paintbrush as in experiment one, under the following conditions:

1. Condition 1: The stroking was applied at the same time and in the same location on the virtual hand and on the subject's real left hand, creating synchronous stroking.
2. Condition 2: A delay of 300ms was introduced to the feed of the headset creating asynchronous stroking, so that the stroking was applied in the same location, but at a slightly delayed time to the virtual hand, to that of the subject's real left hand.

Condition two was the control. Previous studies, (Zoulias, et al., 2016) indicate a delay of 200-300ms creates attenuation of the illusion. Finally, a pilot study was conducted with five subjects to decide the minimal parameter for rendering the virtual hand. None of the subjects in the pilot took part in any experiments.

The results from the pilot study (see Fig 1.) indicate that setting the resolution to 45% rendered the virtual hand too poorly, the same was true at 50%. However, at 55% the virtual hand although heavily pixelated, was easily identifiable as a hand, so 55% was selected as the minimal parameter for the resolution of the virtual hand. Conversely setting the resolution to 60% meant the virtual hand had enough detail for subjects to identify it as their own hand, and so was deemed above the minimal parameter required.

2.4. Apparatus

2.4.1. Experiment 1

A similar setup (see Fig 2a.) was used to the original rubber hand experiment. The subject was seated in front of a table, with a tape measure affixed to the nearside edge.

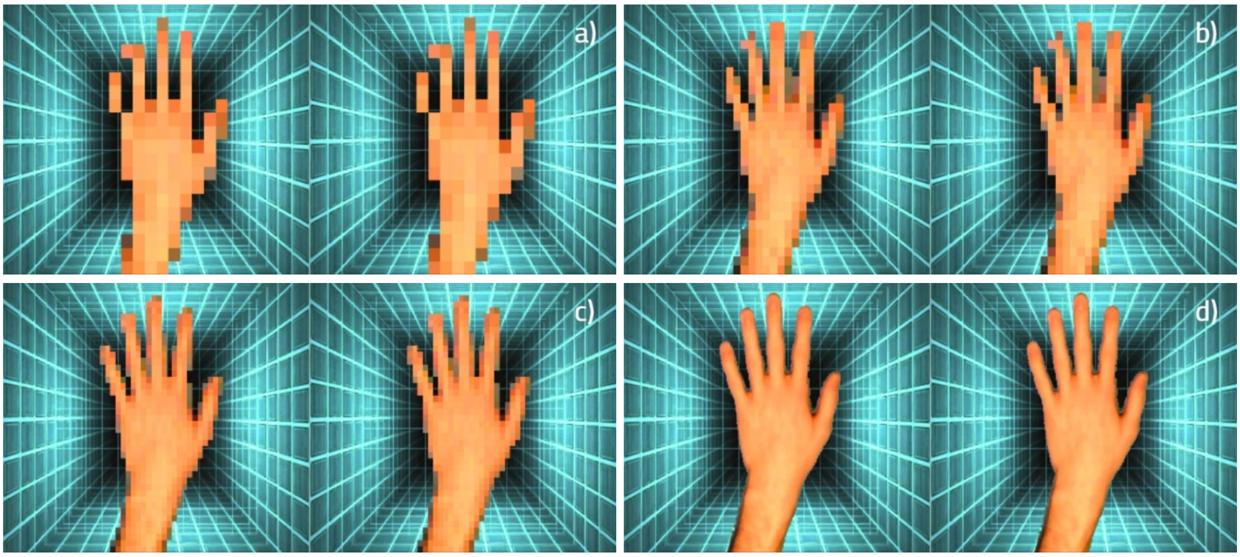

Figure 1: Resolution settings for the virtual hand at a) 45%, b) 50%, c) 55%, and D) 100%

The tape measured 150cm in length. The tape was affixed from the right-hand side of the desk, toward the centre. The subject's seat was positioned central to the tape measure. The subject's left hand was positioned pronate and relaxed on the table. A display (a desktop screen) was placed on top of the table perpendicular to the subject, to obscure the subject's left arm from view. A rubber hand (commonly found in joke shops) was placed on the table, in front of the subject. The rubber hand was located between 20-25cm from the subject's real left hand. The distance varied as a level of adjustment was required for each subject being of different size, to ensure they were seated comfortably. Two identical paintbrushes were used for the stroking.

