The effects of approaching stimuli and misalignment in a Virtual Hand Illusion

Master thesis neuropsychology

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Abstract

***Background**:* The Rubber Hand Illusion can be explained using the predictive coding framework. This theory states that the brain learns what probabilistically most likely belongs to 'me', through repeated exposure to events and constantly generating and updating predictions based on prior representations about the body. Context thus plays an important role in how the brain generates predictions and what gets processed more likely as 'me' and what not. Therefore, this study further explores the effects of approaching stimuli and misalignment on the strength of the RHI.

***Methods**:* Two experiments were conducted where participants saw a ball coming towards them in a virtual world. The ball either moved in a predictable manner (either touching or not touching the virtual hand 100% of the time), or moved in an unpredictable manner (only touching the virtual hand 50% of the time). In the second experiment misalignment was added, ranging from 0º to 80º misalignment and a threshold at which the illusion still occurs was determined. The strength of the RHI got measured using a questionnaire, proprioceptive drift and EMG.

***Results**:* In the first experiment the illusion occurred in all groups, however there were no statistically significant differences found between the groups on any of the outcome measures. In the second experiment there was an effect of misalignment. Sense of ownership was lower when the hand was at or below the determined threshold.

***Conclusion**:* The Oculus Rift works well with the RHI, due to its immersive nature. Mere exposure to the virtual hand alone seems to be enough to induce the illusion.

Keywords: Rubber Hand Illusion, predictive coding, virtual reality, body-ownership, self-recognition, free-energy principle

The effects of approaching stimuli and misalignment in a Virtual Hand Illusion

The experience of owning a body, also known as ‘body ownership’, is the most fundamental aspect of self-consciousness (Serino et al., 2013; Blanke, 2012). One of the most well-known methods to manipulate body ownership is the Rubber Hand Illusion (RHI). In this illusion a fake rubber hand is placed in front of the participant, after which the participant observes the rubber hand being touched while synchronous touches are being applied to the participant’s own unseen hand. This causes for the rubber hand to be attributed to the participant’s own body (Botvinick & Cohen, 1998). To measure the sense of ownership over the rubber hand, Botvinick and Cohen (1998) used a questionnaire measuring the participants subjective experience and proprioceptive drift. This is the shift of the participant’s perception of the location of their own hand towards the rubber hand (Botvinick & Cohen 1998; Tsakiris et al., 2006).

According to the free-energy principle and predictive coding, self-recognition arises through probabilistic learning (Apps & Taskiris, 2014). These theories state that, in order to make sense of the world, the brain needs to minimize the amount of free energy (surprise or prediction errors) that is caused by discrepancies of sensory input and the actual sensory events. The brain does this by either acting upon the environment, causing for more sensory feedback of the body to be generated, or by constantly generating and updating predictions to interpret the body and the environment in the most efficient way, using information from the past, present and future states of the body and the environment (Bubic, Cramon & Schubotz, 2010; Ferri et al,. 2013; Apps & Tsakiris, 2014; De Ridder, Vanneste & Freeman, 2012). The brain thus learns through repeated and consistent exposure to events and constantly generating and updating predictions made based on prior beliefs, what is probabilistic most likely the cause of a sensory event.

The updating of these predictions happen in a hierarchical and probabilistic manner (Apps & Tsakiris, 2014; Friston, 2009). This is a dynamic system where lower level bottom-up prediction errors are explained away by higher level top-down probabilistic representations about sensory events. Hereby creating a generative model with predictions about the body and the environment (Clark, 2013). More than one model gets processed at a time, with models with less evidence not being selected (Clark, 2013). This competition between alternative models show that these probabilistic representations are thus very plastic and change whenever there is surprisal that needs to be explained away. Illusions that manipulate body ownership, like the RHI, illustrate this plasticity by showing how multisensory stimulation can update the brain's representations of what belongs to the self and what not (Botvinick & Cohen, 1998; Blanke, 2012; Apps & Tsakiris, 2014).

The predictive coding framework can thus be used to explain the RHI. According to these theories, the brain learns through repeated exposure to approaching objects that cause a sense of touch on the hand, that the self is probabilistically the most likely object upon which touch can be experienced. Thus observing the rubber hand being touched, while the participant feels the touch on his own hand, causes for a lot of surprise or prediction errors. This because the participant cannot see his own hand, and therefore would not predict that touch (Apps & Tsakiris, 2014). The brain will then try to minimize the amount of surprise through updating the representations of one's own body. The probability that one's own hand belongs to 'me' thus decreases and the probability that the fake rubber hand belongs to 'me' increases (Apps & Tsakiris, 2014).

The RHI can be induced by multiple combinations of multisensory information that contribute to self-recognition (Kalckert & Ehrsson, 2014). Synchronous visuo-tactile stimulation, as described above is one of those conditions. However, the illusion does not get induced when the stroking of the hand occurs a-synchronically or when the rubber hand is incongruent with the brain's body schema, for example when the hand is in an implausible position or when the hand is a non-hand like object (Tsakiris & Haggard, 2005; Farmer, Tajardura-Jimenéz & Tsakiris, 2012; Ferri et al., 2013). However there are studies who found that the RHI still got induced even when the rubber hand was in an incongruent position (White, Weinberg & Davies, 2015; Ide, 2013; Perez-Marcos, Sanchez-Vives & Slater, 2012; Constantini & Haggard, 2007). The sense of ownership over the fake rubber hand did slightly decrease when the spatial mismatch increased, but the RHI never got completely diminished (Constantini & Haggard, 2007). In the study of Ide (2013), they changed the position of the rubber hand ranging from 0° to 315°. Participants had a higher sense of ownership over the rubber hand when it was in positions that were easy to mimic with the real hand (Ide, 2013). These results indicate that the range in which the RHI occurs includes anatomical plausibility, thus the range in which people anatomically are capable of rotating their hand (Ide, 2013; White, Weinberg & Davies, 2015 Perez-Marcos, Sanchez-Vives & Slater, 2012).

The context thus plays an important role in how the brain generates predictions in regards to stimuli, leading in a variability to what is more likely processed as 'me' (Apps & Tsakiris, 2014). When the fake rubber hand is green, shaped like a wooden stick or placed in a position that is not congruent with that participant's real hand, the probability that these objects would be processed as 'me' is very low, simply because these objects are not congruent with the prior learned probabilistic representations the brain has of what a hand is and what is anatomically plausible. The top-down probabilistic representations about the self that get processed before a sensory event can thus modulate what is more likely to be processed as 'me'(Constantini & Haggard, 2007).

The expectation of touch appears to be a sufficient condition to induce the RHI as well. Since seeing an object coming towards the body leads to an expectation of touch, Ferri et al. (2013) hypothesized that seeing an object approach the rubber hand would be enough the induce the RHI. Participants observed the experimenter's hand approaching the rubber hand. The experimenter's hand never touched the rubber hand, but participant's still felt like the experimenter was about to touch their own hand. Actual tactile stimulation is thus not necessary to induce a sense of ownership over a non-body object (Ferri et al., 2013). However, this effect was not due to mere exposure to the fake rubber hand, since that was not enough to induce a sense of ownership (Ferri et al., 2013)

Using the predictive coding framework to interpret these results, seeing an object approach the rubber hand would lead to a high probability that a touch is about to occur on that hand, thereby increasing the probability that the rubber hand belongs to 'me' (Ferri et al., 2013). This supports the notion that the brain generates predictions on what belongs to the body and what not, and does not merely react to external stimuli (Ferri et al., 2013; Clark, 2013).

