Is My Hand Connected to My Body? The Impact of Body Continuity and Arm Alignment on the Virtual Hand Illusion

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Abstract

When a rubber hand is placed on a table top in a plausible position as if part of a person's body, and is stroked synchronously with the person's corresponding hidden real hand, an illusion of ownership over the rubber hand can occur (Botvinick and Cohen 1998). A similar result has been found with respect to a virtual hand portrayed in a virtual environment, a virtual hand illusion (Slater et al. 2008). The conditions under which these illusions occur have been the subject of considerable study. Here we exploited the flexibility of virtual reality to examine four contributory factors: visuo-tactile synchrony while stroking the virtual and the real arms, body continuity, alignment between the real and virtual arms, and the distance between them. We carried out three experiments on a total of 32 participants where these factors were varied. The results show that the subjective illusion of ownership over the virtual arm and the time to evoke this illusion are highly dependent on synchronous visuo-tactile stimulation and on connectivity of the virtual arm with the rest of the virtual body. The alignment between the real and virtual arms and the distance between these were less important. It was found that proprioceptive drift was not a sensitive measure of the illusion, but was only related to the distance between the real and virtual arms.

Key words: virtual hand illusion; rubber hand illusion; body perception; virtual reality; body representation; multisensory integration; virtual environments.

Introduction

In the rubber hand illusion (RHI) synchronous tactile stimulation of a person's hidden real hand and a visible rubber hand in an anatomically plausible position results in an illusion of ownership over the rubber hand, a proprioceptive illusion of displacement of the real hand to the rubber hand, and a referral of the feeling of touch to the rubber hand (Armel and Ramachandran 2003; Botvinick and Cohen 1998).

It has been shown that even a computer-generated virtual arm in an immersive virtual environment (VE) can be integrated into the body representation if there is synchronous visuo-tactile correlation on the hidden real and the visible virtual arm that appears to extend from the real body of the participant (Slater et al. 2008). In this case not only was the perceptual system deceived by this virtual hand illusion (VHI), but also the motor system was recruited, inducing measurable muscle activity correlated with movements of the virtual arm. Furthermore, the VHI can be induced by visuo-motor correlations, even in the absence of visuo-tactile stimulation, where the movements of the tracked real hand are reproduced by movements of the virtual hand (Sanchez-Vives et al. 2010). In this case the visual feedback corresponds to the proprioceptive input and the motor output. The VHI has been also partially reproduced through a motor imagery based brain-computer interface, without the necessity for synchronized visuo-tactile or visuo-motor stimuli (Perez-Marcos et al. 2009).

The RHI, and by extension the VHI, depends on multiple factors. There is general agreement about the critical role of the visuo-tactile integration. If the visual and corresponding tactile sensations are not synchronous and well registered with one another in terms of location, the illusion does not occur (Botvinick and Cohen 1998; Slater et al. 2008). Another factor reported to be relevant for the RHI illusion is appearance, i.e. the resemblance between the subject's real arm and the rubber one. The reported illusion is stronger for a rubber hand with a natural skin texture than one with a white latex glove (Haans et al. 2008).

Other important factors influencing the illusion are congruence, plausibility and connectivity. It has been shown that with the rubber arm placed in an incongruent position the strength of the illusion decreases (Ehrsson et al. 2004; Pavani et al. 2000; Tsakiris and Haggard 2005). The illusion of ownership is not only reduced with postural mismatches (10-30°) but also with stimulation mismatches between the real and virtual hand (Costantini and Haggard 2007). In the cases explored, not only was the rubber arm's position incongruent with the real arm (from -10° to -180°) but also the arm was seen to be disconnected from the real body.

A less vivid illusion was also reported by those participants who were presented an 'anatomically correct' fake but distant hand, with the arm about twice as long as normal (Armel and Ramachandran 2003). In another study, the rubber arm was in a plausible position but incongruent with the position of the real arm (behind the participant's back). This lessened the illusion as shown by a decrease in cross-modal extinction (Farne et al. 2000). The strength of the illusion has also been shown to decrease when the rubber arm is moved from its anatomically plausible position to the limits of reaching space (Lloyd 2007), while an impression of continuity with the body was given by covering up to the wrist with a hairdresser's cape.