Figure 2a: Setup for experiment one.

2.4.2. Experiment 2

The setup (see Fig 2b.) for the second experiment was more technical. The subject was seated in front of a table, at waist height, with a tape measure affixed to the nearside edge. Again, the tape measured 150cm. The end of the tape measure was affixed from the right-hand side of the desk's edge, toward the centre.

Figure 2b: Setup for experiment two.

Both conditions used in experiment two were controlled using Max 7 software patches. Vizzie GRABBR was used to stream live footage of a blue background created using a piece of blue A2 card placed on the table in front of the subject's chair, which was positioned centrally at 120cm. The subject's left hand was positioned atop the card using a small marker at 95cm.

Live footage was supplied by a 3-megapixel webcam connected to the laptop. The webcam was affixed to a tall lamp, used to provide even light distribution for the blue background. A 3D scene was chroma keyed (Cycling '74, 2014) into the blue background, creating a virtual background (see Fig 3a.) for the VR environment. The footage of the subject's hand was heavily pixelated using Vizzie PIXL8R and set to 0.55 (55%) of full resolution. This method provides several advantages in ensuring the virtual hand is anatomically correct and provides control for the experiment.

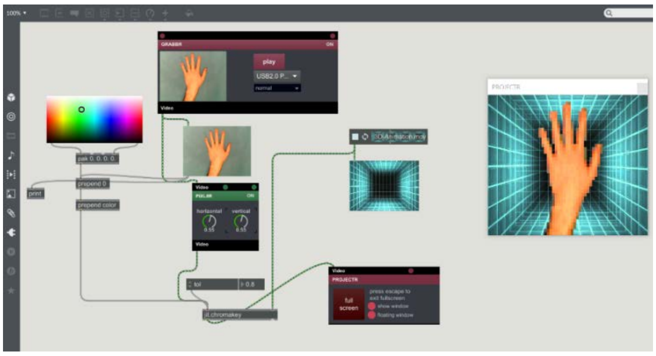

Figure 3a: Synchronous condition Max patch

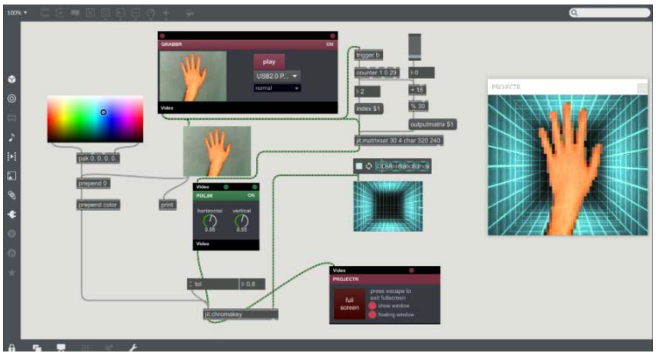

Figure 3b: Asynchronous condition Max patch

Max 7 provided a live stream of the merged chroma keyed background and augmented virtual hand. A stereoscopic image of the live footage was created and streamed from the laptop, using VR Steamer (Swatter Co, 2016) to a mobile phone. An Android 6.0 mobile phone with a resolution of 720 x 1280 pixels (~294 ppi pixel density) was used to display the stereoscopic images used for the virtual environment, and connected via a USB cable. The mobile device was placed in a generic VR headset with a stereoscopic display similar to Google Cardboard (Google, 2016). However, being made of plastic the headset provided adjustment for head size, was more robust than cardboard, and easy to clean.