Recent research has shown that the RHI can be induced through virtual reality (Ma & Hommel, 2013; Slater, Perez-Marcos, Ehrsson & Sanchez-Vives, 2008), so in the current study we are going to further explore the role of approaching stimuli and misalignment in the RHI using virtual reality. The current study will use the Oculus Rift VR headset. Two experiments will be conducted where participants will see a ball coming towards them in a virtual world. In both experiments the expectation of touch will be manipulated through changing the trajectory of the ball. The ball will either move in a predictable manner (always touching, never touching or always moving away from the virtual hand) or in an unpredictable manner (only touching the virtual hand half of the time). In the second experiment, the position of the participant's real hand will be changed as well. The positions range from a 0° to a 80° misalignment and a threshold at which the RHI is still induced will be determined. The current study thus manipulates high level top –down predictions of touch through exposure to different conditions and changing the position of the hand, and low-level bottom-up predictions through manipulating the trajectory of the ball.

The crucial role of the context within which stimuli are perceived could mean that more ambiguous or dangerous stimuli approaching the hand, could have an effect on the strength of the RHI. With an unpredictable stimulus, the expectations will be updated every time the prediction changes, and therefore there will be more surprise that needs to be explained away by top-down probabilistic representations. It also shown that the processing of more unpredictable stimuli cause for greater neural activity in the brain (Ahlheim, Stadler & Schubotz, 2014; Ranganath & Rainer, 2003). Unpredictable stimuli also get processed more consciously by the brain, since it is crucial to experience these stimuli in order to update our representations about them, which in turn is crucial for survival (De Ridder, Vanneste & Freeman, 2012; Ranganath & Rainer, 2003).

Distance seems to play a role in this as well. In the experiment of Ferri et al. (2013), the illusion could only be induced when the experimenter’s hand moved in the peripersonal space. This could be explained due to the fact that the brain processes stimuli in the persipersonal space differently than stimuli in the extrapersonal space. Bimodal neurons in the ventral premotor cortex react stronger to stimuli in the peripersonal space (Graziano, Hu & Gross, 1997). This can be explained through the importance of stimuli close to us, as we are able to interact with them and they may pose a possible threat. Thus when an object moves in the peripersonal space, the probability of a touch occurring on the hand would be higher than when an objects moves in the extrapersonal space, which leads to a higher probability that the hand belongs to ‘me’.

We therefore predict that high level prior predictions of the ball not touching the hand will cause for a smaller illusion when compared to the high level prior predictions of the ball touching the hand, even when the trajectory of the ball would indicate a touch will occur. Our second prediction is that high level top-down unpredictability about whether the ball will touch the hand or not, will cause for a greater illusion than high level top-down predictions about the ball touching the hand, since it is crucial for the brain to process unpredictable stimuli. Unpredictable stimuli might lead to a higher somatosensory preparation for touch, thereby increasing the probability that the fake rubber hand belongs to 'me'. Lastly, we predict that the illusion will be smaller when the hand is in an incongruent position

Experiment 1

Methods

Participants

Participants were recruited through the website Proefbunny and through posters and flyers. Eligibility criteria for this study were normal or corrected vision through prescribed lenses, and right-handedness. Participants with glasses got excluded from this study, due to the fact that glasses don't fit with the Oculus Rift VR headset. All participants gave informed consent and received either study credits or money as compensation.

Research design

In this experiment we investigated the role of approaching stimuli on the strength of the RHI. A between-subjects design was used, to control for carry-over effects from the different conditions. Participants were divided into four different groups. In each group the probability of touch got manipulated through changing the trajectory of the ball the participants saw coming towards them in the virtual world. In group 1 (approaching predictable touch), the ball always moved towards and touched the virtual hand. In group 2 (approaching predictable no touch), the ball always moved towards the virtual hand as well, but it never touched the hand. Instead the ball moved to the left of the hand. In group 3 (approaching unpredictable), the ball also always came towards the virtual hand but only touched the virtual hand 50% of the time. The other 50% of the time, the ball moved to the left of the hand and thus did not touch the hand. This happened in a random fashion, so it was highly unpredictable when the ball was going to touch the virtual hand. In group 4 (retracting predictable no touch), the ball appeared near the hand and moved away to the opposite end of the table. In this group the ball thus also never touched the virtual hand.

This experiment further consisted out of two different blocks. The first block was the priming block in which participants got exposed to the group they were assigned to and the second block was the RHI block where the actual illusion got induced.

Before the experiment started, participants were randomly assigned to one of the groups, using an online randomization program. Participants were not aware of the group they were assigned to and were naïve to the purpose of the experiment.

Priming block

In this block, participants got exposed to the group they were assigned to and thus learned that the ball was either always going to touch them in group 1, never going to touch them in group 2 and 4, and will touch them 50% of the time in group 3. When the ball touched the virtual hand (thus only in group 1 and 3), participants would feel a vibration on their right middle finger where a small motor was placed. When this happened, participants were instructed to press the spacebar as fast as possible. This block consisted of 15 trials and lasted about 5 minutes.

RHI block

This block was the actual RHI experiment. Participants again saw a ball coming towards them, however in contrast to the priming block, here the ball never actually touched the virtual hand. In group 1 where the ball always comes towards the virtual hand, the ball stopped in front of the hand, instead of actually touching the hand. In group 3 the ball stopped in front of the hand as well, but only 50% of the time, the other 50% the ball moved to the left of the hand just as in the priming block. In group 2 and 4, the ball moved the same as in the priming block.

This block consisted of 24 trials and lasted about 20 minutes. After each trial participants had to indicate where they felt the location of their middle finger was for both hands and after every six trials they had to fill in the questionnaire.

Procedure

Participants were welcomed in the lab of the University of Utrecht. Once the participant was seated, the experimenter would explain what was about to happen during the experiment and gave instructions of the two blocks. The same instructions were given to each participant, regardless of the group they were assigned to. For the first block, each participant was instructed to press the space bar as fast as possible when they felt a vibration through a motor that was placed on their middle finger. For the second block, each participant was instructed to indicate where they felt their middle finger of each hand was located by telling the experimenter in what direction to move the pointer at the bottom of the screen. Furthermore, instructions about the questionnaire were given. After the instructions the participants were seated behind a headrest and the electrodes and the motor were placed on their hands. The experimenter would place their hands 30 cm apart on the marked places on the table. After the experiment finished, the electrodes and the motor would be removed, after which participants received information about the purpose of the experiment and compensation for participation.

Virtual environment and stimuli

The virtual environment and stimuli were created using Unity software for game development. As shown in figure 1, participants saw a realistic looking right hand, which was placed on a wooden table, 10 cm to the left of the participants' real right hand. The xyz coordinates for the virtual hand are: 0.2, 0.108 and 0.2 units in the virtual world (1 unit = 1 meter). Three seconds after the start of the trial, participants would see a ball coming towards them, starting at the opposite end of the table at 8 units in groups 1, 2 and 3, and starting near the hand at 1,3 units in group 4. The ball always moved in an erratic manner and changed trajectory either five or eight times. The ball moved at an speed of 0.8 units per second.