These findings and other not cited here (see Discussion) show a diversity of results regarding the relative position of the real and the fake arms and characteristics of the visuo-tactile correlations. Furthermore, when evaluating the responses to different experimental conditions, often body continuity is not taken into account, adding an implicit additional aspect to the experimental design.

Here we investigate for the first time the impact of four different factors on the strength of the VHI: (1) visuo-tactile synchrony (2) the degree of alignment between the real arm and the virtual arm (3) independently of alignment the amount of displacement between the real and virtual hands, and (4) body continuity in the sense of whether the virtual hand is connected or not to the rest of the body. Since earlier results have shown that the illusion of ownership over a virtual hand can be obtained in the same manner as over a rubber hand, we use virtual reality for this study, further illustrating its power and flexibility generally in the study of body ownership illusions.

Methods

Virtual Reality System

Participants experienced a virtual body through a head-tracked stereo head-mounted display. This was a Fakespace Wide5, which has a field of view of $150^{o} \times 88^{o}$ with an estimated 1600×1200 resolution displayed at 60Hz. The head-tracking was realised with a 6-DOF Intersense IS-900 device. A 6-DOF Wand device was used by the experimenter to deliver tactile sensations to the real hand of the participant. The tracked Wand was represented in the virtual reality by a small yellow ball that was slaved to the movements of the real tracker. Hence when the real Wand touched the hand of the participant the virtual ball similarly was seen to touch the virtual hand in a corresponding location. The application was programmed using the XVR system (Tecchia et al. 2010) and the virtual body used the HALCA library (Gillies and Spanlang 2010).

Participants

There were three experiments and altogether 32 participants (22 females) were recruited. Their mean±SD age was 24±4. They had normal or normal-to-corrected vision and no history of neurological or psychological disorders. All but two subjects were right-handed. Handedness was assessed by the Edinburgh Handedness Inventory (Oldfield 1971). Upon arrival at the laboratory they were asked to read and sign a consent form, the experiment having been carried out in accordance with the regulations Comisión de Bioética de la Universitat de Barcelona. All the participants were paid 5€ for their participation in each session.

Experimental setup

This study consisted of three experiments. All experiments were carried out with the lights off. Participants sat on a chair with both arms resting palm-down on a desktop. They wore a white coat commensurate with that worn by the virtual body (Figs. 1A-B). After putting on the HMD, participants were asked to look around in order to familiarise themselves with the environment and the wearing of the HMD. Participants had a virtual body that was co-located with their own. They saw this body from a first person perspective as if they were looking through the eyes of this virtual body. Thus when they looked down towards their own body, they would see the virtual body instead. The virtual body was gender matched. It could be seen as seated in the same posture as their own, and particularly with both arms connected through the shoulders to the rest of the virtual body. The right arm of the participant rested on the table and was always pointed straight forward, and was co-located with the virtual right arm, also seen to be resting on the corresponding virtual table. The relative position and orientation of the real and virtual left arms could differ depending on the experiment and condition.

In each of the three experiments the experimenter tapped and stroked the real left hand of the participant with the Wand for three minutes while the virtual ball tapped and stroked the virtual left hand. Participants were asked to concentrate their attention on the back of the left virtual hand. In one condition of experiment 1 and all conditions of experiments 2 and 3 the seen virtual stimulation was synchronous with the real tactile stimulation, and registered at the same positions on the virtual hand as the stimulation was applied on the real hand. In experiment 1 there was an asynchronous condition, where a pre-recorded tapping and stroking motion of the ball on the virtual hand was used.

In each case the experiment was a repeated measures design with one factor at two levels (e.g., in the case of experiment 1 synchronous or asynchronous visuo-tactile stimulation). The conditions were applied in counter-balanced order across the participants. Details of each particular experiment are given in the results section.