For the synchronous condition subjects viewed a live feed of the brush stroking the pixelated virtual hand with no delay in real time. However, for the asynchronous condition a delay of 30% (300ms) was set (see Fig 3b.) using the Jitter Matrixset object (dearjohnreed, 2013). The VR headset subjects wore had the head tracking function disabled to ensure subjects remained focused on the virtual hand. The image of the virtual hand was positioned 5cm left of centre in the virtual environment. Subjects were asked to look down at the table (as they would do if looking at their own hand), and were unable to see their own hand while wearing the headset.

2.5. Measures

2.5.1. Drift measure

Subjects were asked to position their right index finger below the edge of the table, and with eyes closed - slide their right index finger along the underside of the table, in one smooth and continuous movement until they felt their right index finger was aligned with the index finger of their left hand. The resting location of their right index finger was recorded using the tape measure. This drift measure, often referred to as the 'proprioceptive drift' (Ehrsson, et al., 2005) was recorded three times before and after each condition.

2.5.2. Experiential insight

Once each experiment had been completed, subjects provided first-hand subjective data about their thoughts and feelings by answering open questions (see Fig 4.) to quantify the subjective aspects of the experience.

1. Please describe the experience you just had.
2. How did the experience make you feel?
3. What were your thoughts during the experience?
4. What else can you tell us about your experience?

Figure 4. Open experiential questions

2.5.3. RHI Questionnaire

Finally, the (Botvinick & Cohen, 1998) questionnaire (see Fig 5.) was used for both experiments, with references to the virtual hand used for experiment two. For the questionnaire subjects rated their experience on a 7-point sliding scale ranging from -3 (totally disagree) to +3 (totally agree), with 0 indicating 'neutral'.

1. I felt the touch of the paintbrush in the same location as I saw the rubber/virtual hand touched.
2. It seemed as though the touch I felt was caused by the paintbrush touching the rubber/virtual hand.
3. I felt as if the rubber/virtual hand were my hand.
4. It felt as if my (real) hand were drifting towards the right (towards the rubber/virtual hand).
5. It seemed as if I might have more than one left hand or arm.
6. It seemed as if the touch I felt came from somewhere between my own hand and the rubber/virtual hand.
7. It felt as if my (real) hand were turning rubbery/digital.
8. It appeared (visually) as if the rubber/virtual hand were drifting towards the left (towards my hand).
9. The rubber hand began to resemble my real hand, in terms of shape, skin tone, and other features.

Figure 5. Questionnaire statements

3. Results

3.1. Experiment 1: RHI

The results support the findings from the original RHI and resemble the results of the original study. Subjects were found to experience the rubber hand as being their own with a noticeable drift toward the rubber hand and presented similar responses to the questionnaire.

3.1.1. Drift measure

The drift measures for experiment one were analysed for normality using the Shapiro–Wilk test and were not significant; $p > 0.05$. Levene's test assumed equal variances, with $F = 0.59$, $p = 0.44$. The control group had a mean drift of 1mm, compared to the 40mm drift towards the rubber hand shown by the synchronous group; with $t(30) = -2.58$, $p = .007$, $d = 0.94$ for the independent one-tailed t-test with the null hypothesis being there would be no significant difference in the drift toward the rubber hand for the control and experimental group.

3.1.2. RHI Questionnaire

Three subjects from each group did not return questionnaire responses. Ordinal questionnaire responses from 26 subjects (13 in each group) were analysed using the Mann-Whitney U test (see Fig 6.) to compare differences between the independent asynchronous and synchronous groups with the null hypothesis being that there would be no significant difference in the responses between the asynchronous and synchronous groups.

The questionnaire results closely reflect the original RHI findings (see Fig 7.), with statements one, two, three and seven proving significant for the synchronous group; one tailed $p < 0.05$. Looking at the most significant results 7 out of 13 subjects from the synchronous group agreed to some extent with statement three 'I felt as if the rubber hand were my hand' compared to 0 from the asynchronous control group. 9 out of 13 subjects from the synchronous group, compared to 3 from the control group also agreed with statement two 'It seemed as though the touch I felt was caused by the paintbrush touching the rubber hand'. Unlike the original RHI 5 out of 13 subjects from the synchronous group agreed with statement seven 'It felt as if my (real) hand were turning rubbery' compared to 1 from the control group. Finally, 54% of the synchronous group agreed with statement nine 'The rubber hand began to resemble my real hand, in terms of shape, skin tone, and other features'.