Measures and materials

Proprioceptive Drift

The strength of the illusion was measured through Proprioceptive Drift, which is the shift of the participants' perception of the location of his own hand towards the virtual hand. Proprioceptive Drift was measured in the Oculus Rift headset itself, using a pointer at the bottom of the screen, as shown in figure 2. Each trial, the pointer appeared in a different, random location. The experimenter moved the pointer in the direction indicated by the participant, in discrete steps, until the pointer stood in the location where the participant felt the middle finger on both hands was located.

Questionnaire

Participants also had to fill in a modified version of the original 9 item questionnaire developed by Botvinick & Cohen (1998). In this experiment only 8 questions were used. The 8 questions were as followed:

1. It felt as if the ball was about to touch my real hand.

2. I felt as if the virtual hand was my real hand.
3. I felt as if my real hand was drifting towards the virtual hand.
4. I felt as if the virtual hand drifted towards my real hand.
5. The virtual hand began to resemble my real hand, in terms of shape, skin tone, freckles, or other visual features.
6. It seemed as if the ball was about to touch me somewhere between my real hand and the virtual hand.
7. There were moments in which I the sensation of having more than one right hand.
8. I felt as if my real hand was becoming virtual.

Questions 1 and 2 correspond to the illusion and questions 3 through 8 are control questions. Participants had to rate each statement on a 7-point Likert scale, ranging from 1 (strongly disagree) to 7 (strongly agree). Participants usually score higher on questions 1 and 2 when the illusion gets induced, and score lower on the control question regardless if the illusion gets induced or not (Ma & Hommel, 2013).

EMG

EMG was used to measure the strength of the illusion as well. A study of Slater et al. (2008), found a positive correlation of the strength of the illusion and EMG activity. Using EMG to measure the strength of the RHI thus allows for a more objective evaluation of the RHI (Slater et al., 2008).

During the illusion, the muscle activity of both hands was measured through placing two electrodes on the First Dorsal Interosseous (FDI Muscle) on each hand in a belly to tendon manner (Makin et al., 2009). EMG data was acquired using a Biosemi ActiveTwo amplifier.

Statistical analyses

In order to analyze the effect of unpredictability on the strength of the illusion we used multiple one-way ANOVA's and one mixed between-within subjects analysis of variance. Then with post hoc tests we further investigated the differences when needed. The independent variable was the trajectory of the ball, which differed for each group. The dependent variables were the outcome measures, namely the scores on the questionnaire, the proprioceptive drift scores and the EMG activity. We expected to see a smaller illusion in group 4 compared to group 2, since retracting stimuli would not lead to a bottom-up prediction of touch. Furthermore, we expected to see a smaller illusion in group 2 compared to group 1, since top-down expectations of a touch not occurring would lead to a lower probability that the virtual hand would belong to 'me'. Lastly, we expected to see a greater illusion in group 3 compared to group 1. Top-down unpredictability would lead to a greater illusion, since unpredictable stimuli are more important to process, which could lead to a higher probability that the virtual hand belongs to 'me'.

Results and discussion

In total 24 subjects participated in this experiment, among which were 15 females and 9 males. Participants were between 18 and 34 years of age (M = 21.88, SD = 4.49).

Questionnaire

In order to analyze the effect of group on the subjective experience we used one-way ANOVA's with the questions of the modified questionnaire as dependent variables, and the different groups as the independent variable. The results showed a statistically significant effect between the groups on the first question (It felt as if the ball was about to touch my real hand), F (3, 23) = 4.6, p = .014. A post-hoc Tukey test showed that the mean for group 2 (M

= 1.75, SD = .81) was significantly different from the mean for group 3 (M = 4.04, SD = 1.35). This means that participants in group 2 felt it was less likely that the ball was about to touch their hand than the participants in group 3.

There were no significant differences found between the groups on the second question (It felt as if the virtual hand was my real hand), F (3, 23) = .32, p = .81. As shown in table 1, the scores on question 2 were high in all the groups. These results thus indicate that the RHI got induced, irrespective of the group the participant was assigned to.

There were also no significant differences found between the groups on the control questions.

Proprioceptive Drift

As stated above, the hands were placed 30 cm apart and the virtual hand was placed at 2 units which corresponds to 20 cm in real life. Proprioceptive drift was then calculated by subtracting the position of the participant's own hand of the proprioceptive drift scores from both the right and the left hand. As shown in figure 3, there was a high proprioceptive drift in all groups, especially for the right hand. To analyze the difference between the right and the left hand, we used a paired sample T-test. There was a significant difference on proprioceptive drift between the right (M = 7.55, SD = 4.18) and the left hand (M = 1.69, SD = 5.06), $t(3) = 5.38$, $p = .01$.

To analyze the effect of group on proprioceptive drift we used multiple one-way ANOVA's with the proprioceptive drift scores from the right and the left hand as dependent variables, and the different groups as the independent variable. There were no significant effects found of group on the proprioceptive drift scores on the right hand, $F(4, 25) = 2.11$, $p = .11$. The results also didn't show an effect of group for the left hand, $F(4,25) = .53$, $p = .71$.

EMG

In order to analyze the EMG data a band pass filter of 30 – 500 Hz and a notch filter of 50 Hz was applied to the raw EMG data. After this the data for each participant was segmented in intervals of 500 to 4500 ms for the 4 second trials, and 500 to 5500 ms for the 5 second trials. Then a baseline correction was applied after which the data got rectified and segmented again in intervals of -2000 to +500 ms. This is two seconds before the ball stops and reaches the virtual hand and 0.5 seconds after that. Lastly, these segments got averaged for each condition and then binned in 250 ms intervals.

To further analyze the EMG data a mixed between-within subjects analysis of variance was conducted to assess the effect of the four different groups on the EMG signals of the participant's right hand across ten time periods. We also made a distinction between unpredictable contact and unpredictable no contact , to see if there would be a difference between these on the EMG signals. There was no significant interaction effect between time and condition, Wilks' Lambda = .18, F (36, 65.44) = 1.05, p = .42, partial eta squared = .35. There was also no significant main effect found of time, Wilks' Lambda = .62, F (9, 17) = 1.18, p = .37, partial eta squared = .38. The main effect comparing the groups was also not significant, F (4, 25) = .51, p = .73, partial eta squared = .08. This shows that there are no significant differences between the groups or the different time periods.

Discussion

There were no statistically significant differences found between the groups on proprioceptive drift and EMG. Nevertheless, there was a significant difference found on proprioceptive drift between the left and the right hand. Proprioceptive drift was significantly higher for the right hand, which indicates that the right and thus congruent hand was more affected by the illusion.

There was a significant difference found between the groups on the first question of the questionnaire. Participants in group 2 felt less like the ball was about to touch their own hand, than participants in group 3. Furthermore, scores on the second question were remarkably high in group 2 (approaching predictable no touch) and group 4 (retracting predictable no touch). We expected to see a smaller illusion in these groups, since there would be a lower predictability of a touch occurring and therefore a lower probability that the virtual hand belongs to 'me'. The illusion thus got induced, regardless of the group the participant got assigned to. These results could indicate that the visual input of the hand alone might be enough to induce the illusion. Therefore, we conducted a second experiment where we added misalignment. By adding misalignment we created a mismatch between the visual input (the virtual hand the participants sees) and the proprioceptive input (the proprioceptive information the participant has of the location of their hand), making the visual input of the hand alone smaller.

Experiment 2

Methods

Participants

For this experiment participants were recruited through the website Proefbunny and through posters and flyers as well. Eligibility and exclusion criteria for this experiment were the same as for the first experiment. All participants gave informed consent and received either study credits or money as compensation.