Behavioural measures

In experiments 1 and 2, after putting the HMD on and before the visuo-tactile stimulation was started, participants were instructed to close their eyes and point with their right index finger to the position of their left index fingertip. In order to avoid possible cues, the measurement was carried out over a box that the experimenter had placed over the participant's left hand so that there was no physical contact between the fingers of the two hands during the measurement. Immediately after the 3 minutes of visuo-tactile stimulation participants were asked to repeat the action while still wearing the HMD and with closed eyes. In experiment 3, the pointing action was replaced by placing a piece of blue-tack under the table in the position corresponding to where they felt the centre of their palm to be, as described in (Slater et al. 2008). In all cases, the horizontal distance between both markers, pre- and post-stimulation, corresponded to the proprioceptive drift. A positive drift meant a drift toward the virtual hand. Each proprioceptive drift measurement was based on two pointing actions - one pre- and one post-stimulation.

The time for an ownership illusion to occur, if at all, was recorded following Lloyd (2007). Participants had been instructed to say aloud when they felt for the first time, if ever, the virtual hand as their own. In any case the stimulation lasted for the full 3 minutes. Hence this 'time to the illusion' response is a censored variable, meaning that there was a cut-off of 180s and that if the participant did not report the illusion by then, the experiment was stopped and their time to the illusion was recorded as 180s. Hence in the results the mean time to the illusion is always an underestimate since it cannot be known at what point in time, if ever, those participants who did not report the illusion within 180s might have reported it.

Questionnaire

After each of their two trials, and upon completing the drift measurements, participants filled in a 10-item questionnaire in Spanish. Most questions were adapted and translated from (Botvinick and Cohen 1998) and new a question related to agency was added:

Q1. Sometimes I had the feeling that I was receiving the hits in the location of the virtual arm.
Q2. During the experiment there were moments in which it seemed as if what I was feeling was caused by the yellow ball that I was seeing on the screen.
Q3. During the experiment there were moments in which I felt as if the virtual arm was my own arm.
Q4. During the experiment there were moments in which I felt that if I moved my (real) arm the virtual arm would move.
Q5. During the experiment there were moments in which it seemed that my real arm was being displaced towards the right (towards the virtual arm).
Q6. During the experiment there were moments in which it seemed that the hits that I was feeling originated in some place in between my own arm and the virtual arm.
Q7. During the experiment there were moments in which I felt as if my real arm was becoming virtual.
Q8. During the experiment there were moments in which it seemed (visually) that the virtual arm was being displaced towards the left (towards my real arm).
Q9. During the experiment there were moments in which the virtual arm started to look like my own arm in some aspects (physically).
Q10. During the experiment there were moments in which I had the sensation of having more than one left arm.

Q1 and Q2 elicit information about referral of touch, Q3 refers to ownership of the virtual arm and Q4 refers to the sense of agency, the feeling of being able to control the virtual arm, causing or generating its movement (Tsakiris et al. 2006). Q1-Q3 are the illusion related questions in the original Botvinick and Cohen questionnaire. The remaining questions, apart from Q4, are considered control questions. Each question was scored according to a 7-point Likert Scale, 1 meaning 'totally disagree' and 7 'totally agree'. Questions were presented in a different random order for each participant.

Results

Experiment 1 - Synchronous / Asynchronous (S-AS)

The first experiment (S-AS) was the normal VHI but carried out using the HMD (the original VHI experiments used a stereo large single screen system with head-tracking (Slater et al. 2008)). The hand was stroked with a ball attached to the hand-held wand that was tracked and represented in the virtual world as a yellow ball hitting the virtual hand (Fig. 1B). This was a single factor within-groups (repeated measures) design, the visuo-tactile stimulation being either synchronous or asynchronous, as described earlier. The virtual and real arms were parallel to one another (we refer to this as being *aligned*) with a distance of 20cm between the positions of the real and virtual hands.