Mann-Whitney Test

Statements	1	2	3	4	5	6	7	8	9
Mann-Whitney U	50.000	37.000	31.500	75.500	79.500	73.500	50.500	78.500	68.500
Exact Sig. (1-tailed)	.036	.006	.002	.324	.404	.291	.036	.379	.211

Figure 6. Experiment 1 Mann-Whitney U test questionnaire results.

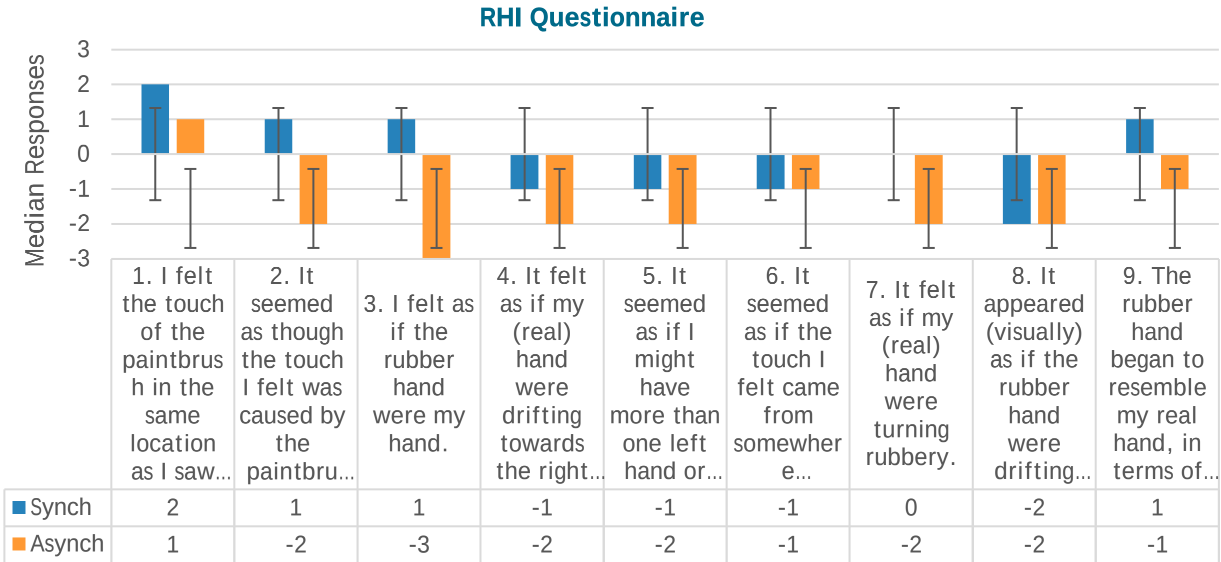

Figure 7. Experiment 1 median questionnaire responses.

3.1.3. Experiential insight

The descriptions submitted were coded and then analysed using cluster analysis and comparison diagrams (see Fig 8.) to explore themes and relationships in the data. Two main contrasting themes emerged. Subjects in the asynchronous group employed terms consistently relating to 'Feeling Uncomfortable' such as "It felt weird and slightly unpleasant" and "The experiment felt quite awkward". Conversely subjects in the synchronous group repeatedly used terms relating to 'Relaxing' the second theme such as "It felt comfortable, relaxing" and "It made me feel relaxed". In addition, many subjects spontaneously employed terms of ownership in their descriptions, such as: "Although I knew that the rubber hand wasn't really my hand, my body told me it was belonging to my body". Additional themes relating to 'Confusion' and 'Morphing' were found in the descriptions from the experimental group, such as "My hand started to feel rubbery I think I started to believe the fake hand was mine" and "It made me feel a bit confused. Just because I know it wasn't my hand but it still felt as though it was".