Research design and procedure

In this experiment we further investigated the role of approaching stimuli on the strength of the RHI and we added misalignment. In contrast with the first experiment, here we used a within-subjects design. We chose for this design, because it requires less participants and it controls for variance between the participants.

Before the start of the experiment, each participant's individual threshold at which the illusion still occurred would be determined. This was done by changing the position of the participant's own left hand. As shown in figure 4, the positions were marked on a sheet of paper. Positions ranged from 0º to 80º misalignment, in steps of 10º. The participants own left hand was placed in all the different positions in a random fashion. After each time the position of the hand was changed, the experimenter asked the participant if they could indicate on a scale of 1 to 7, how much the virtual hand that they saw felt like their own hand. Then looking at the scores on the asked question, a threshold would be determined.

After the threshold was determined the actual RHI experiment could start. We manipulated the trajectory of the ball, alignment of the hand and movement of the ball. There were four different trajectory conditions. In the first trajectory condition (approaching predictable touch), the ball always moved towards the hand and stopped in front of the hand. In the second trajectory condition (approaching predictable no touch), the ball always moved towards the hand as well, only it moved away and stopped to the right of the hand. In the third condition (approaching unpredictable), the ball moves towards the virtual hand too, but only stops in front of the hand 50% of the time, the other 50% of the time the ball will move away and stop to the right of the hand. In the fourth trajectory condition (retracting predictable no touch), the ball always moved away from the virtual hand to the opposite end of the table.

There were three different conditions for alignment. Before the start of the experiment, a threshold at which the illusion still occurred was determined. In the first alignment condition (above threshold), the participant's own left hand was placed 10º above this threshold. In the second alignment condition (at threshold), the hand was placed at the threshold, and in the third alignment condition (below threshold), the hand was placed 10º below the threshold.

Lastly, there were two different movement conditions. The first condition is the straight movement condition. Here the ball moves in a straight line, either towards or away from the virtual hand. The second condition is the erratic movement condition, where the ball moves in an erratic manner and changes direction either 4 or 5 times.

Before the start of each trial, the experimenter would change the position of the participants own left hand to either at the determined threshold, 10º above the threshold, or 10º below the threshold. This happened in a random manner and participants were naïve to the different positions and the threshold. The marked hand positions were covered with a cloth, so the participants would not be able to see the positions beforehand.

At the start of the trial, before the hand and the ball would appear, there appeared either one or two squares on the screen. These squares indicated the final location of the ball. This means that in the first trajectory condition there was one square at the location of the virtual hand. In the second trajectory condition, the square was at a location to the right of the virtual hand. In the third trajectory condition there were two squares. One square was at the location of the virtual hand, and the other was in a location to the right of the virtual hand. Either of those locations could thus be the final location of the ball. The changing of locations happened in a random manner, thus it was very unpredictable which location would be the final location of the ball, and if the ball would thus come towards the hand or move away from the hand. And lastly, in the fourth trajectory condition the square was at a location on the opposite end of the table.

After each trial participants would have to indicate in which direction they felt that their left middle finger was pointing, in the same fashion as in the first experiment. Further, they had to answer a short questionnaire. The experiment consisted of 24 trials and lasted for about 45 minutes in total. All participants gave written informed consent and were naïve to the goal of the experiment. After the experiment finished, participants received information about the goal of the experiment and compensation for participation.

Virtual environment and stimuli

The virtual environment and stimuli for this second experiment were also created using the Unity software. As shown in figure 5, in this experiment the participants saw a realistic looking left hand. The coordinates (xyz) of the hand were 0.2, 0.17, and 0.3 units. At the start of each trial, participants would see the left hand and one or two white squares which indicated the locations at which the ball stopped. After the squares disappeared, participants would see the ball coming towards them. The ball started at the opposite end of the table at 8 units in the trajectory conditions 1, 2 and 3 and at 1.3 units in the fourth trajectory condition. The ball either moved in an erratic manner and changed directions either 4 or 5 times or moved in a straight line. Lastly, the ball moved at a speed of 2 units per second.

Measures and materials

Rotational drift

As shown in figure 6, for this experiment we used a rotational version of the proprioceptive drift measurement as used in experiment 1. We decided to use a rotational version, because this way the positions of the pointer matched the different positions the participants real hand could be placed on, thus ranging from a 0° to a 80° angle. After each trial participants had to indicate in which direction they felt their left middle finger was pointing. The experimenter would then move the pointer in discreet steps, until the pointer was at the right location.

Questionnaire

In this experiment participants only had to answer questions 1, 2, 6, and 7 of the questionnaire used in the first experiment. They had to answer these questions after each trial.

Statistical analysis

To analyze the effect of unpredictability and misalignment on the strength of the illusion we used multiple repeated measures ANOVA's and paired sample T-tests. The independent variables are the different conditions, the movement of the ball and the threshold level. The dependent variables were the scores on the questionnaire and the proprioceptive drift scores. We expected to see a smaller illusion in condition 4, compared to conditions 1, 2 and 3. We also expected to see a bigger illusion when the hand was above threshold level compared to at threshold or below threshold level, and a bigger illusion when the ball moved in an erratic manner compared to straight movement.

Results and discussion

In total 15 subjects participated in this experiment, among which were 7 males and 8 females. Participants were between 18 and 35 years of age (M = 23062, SD = 5.08). Due to technical difficulties there was incomplete data for some subjects, therefore 8 participants were excluded from analysis.

Threshold

Participants still experienced the illusion when their real hand was in an incongruent position. The mean threshold at which participants still experienced the illusion was 37.33º (SD = 13.35º). The mean score on the question if the virtual hand they saw felt like their own was 2.67 (SD = 0.82).

Questionnaire

As shown in table 2, the mean scores on all trajectory, alignment and movement conditions were lower than the mean scores on the questionnaire in the first experiment. To see if there was a change in illusion from the retracting trajectory condition compared to the approaching trajectory conditions, we conducted paired sample T-tests. There were no significant differences between the retracting condition (M = 3.12, SD = 1.38) and the approaching predictable touch condition (M = 2.95, SD = 1.34), $p = .78$, approaching predictable no touch condition (M = 2.5, SD = 1.23), $p = .27$, and the approaching unpredictable condition (M = 2.83, SD = 1.46), $p = .66$. The illusion thus got induced in all trajectory conditions.

To analyze the effect of approaching stimuli and misalignment on the subjective experience, we conducted repeated measures ANOVA's. The within subject factors were trajectory (approaching predictable touch, approaching predictable no touch, approaching unpredictable and retracting predictable no touch), alignment (above, at and below threshold) and movement (straight and erratic movement). The dependent variable were the scores on question 1 and 2 of the questionnaire, since these questions respond to the illusion.

For the first question the main effect for trajectory was significant, $F(3, 18) = 5.34$, $p = .01$. The main effects of alignment ($F(2, 12) = .36$, $p = .71$) and movement ($F(1, 6) = .39$, $p = .55$) were not significant. The interaction effects of trajectory and alignment ($F(6, 36) = .75$, $p = .62$) and trajectory and movement ($F(3, 18) = 1.17$, $p = .35$) were not significant either.