There were 15 participants in this repeated-measures experiment (mean±SD age 23±4; one male), 8 of whom received first the synchronous condition followed by the asynchronous (group SA) and the remainder in the opposite order (group AS). They were randomly assigned to these groups. Hence all participants completed both conditions in the order depending on their assigned group.

In each of the two trials, after the 3 minutes of tapping the subjects first carried out the proprioceptive drift task to test the illusion of displacement while wearing the HMD. Then they removed the HMD and completed the 10-item questionnaire (Methods).

In order to test for order effects (i.e., differences between the two groups AS and SA), a repeated-measures ANOVA was carried out on all of the response variables (Q1-Q10, the time to the illusion, and the drift). The results are shown in Supplementary Table 1. Since no order effects were detected, the results from both groups were combined for analysis (hence n = 30). Two-factor ANOVA was used, where one factor was the participant, and the other was the synchronous/asynchronous condition. Care was taken to ensure that the assumption of normality of residual errors was not violated, using the Jarque-Bera non-parametric test for normality (Jarque and Bera 1980), where a 0.05 significance level cut-off was used. The assumption of normality was rejected for three responses, Q5, Q10, and the drift. In each case two outliers were found by inspection of the residual errors, and when these were removed the Jarque-Bera test no longer rejected normality. In the case of Q5 only this resulted in the difference between synchronous and asynchronous being significantly different, but had no effect on Q10 or drift which both remained non-significant.

The questionnaire results are shown in Fig. 2A. These are in line with the original findings in (Botvinick and Cohen 1998) and with the original VHI study: Q1-Q3 are significantly higher in the synchronous compared to the asynchronous condition. However, Q5 also shows a significant difference (the feeling of the real arm drifting towards the virtual one was greater in the synchronous case). Q4 relating to agency shows no significant difference between synchronous and asynchronous, the scores being rather high in both cases. Q9 also shows high scores, but no difference between the conditions. This question was also shown as related to the illusion in (Slater et al. 2008).

The time taken to report the onset of the illusion is significantly lower in the synchronous compared to the asynchronous condition (Fig. 2C). The proprioceptive drift was significantly greater than 0 over both conditions with mean value of 35.8 ± 42.7 mm (n=30; mean ± SD; Fig. 2B).

Experiment 2 - Connected/ Unconnected /Not Aligned

The purpose of this experiment was to test whether the VHI can be induced when the real and virtual arm are not aligned. The idea was that this would depend on whether or not the arm was connected to the rest of the body. Often in the rubber hand illusion the rubber hand is on the table, and clearly unconnected to the real body, although some experiments have used the device of partially covering the rubber arm and corresponding real shoulder with a cloth to give the impression of connectivity between the rubber hand and real body. Our hypothesis was that when the arm is visibly connected to the rest of the body the illusion of ownership would occur even when the real and virtual arms are not parallel to one another. In experiment 2 the left real arm was straight (Fig. 1A) and the virtual arm bent at 64 degrees away from it (Fig. 1C). The response variables and design were otherwise the same as for S-AS (experiment 1). The estimated horizontal distance between the real and the virtual hand was 21.9 cm for males and 21.4 cm for females.

This was a repeated measures single factor experiment where the factor was connectivity of the virtual arm to the virtual body (unconnected or connected) (Fig. 1C-D). In both the connected and unconnected conditions synchronous stimulation only was used.

The number of participants with complete data was n = 13 (mean± SD age 24 ± 5, one male), a subset of those who took part in experiment S-AS. Experiment 2 was carried out more than 30 days after experiment 1. Six participants experienced first the connected and then the unconnected conditions (group CU), and the remainder in the opposite order (UC). Hence all participants completed both conditions in the order given by the group to which they were assigned. The order effects were explored using ANOVA (Supplementary Table 2). Since no order effects were detected, the results from both groups were further analysed together (n = 26).