3.2. Experiment 2: VHI

The results support the hypothesis that the illusion can be created using a virtual hand when minimal parameters are applied. Subjects successfully experienced the virtual hand as being their own, with a noticeable drift towards the virtual hand and similar responses to the questionnaire as in the first experiment.

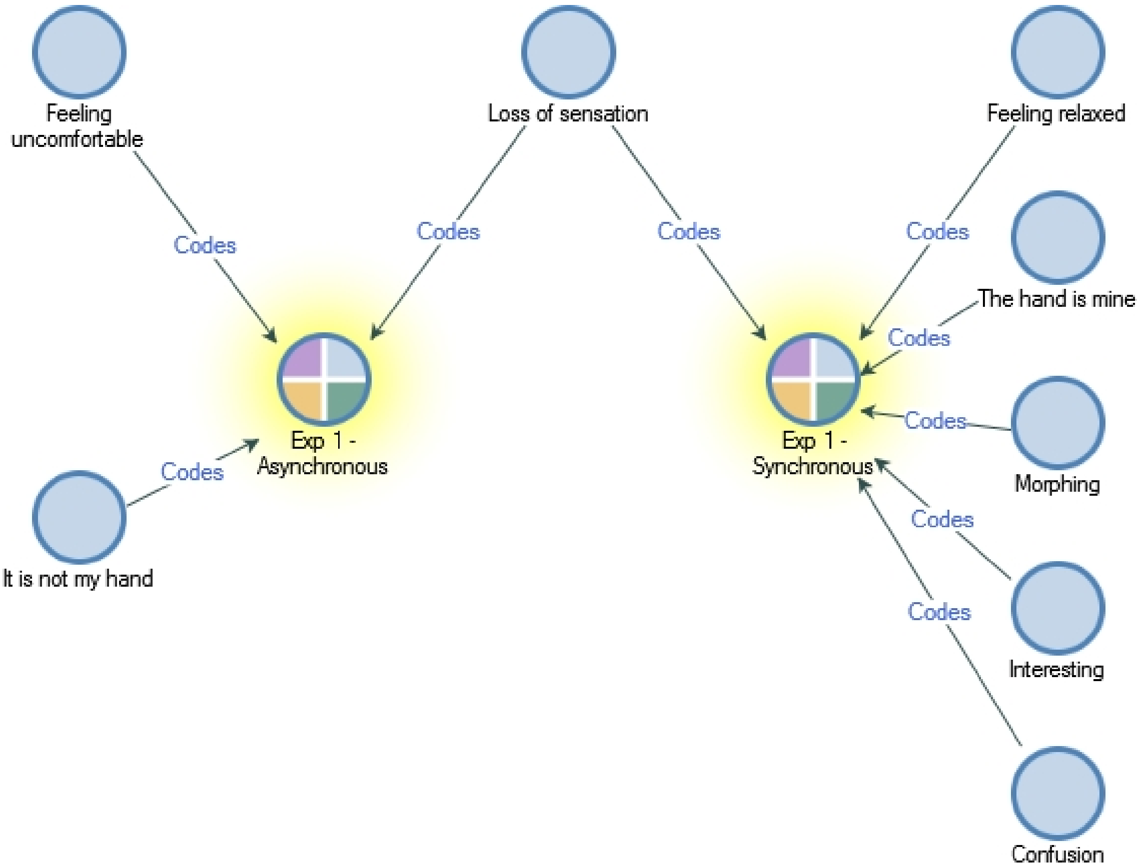

Figure 8. Experiment 1 comparison diagram of theme codes.

3.2.1. Drift measure

As before a Shapiro–Wilk test was not significant; $p > 0.05$. Levene's test assumed equal variances, with $F = 1.58$, $p = 0.21$. The control group had a mean drift of -10mm away from the virtual hand, compared to the 29mm drift towards the rubber hand shown by the synchronous group; with $t(28) = -5.61$, $p < .001$, $d = 2.12$ for the independent one-tailed t-test with the null hypothesis being there would be no significant difference in the drift toward the virtual hand for the control and experimental group.