For the second question there was a significant main effect of alignment, $F(2,12) = 9.38$, $p = .004$. The main effects for trajectory (F(3, 18) = 1.46, $p = .26$) and movement ($F(1, 6) = .15$, $p = .71$) were not significant. Likewise, the interaction effects of trajectory and alignment ($F(6, 36) = .95$, $p = .74$) and trajectory and movement ($F(3, 18) = 1.77$, $p = .19$) were not significant either.

To further explore the differences, planned contrasts were performed comparing all trajectory conditions to the fourth trajectory condition (retracting predictable no touch), all alignment conditions to the first alignment condition (above threshold) and all movement conditions to the straight movement condition. Contrasts for question 1 revealed that there was a significant difference between the approaching predictable touch condition (M = 2.98, SD = .31) and the retracting condition (M = 1.48, SD = .27), $F(1, 6) = 22.09$, $p = .003$, and between the approaching unpredictable condition (M = 3.52, SD = .66) and the retracting condition, $F(1, 6) = 7.28$, $p = .04$. Participants thus felt that the ball was more likely to touch their own hand in the approaching predictable touch and approaching unpredictable condition than in the retracting condition.

Contrasts for question 2 revealed that there was a significant difference between the at threshold (M = 2.54, SD = .38) and above threshold alignment (M = 3.41, SD = .43), $F(1, 6) = 11.61$, $p = .01$, and between the below threshold (M = 2.34, SD = .36) and above threshold alignment, $F(1, 6) = 12.11$, $p = .01$. Participants thus had a lower sense of ownership over the virtual hand when the hand was at and below the determined threshold.

Rotational Drift

As shown in figure 7, there was a considerable amount of rotational drift in all conditions. To assess the effect of approaching stimuli and misalignment on rotational drift we conducted repeated measures ANOVA's. The within subject factors were trajectory (approaching predictable touch, approaching predictable no touch, approaching unpredictable and retracting predictable no touch), alignment (above, at and below threshold) and movement (straight and erratic movement). The dependent variables were the rotational drift scores.

There were no statistically significant differences found on trajectory ($F(3,18) = .35$, $p = .79$), alignment ($F(2,12) = .51$, $p = .61$), and movement ($F(1,6) = 1.56$, $p = .26$). The interaction effect of trajectory and alignment ($F(6,36) = 2.31$, $p = .06$) and the interaction effect of trajectory and movement ($F(3,18) = 0.2$, $p = 0.9$) were not significant either.

Discussion

There was a significant difference found on the first question on trajectory. Participants felt that the ball was more likely to touch their own hand in the approaching predictable touch and unpredictable condition than in the retracting trajectory condition. This indicates that participants updated their top-down expectations that the ball was not going to touch the virtual had in the retracting trajectory condition. However, there were no significant differences found on the second question for trajectory and there was a remarkably high score on the second question in the retracting condition. This is in line with the results found in the first experiment.

Furthermore, there was a significant effect found of alignment. Sense of ownership over the virtual hand was lower when the hand was at or below the determined threshold. Sense of ownership thus decreased when the misalignment of the hand increased.

Lastly, there were no significant results found for rotational drift.

General discussion

This is the first study that looks at the effect of approaching stimuli and misalignment on the strength of the RHI using virtual reality. Two experiments were conducted. In the first experiment we examined the role of approaching stimuli. The high scores on the questionnaire and the strong proprioceptive drift in the first experiment, indicate that the illusion got induced in all four groups. However, there were no statistically significant differences found between the four groups on any of the outcome measures. These results thus do not support our hypotheses that bottom up predictions an top down expectations about a touch not occurring would lead to a smaller illusion and that top down unpredictability would lead to a stronger illusion compared to top down expectations about a touch occurring.

Remarkable are also then the high scores on the second question of the questionnaire and the strong proprioceptive drift in group 2 (approaching predictable no touch) and group 4 (retracting predictable no touch). We expected to see a less strong illusion in these groups, seeing that a low predictability of a touch occurring on the virtual hand would lead to a lower probability that the virtual hand belongs to 'me'. We expected to see this in particular in group 4, since retracting stimuli would not lead to a bottom up prediction of touch.

In the second experiment we found similar results. There the scores on the second question of the questionnaire were also remarkably high in the retracting trajectory condition where the ball moved away from the virtual hand.

These results could be explained due to the fact that any approaching stimuli or stimuli that move in the peripersonal space might lead to a prediction of touch on the hand. So there might have still been a bottom up prediction that a touch was about to occur on the virtual hand. Participant's might thus not have updated their top down probabilistic expectations that the ball would not touch the virtual hand, and therefore there was still a higher probability that the virtual hand belongs to 'me'. However, if you look at the results on the first question (It felt like the ball was about to touch my real hand), participants in group 2 in the first experiment had a significantly lower score. Meaning that they did not feel like the ball was going to touch their hand. In the second experiment, participants in the retracting trajectory condition had a significantly lower score as well. These results indicate that participants did update their expectations about the ball not touching the virtual hand.

Another explanation could be that the visual input of the hand alone might already be enough to induce the RHI. It is not clear from previous research if observing the fake hand alone is enough to induce the RHI. In the studies of Ferri et al. (2013) and Longo, Cardozo & Haggard (2008), the RHI did not get fully induced by mere exposure to the fake rubber hand, while in the studies of Ma & Hommel (2013) and Moguillansky, O'Regan & Petitmengin (2013) the illusion did get induced without any tactile stimulation.

Similar to the current study, in the study of Ma & Hommel (2013) participants also saw balls coming towards the hand in a virtual environment, except in this study a tactile stimulus on the participant's own unseen hand was given each time the ball touched the hand. In their visual only condition this tactile stimulation did not get administered. The effect might thus be due to a bottom up prediction of a touch occurring on the virtual hand, instead of a pure visual effect of the hand alone.

In the study of Ferri et al. (2013), only a questionnaire was used to measure the strength of the illusion in their visual only condition. Likewise, the study of Moguillansky, O'Regan & Petitmenging (2013), only interviewed their subjects on their subjective experience during and after the illusion. These studies thus did not use more objective measures which were used in the current study. Furthermore, in the study of Ferri et al. (2013), participants were instructed to pay attention to the experimenter's hand moving towards the fake rubber hand, and not to the rubber hand itself. Whereas in the current study participants were instructed to pay attention to the virtual hand. This together with the immersive nature of the Oculus Rift VR headset, that was used in the current study, could explain why mere exposure to the virtual hand alone is enough to induce the illusion.

In the second experiment we added misalignment. Our results show that the illusion still occurred when the hand was in an incongruent position. This is in agreement with previous research (Constantini & Haggard, 2007; Ide, 2013; White, Weinberg & Davies, 2013;Perez-Marcos, Sanchez-Vives & Slater, 2012). However, in the current study the illusion already got diminished when the participant's own hand was at a 47º angle, while in the studies of Ide (2013); Perez-Marcos, Sanchez-Vives & Slater (2012) and White, Weinberg and Davies (2015), the illusion still occurred at greater angles. An explanation for this might be that in the studies of Ide (2013) and Perez-Marcos, Sanchez-Vives and Slater (2012), they changed the position of the fake rubber hand, while the participant's own hand remained in the same position. In the current study the position of the participant's own hand was changed. The illusion might thus be more sensitive to visual information, than to proprioceptive information.

Furthermore the illusion decreased, but did not get completely diminished when the hand was at or below the participant's individual threshold. These results show that the brains pre-existing body representations influence what gets attributed to the body and what not. These representations get processed in a hand-centered frame of reference, which also includes anatomical plausibility (Constantini & Haggard, 2007; Ide, 2013; White, Weinberg & Davies, 2015 Perez-Marcos, Sanchez-Vives & Slater, 2012).