Figure 3 illustrates the results regarding the questionnaires (Fig. 3A), proprioceptive drift (Fig. 3B) and time to the perception of the illusion (Fig. 3C) using the same methods as in experiment 1. With respect to the questionnaires Q3 (ownership) showed a significantly higher mean score for the connected condition, and Q2 the same but just outside the 5% significance level (Fig. 3A). There were no significant differences for the control questions, Q5-Q10, except Q7 just inside the 5% significance level. Q7 was also found to be related to the illusion in (Slater et al. 2008).

There were no differences in the proprioceptive drift between the connected and unconnected conditions, the mean drift being 50.5 ± 48.8 mm (n=26; mean ± SD) (Fig. 3B). However, the drift over both conditions was significantly greater than 0. Finally, the mean time to experience the illusion was significantly less in the connected than in the unconnected condition (Fig. 3C).

This experiment suggests that the illusion of ownership can be evoked by the synchronous visuo-tactile stimulation of a real and a virtual arm, even when they are not aligned (the real arm straight and the virtual arm bent), and that this is aided by the virtual arm being connected to the body (Fig. 1C and 1D).

Experiment 3 - Connected/ Unconnected/Co-located

This experiment also investigated the difference between connected (Fig. 1C) and unconnected (Fig. 1D) conditions. The crucial difference was that in this experiment the virtual and real arms were coincident, and therefore aligned and with no displacement at all between real and virtual hand positions. In this case the real arm was also bent 64 degrees, co-located with the virtual arm as in Fig. 1C. This was carried out with a different set of participants.

Seventeen participants (mean±SD age 25 ± 4; 9 males) were recruited, with 8 experiencing first the connected and then the unconnected connected conditions, and the remainder in the opposite order. Otherwise everything was the same as the previous experiment, including the fact that all stimulations were synchronous. Hence all participants completed both conditions in the order given by the group to which they were assigned. Supplementary Table 3 shows the within-groups ANOVA for experiment 3. There were no order or interaction effects and therefore the results were analysed together (n = 34).

Similarly to the results reported for Experiment 2, there was a significant difference between the connected and unconnected conditions for Q3, so that the participants felt the virtual arm as their own arm more when the arm was connected to their own body (Fig. 4A). Note that although for Q1 and Q2 there was no significant difference between the conditions, the responses were very high in both conditions, and the response to agency (Q4) was also high. Once again Q7 and Q9 although showing no significant differences between the conditions, also had quite high scores overall, again similarly to (Slater et al. 2008).

The time to perceive the illusion was also significantly less for the connected than for the unconnected hand (Fig. 4C). As expected, since both the virtual and real arms were co-located, the proprioceptive drift was not significantly different from 0 in any condition (Fig. 4B).

Comparisons across all conditions

In the experiments described above we have considered individually the impact of various factors on ownership: visuo-tactile synchronous stimulation, alignment, and body connectivity. Implicitly there was a fourth factor, which was the displacement, i.e., the distance between the real and virtual hands in each case. What is of most interest is not these factors considered separately but their relative effects when considered together. It is possible to explore this by combining all the data together and carrying out a regression analysis of the response variables (Q1-Q10, time and drift) on all four factors (n = 90): (1) Synchrony *versus* asynchrony of the visuo-tactile stimulation, (2) Alignment of the virtual with respect of the real arm, regarding whether or not the arm was parallel or not with the virtual arm. (3) Displacement, i.e. the distance between the position of the real and virtual hands, and (4) Body continuity (connected *versus* unconnected).

The variation in these factors across the three experiments was:

- Experiment 1: displacement = 20cm, alignment = 1 (parallel); Synchronous *vs.* Asynchronous; Connected; n = 30
- Experiment 2: displacement > 21cm, alignment = 0 (at an angle); Synchronous; Connected *vs.* Unconnected; n = 26
- Experiment 3: displacement = 0cm, alignment = 1 (coincident); Synchronous; Connected *vs.* Unconnected; n = 34.