3.2.2. RHI Questionnaire

Ordinal questionnaire responses from 30 subjects (15 in each group) were analysed using the Mann-Whitney U test (see Fig 9.) to compare differences between the independent asynchronous and synchronous groups with the null hypothesis being that there would be no significant difference in the responses between the asynchronous and synchronous groups. The questionnaire results indicate statements one, four, and six had significance for the synchronous group; one tailed $p < 0.05$. 13 out of 15 subjects from the experimental group agreed to some extent with statement one 'I felt the touch of the paintbrush in the same location as I saw the rubber hand touched' compared to 5 from the asynchronous control group.

Although statistically significant only 3 out of 15 subjects from the synchronous group, compared to 1 from the control group also agreed with statement four 'It felt as if my (real) hand were drifting towards the right (towards the virtual hand)'. Unlike the original RHI (see Fig 10.) 8 subjects from the synchronous group and 9 subjects from the control group agreed with statement three 'I felt as if the virtual hand were my hand'. Finally, 47% of the synchronous group agreed with statement six 'It seemed as if the touch I felt came from somewhere between my own hand and the rubber hand'.

Mann-Whitney Test

Statements	1	2	3	4	5	6	7	8	9
Mann-Whitney U	42.000	89.500	108.000	56.000	82.000	65.500	74.500	91.500	82.500
Exact Sig. (1-tailed)	.001	.170	.432	.007	.097	.023	.052	.169	.107

Figure 9. Experiment 2 Mann-Whitney U test questionnaire results.

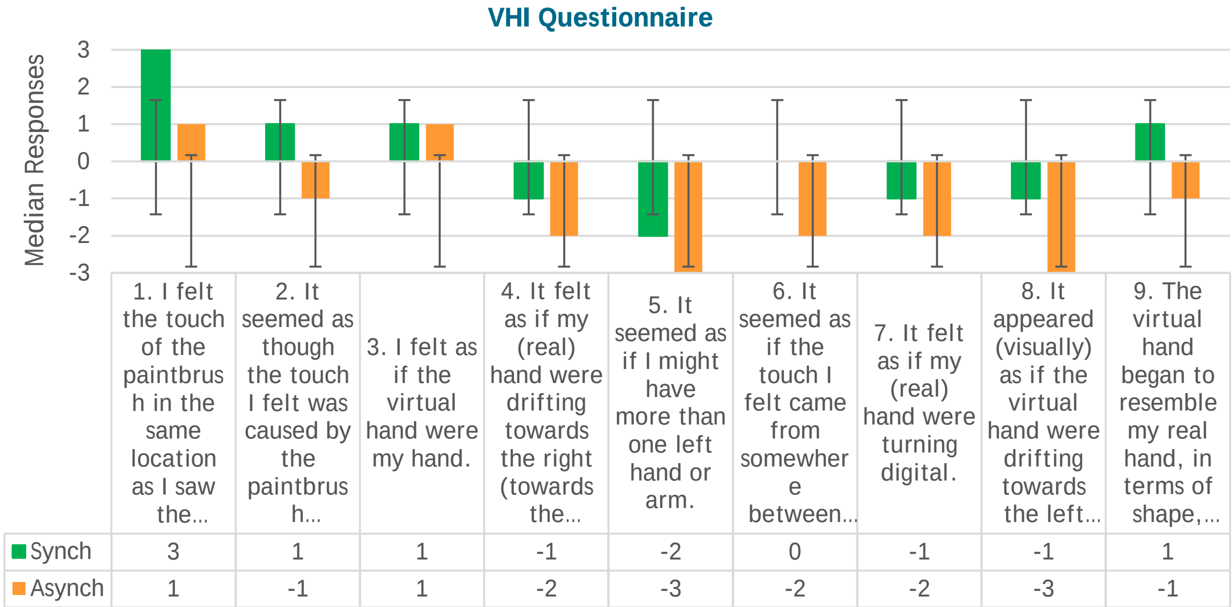

Figure 10. Experiment 2 Median questionnaire responses.