The current study gives more insight into the virtual hand illusion and in which conditions the illusion occurs. It shows that the Oculus Rift and virtual reality work well with the RHI. Furthermore, it seems the visual input of the hand alone is very strong in virtual reality, and that mere exposure to the virtual hand alone is enough to induce the illusion.

Future research can further explore the effect of approaching stimuli on the RHI, by making a better distinction between predictable and unpredictable stimuli and between the touch and the no touch groups, so it is clearer that the ball is not going to touch the virtual hand and participants thus update their expectations that a touch is not going to occur on the virtual hand. Furthermore they can investigate the role of the visual input of the hand alone, by creating different control conditions and using multiple measurements to measure the strength of the illusion.

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Tables and Figures

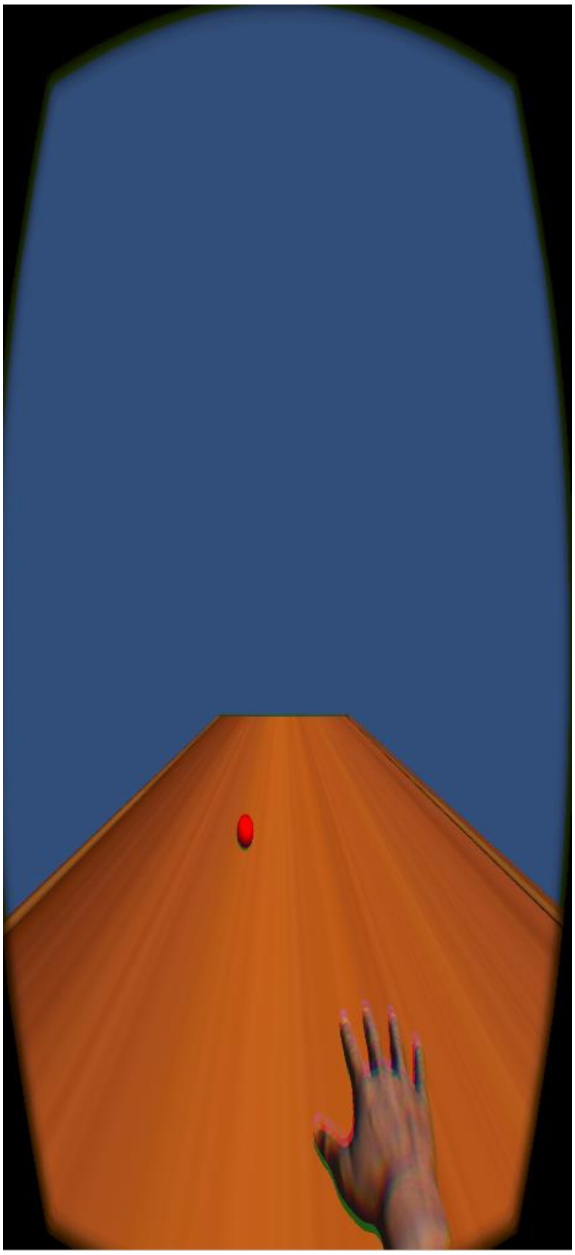

Figure 1: The virtual right hand in experiment 1.

Figure 2: Proprioceptive drift measurement in experiment 1

Table 1

Means and standard deviations of the results of the questionnaire in experiment 1.

Group	Questions							
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8
Group 1	3.5(1.2)	3.8(1.1)	3 (1.4)	3.1(1.3)	2.5(.8)	2.8(1.3)	1.8(.7)	3.1(.9)
Group 2	1.8(.8)	4.5(2.1)	3.2(1.7)	2 (.9)	3.1(2.1)	1.9(1.1)	1.3(.4)	2.9(2)
Group 3	4(1.3)	4.6(1.9)	4.5(2.6)	2.7 (2)	2.9(2)	2.2(1.4)	2.2(1.1)	3.2(1.7)
Group 4	2.3(1.5)	4(1.2)	4.1(1.2)	3.3 (.9)	2.7(2.2)	2.2(1.7)	2.8(1.6)	4(1)

Note: Group 1 = approaching predictable touch; group 2 = approaching predictable no touch; group 3 = approaching unpredictable; group 4 = retracting predictable no touch.

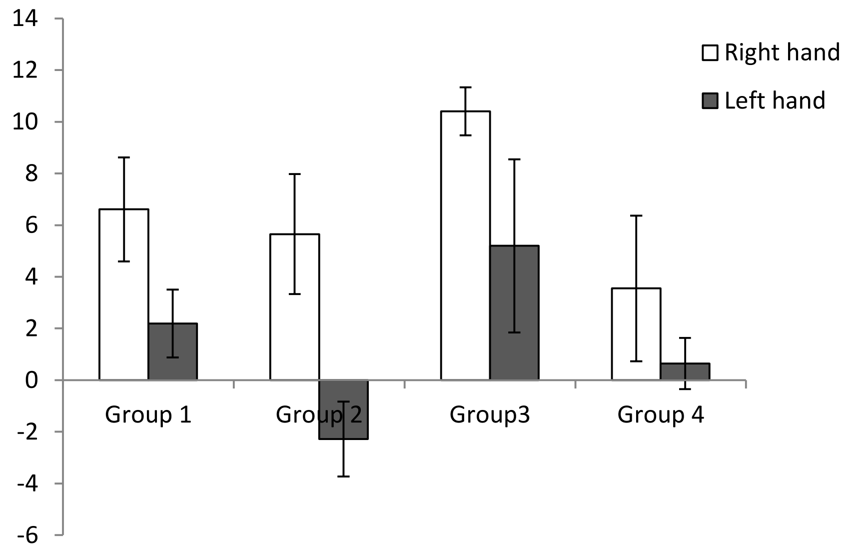

Figure 3: Mean drift (cm) of the right and left hand towards the virtual hand in experiment 1. The error bars indicate the standard error of the means.