For almost every regression fit the residual errors were non-normal (Jarque-Bera test) caused by outliers. In some cases removal of outliers did not resolve the problem. Since outliers can greatly bias the results of a regression, we decided to use instead robust regression, which takes account of influential points and applies weights to those according to their effect on the regression parameters (Holland and Welsch 1977) (implemented in MATLAB R2009A). However, in fact robust regression did not produce qualitatively different results compared to standard regression analysis.

Table 1 shows the results of the regression analysis. These show that the three illusion-related questions Q1-Q3 were heavily dependent on synchronous stimulation. Q1 ("Sometimes I had the feeling that I was receiving the hits in the location of the virtual arm") depended also on alignment, while Q3 ("During the experiment there were moments in which I felt as if the virtual arm was my own arm"), the most relevant one regarding ownership, depended also on connectivity. None of the control questions showed any relationship with the three factors.

The time that it took for the illusion to occur was influenced by two factors. This time was reduced by synchronous stimulation and by connectivity. Other things being equal synchronous compared to asynchronous on the average reduced the time to the illusion by 89s. Similarly, connectivity reduced the time by about 47s.

The proprioceptive drift was only associated with displacement, such that the greater the distance of the virtual to the real hand, the greater the drift. This is to be expected and should be considered as a consistency result.

Our analysis also suggests that alignment does not contribute to the illusion of ownership, but does contribute to referral of touch (Q1).

Discussion

In this study we have demonstrated the influence of body continuity and arm alignment on the illusion of ownership over a virtual hand. By body continuity we mean the visual connection between the body and arm. We find that body continuity can compensate for other factors such as misalignment. A mismatched or misaligned (64°) virtual arm with respect to the real arm while in a plausible position can evoke an illusion of ownership when the body continuity is preserved.

It is found that the time to evoke the illusion is sensitive to the different experimental conditions, while the proprioceptive drift is less sensitive given that it is a function only of the displacement between the real and the virtual arms. Lloyd and colleagues earlier reported a strong nonlinear relationship between the time taken to rate the strength of the illusion and the position of the rubber hand (Lloyd 2007), this time being shorter for closer hand positions.

Proprioceptive drift

The illusion of positional displacement or proprioceptive drift has been classically considered an objective measurement of the RHI since Botvinick and Cohen (1998). The VHI also induces a proprioceptive drift towards the virtual arm (Slater et al. 2008). However, the relationship between the subjective illusion of ownership and the proprioceptive drift is a matter of debate. Holmes et al. (2006) found that the subjective illusion of ownership of a rubber hand did not correlate with the proprioceptive recalibration, which existed in cases when the illusion was not reported. Haans et al. (2008) also found proprioceptive displacement following visuo-tactile synchronous stimulation of a table top and the real hand, even when no RHI for the table top was evoked. A recent paper by Rohde et al. (2011) further demonstrates that there may be a proprioceptive displacement while there is no illusion of ownership. Proprioceptive displacement was evoked not only by just the vision of the rubber hand – and no visuo-tactile correlated stimulation - but also during short periods of asynchronous stimulation. In their experiments, only long (120s) asynchronous stroking had the power to block proprioceptive displacement. Further evidence that visuo-tactile stimulation is not necessary for proprioceptive displacement is provided by Durgin et al. (2007), where stroking of the fake hand with the light from a laser pointer, even in absence of real touch induced ownership and proprioceptive displacement.

The results of our experiment suggest that proprioceptive displacement may occur even when there is no subjective illusion of ownership. This was the case in the asynchronous visuo-tactile condition. Even when proprioceptive displacement has been found for short asynchronous stimulation (Rohde et al. 2011) to our knowledge this is the first time that significant proprioceptive displacement has been reported for continuous asynchronous stimulation. How can we explain this? We suggest that this is due to the relevance of first person perspective provided by a HMD. In the HMD the visual information is that of a body which is co-located with one's own and of two arms that are connected to the virtual body. Our previous studies using a HMD found that the first person perspective is the most important factor in order to feel a whole virtual body as one's own (Slater et al 2010). It would seem that the first person view of one's own body is powerful enough to counteract the visuo-tactile conflict during asynchronous stimulation. It should be mentioned though that even calibrated HMDs are not free of geometric distortions (Kuhl et al. 2009) which could have some influence on the estimation of the relative position of the virtual with respect to the real hand. However, it has also been found that such egocentric distance judgments improve when the participant is represented by an avatar (Mohler et al. 2010).