3.2.3. Experiential insight

Again, descriptions submitted by subjects were coded and analysed using cluster analysis and comparison diagrams (see Fig 11.) to explore themes and relationships in the data. Again, the two main contrasting themes related to feeling relaxed and uncomfortable. Subjects in the asynchronous group employed terms consistently relating to 'Feeling Uncomfortable' such as "Unsettled - when the delay is enough you get confused as to where the real hand is being touched" and "Slightly queasy". Again, subjects in the synchronous group repeatedly used terms relating to the theme 'Relaxing' such as "Initially I didn't notice much difference but became more relaxed and dazed" and "It was fun, feeling relaxed from the beginning". In addition, subjects spontaneously employed terms of ownership in their free-report descriptions, such as "The image of my hand was rather pixelated yet it still felt as if it was my own". Additional themes relating to 'Confusion' were found in the descriptions from the experimental group, such as "My hand started to feel rubbery I think I started to believe the fake hand was mine" and unlike experiment one the theme 'Morphing' was found in anecdotal descriptions from both groups, such as "The two versions of the hand began to merge". A loss of sensation to the subject's own hand was also mentioned by one subject in the control group.

4. Discussion

The results from the first experiment corroborate the findings of the original RHI, enabling a successful recreation of the illusion using the same experimental design and supporting the hypothesis that intermodal matching is sufficient for the self-attribution of body parts.

The results from the second experiment for the drift measure suggest a delay of 300ms is sufficient to create asynchrony and break the illusion.