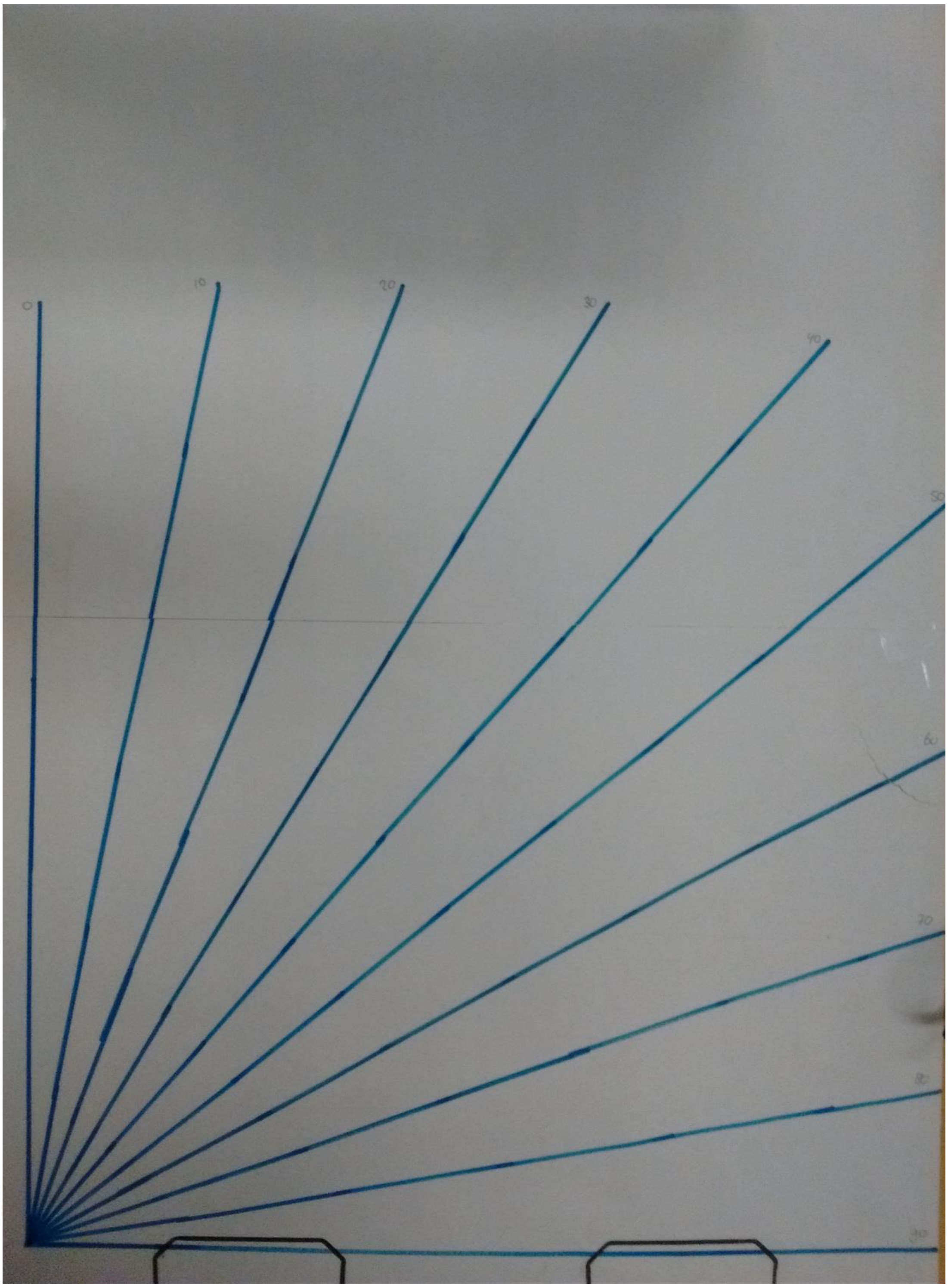

Figure 4: Marked hand positions ranging from 0º to 80º and marked positions for the headrest on the bottom.

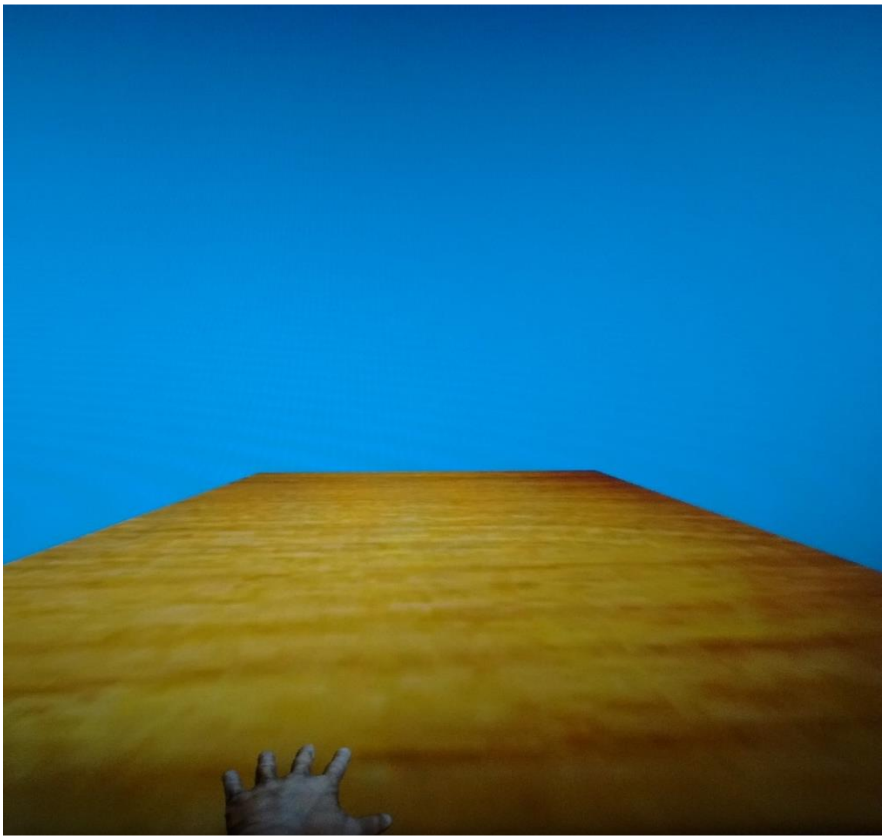

Figure 5: Virtual left hand in experiment 2.

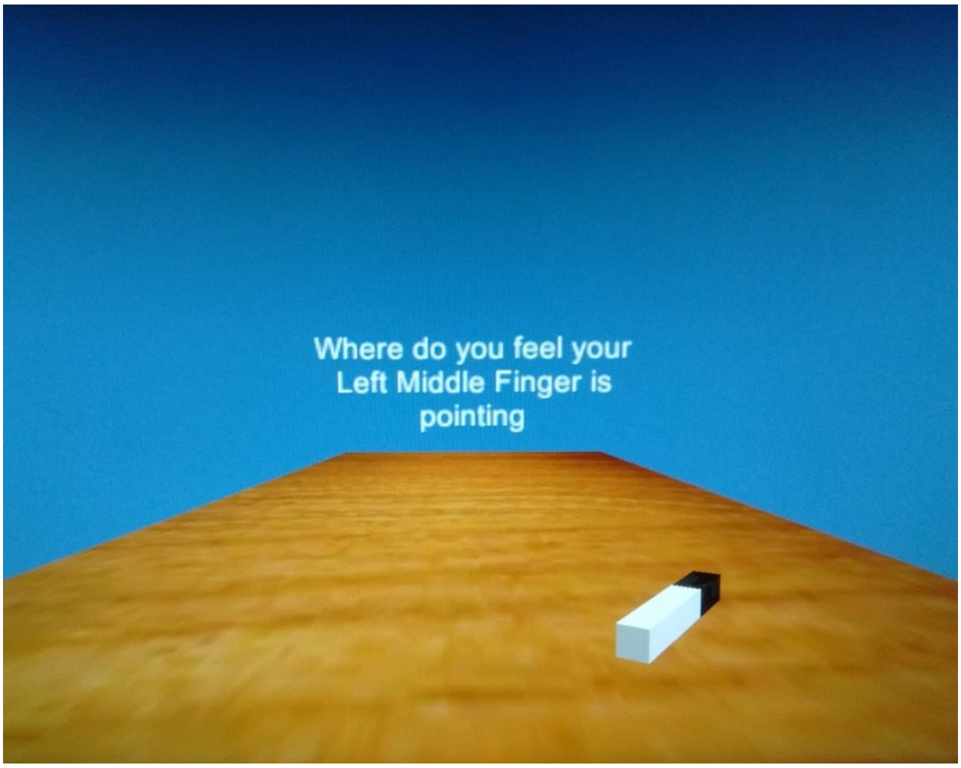

Figure 6: Rotational drift measurement in experiment 2.