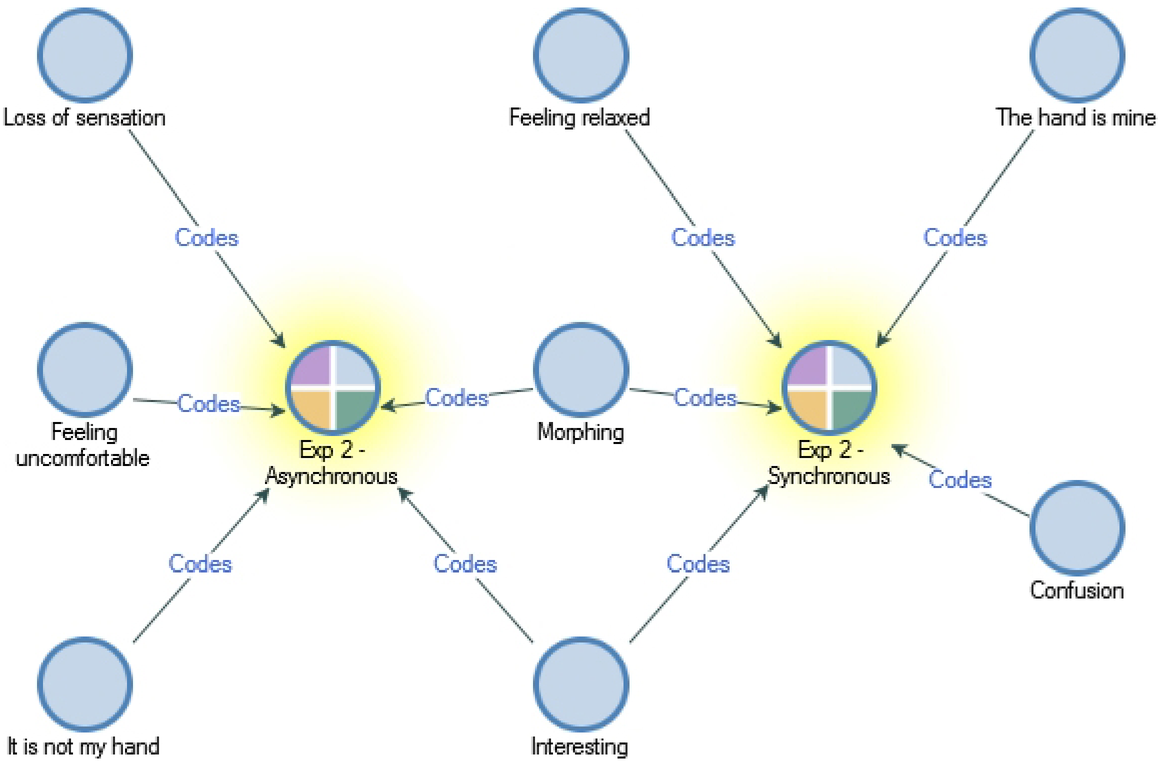

Figure 11. Experiment 2 comparison diagram of theme codes.

The drift measure was more extreme than in experiment one, as subjects actively rejected the virtual hand and drifted in the opposite direction to the virtual hand.

In addition, using a resolution as low as 55% is sufficient to create the illusion. The questionnaire results (see Fig 10.) revealed that 8 out 15 subjects in the experimental group felt the hand was their own. Additionally, a higher number - 9 out 15 (60%) subjects in the control group also felt that the virtual hand was their own (contrary to previous studies), despite the drift measures showing not significance. This suggests avatar bodily representations that are anatomically correct or similar can elicit a sense of ownership and self-attribution.

This added dimension of body ownership towards a virtual avatar limb could be utilised to improve the degree of immersion users experience in virtual reality, as users become more invested in the avatar there is potential to improve user's ability to learn and conduct tasks as their experience becomes more realistic. This aspect could be implemented by allowing users to select and customise their avatars sex, skin and hair colour or height, consequently creating a greater sense of ownership toward the virtual avatar.

A limitation in the second experiment may be the live footage of each subject's own hand, used to depict the virtual hand. The footage may have been recognisable to subjects as their own hand. However, the pilot study conducted prior to the experiment did not indicate subjects were able to recognise the virtual hand as their own. Nor did the experiential descriptions subjects provided. Research using generic virtual avatars tailored to subjects is recommended for future experiments.

5. Conclusions

Two experiments were conducted. The first investigating if the results from the original 'Rubber Hand Illusion' could be successfully reproduced using the same experimental design. The results corroborated the original findings with a mean drift result of 40mm toward the rubber hand for the experimental group; with $t(30) = -2.58$, $p = .007$, $d = 0.94$ (one-tailed t-test).

The questionnaire results also closely reflected the original findings, with statements one, two, three and seven proving significant for the experimental group; with $p < 0.05$ (one-tailed t-test).

The second experiment investigated the constraints of the phenomena. Exploring if the illusion occurred using an anatomically correct virtual hand. Resolution of the virtual hand was set to 55% for both groups. The asynchronous stroking delay was set to 300ms for the control group. Results appear to show the minimal parameters applied were sufficient in eliciting the illusion using a virtual hand. Using a delay of 300ms in the asynchronous stroking is sufficient to break the illusion, with a mean drift of -10mm away from the virtual hand for the control group compared to a 29mm drift toward the virtual hand for the experimental group; with $t(28) = -5.61$, $p < .001$, $d = 2.12$ (one-tailed t-test). Additionally, using a resolution as low as 55% is sufficient to create the illusion. The questionnaire revealed 8 out 15 subjects in the experimental group felt the hand was their own. Further, a higher number, 9 out 15 (60%) subjects in the control group also felt that the virtual hand was their own, suggesting avatar bodily representations that are anatomically correct/similar elicit a sense of ownership.

A limitation in the second experiment may be the live footage of each subject's own hand, used to depict the virtual hand was potentially recognisable by subjects as their own hand. Research using generic virtual avatars tailored to subjects is recommended for future experiments. A greater sense of ownership towards virtual avatars may improve the degree of immersion users experience in virtual reality, due to the potential impact for virtual applications, such as training, remote working, and collaboration, and should be investigated further. Future experiments could apply haptics to avatar limbs using virtual scenarios, and measure levels of immersion or the efficiency with which subjects learn compared to those experienced when no haptics or anatomical correctness are applied.

Acknowledgements

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