Table 2a

Means and standard deviations of the questionnaire scores of the trajectory conditions in experiment 2.

Conditions	Questions			
	Q1	Q2	Q3	Q4
Condition 1	2.98(1.35)	2.95(1.34)	2.38(1.51)	1.52(0.99)
Condition 2	2.38(1.55)	2.5(1.23)	2.11(1.5)	1.47(1.06)
Condition 3	2.88(1.67)	2.83(1.46)	2.4(1.36)	1.62(1.23)
Condition 4	1.83(1.1)	3.12(1.38)	1.69(1.07)	1.62(1.21)

Note: Condition 1 = approaching predictable touch; condition 2 = approaching predictable no touch; condition 3 = approaching unpredictable; condition 4 = retracting predictable touch.

Table 2b

Means and standard deviations of the questionnaire scores of the alignment conditions in experiment 2.

Alignment	Questions			
	Q1	Q2	Q3	Q4
Above threshold	2.52(1.38)	3.52(1.34)	2(1.38)	1.5(1.08)
At threshold	2.61(1.61)	2.64(1.23)	2.13(1.31)	1.52(0.95)
Below threshold	2.43(1.5)	2.39(1.29)	2.32(1.49)	1.66(1.31)

Table 2c

Means and standard deviations of the questionnaire scores of the movement conditions in experiment 2.

Movement	Questions			
	Q1	Q2	Q3	Q4
Straight	2.48(1.55)	2.9(1.39)	2.08(1.42)	1.56(1.13)
Erratic	2.56(1.44)	2.8(1.35)	2.21(1.36)	1.561(1.11)

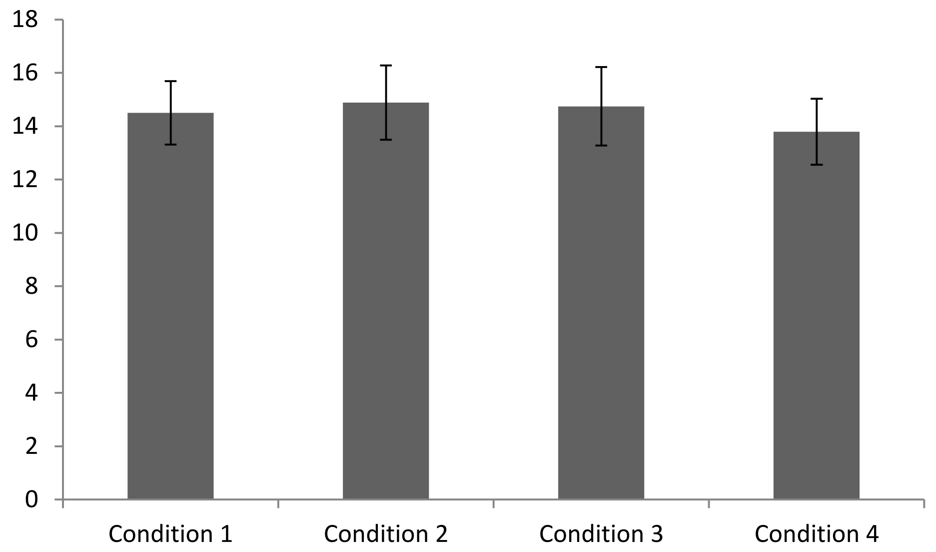

Figure 8a: Mean drift (degrees) towards the virtual hand in the trajectory conditions in experiment 2. Condition 1 is approaching predictable touch, condition 2 is approaching predictable no touch, condition 3 is approaching unpredictable and condition 4 is retracting predictable touch. The error bars indicate the standard errors of the means.

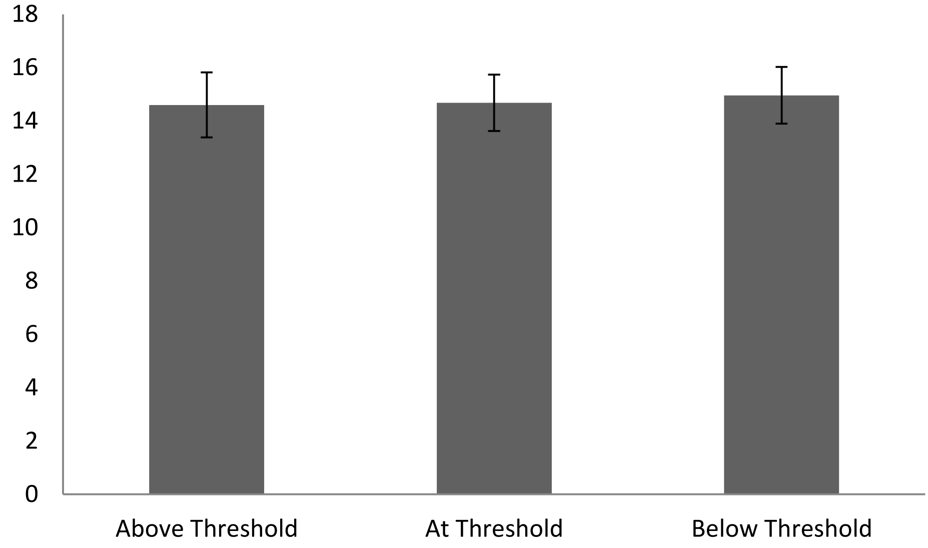

Figure 8b: Mean drift (degrees) towards the virtual hand in the alignment conditions in experiment 2. Error bars indicate the standard errors of the means.

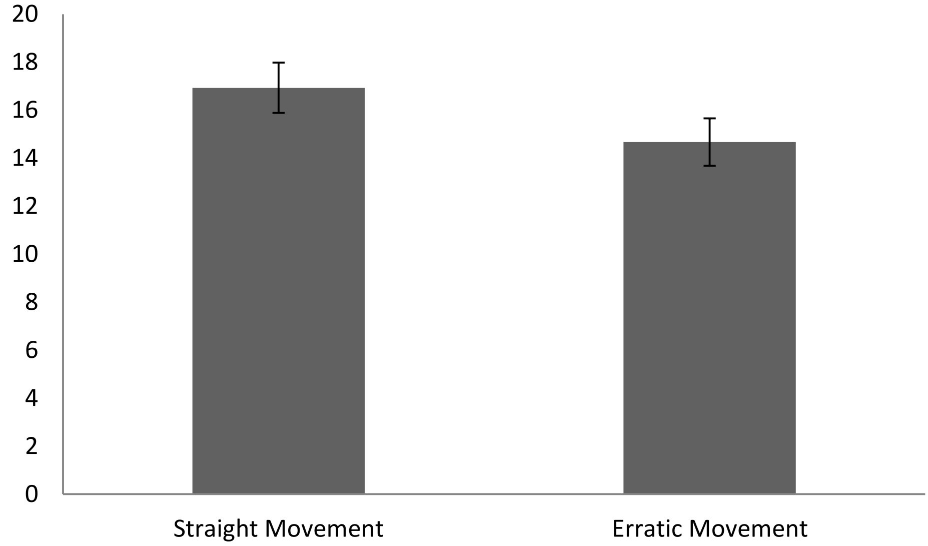

Figure 8c: Mean drift (degrees) towards the virtual hand in the movement conditions in experiment 2. Error bars indicate the standard errors of the means.