The Control Questions

In addition to the illusion related questions Q1-Q3, we found that three of the control questions had high scores - Q5 (the feeling of displacement of the real arm towards the virtual), Q7 (the feeling of the real arm becoming virtual) and Q9 (the feeling of the virtual arm coming to look like the real arm). This reflects what was also found in (Slater et al. 2008). Considering some of the questions as 'controls', in the sense of being unrelated to the illusion of ownership, is likely to be unsupportable. In fact there is no reason to believe that the illusion should not be accompanied by the types of sensation reported in those questions, and researchers in the field continue to use these questions largely for the historical reason that they were used in the original RHI paper (Botvinick and Cohen 1998).

Alignment and Body Continuity

While alignment between the real and rubber arm has been explored in the literature, this has not been the case with body continuity. Body continuity or connectivity refers to the existence of an apparent connection between the body and the virtual arm and hand. A common strategy to achieve this with a rubber arm has been to create an illusion of body continuity by a cloth that gives the impression of a sleeve and provides an illusion of continuity between the body and the rubber arm. However, the use of a HMD obviates the need for this, since the whole body as a connected structure seen from a first person position can be attained. One possibility is that the fact that the whole environment is virtual, the body is part of this environment, and this enhances the probability of an ownership illusion. For example, results in (Slater et al. 2010) suggested that having a virtual body in such an immersive virtual reality enhances presence, the sense of being in the virtual space, and also the illusion that what is happening there is real.

It could be argued that since participants have to concentrate their gaze and attention towards the fake hand that this fact could avoid the need for a full virtual body, since it may not even be noticed during the stimulation - and this would definitely be the case if a narrow field-of-view HMD were used. However, in the case of our experiment, a wide field-of-view HMD was used so that the virtual body was seen in peripheral vision. Also, at various times participants would clearly have seen the connectivity or lack of it, for example during the initial period of looking around the scene. Indeed, our results show that not only there is a larger subjective ownership illusion with body connectivity, but also the time to evoke the illusion was significantly reduced.

There are differing results in the literature concerning the importance of the spatial relationship between the real and fake arm with respect to inducing the illusion of ownership. For example Ehrsson et al. (2004) used as a control condition not only asynchronous stroking but additionally the rotation of the rubber hand by 180 degrees so that it was pointing towards the body of the subject, arguing that the RHI occurs for synchronous stroking but also "when the rubber hand is aligned with the subject's own hand". This followed the finding reported by Pavani et al. (2000) which found that the illusion required the rubber hand to be spatially aligned with the real hand, where spatial alignment in this case referred to a rotation of the position of the rubber hand with respect to the real hand. In both the Ehrsson et al. and Pavani et al. the rubber hand was not connected to the body. In the case of Ehrsson et al. the hand was additionally not in an anatomically plausible position (pointing towards the subject) and arguably in Pavani et al. it was.

Tsakiris and Haggard (2005) also found that flexion and displacement of the rubber hand with respect to the real hand eliminated the illusion, while Costantini and Haggard (2007) found that the illusion remained if there were small displacements of the real hand with respect to the rubber hand, but not when these were applied to the rubber hand. Again in both of these cases it appears that there was not an attempt to make an apparent connection between the rubber hand and the body of the subject.

Lloyd (2007) described an experiment where the rubber arm was placed in one of 6 different anatomically plausible positions (within peripersonal space). In this case the rubber arm was both rotated and translated away from the real hand. It was found that the illusion diminished with distance, based on both a subjective questionnaire measure, and time to the illusion. The rubber arm was covered by a cloth so that it did appear to connect to the rest of the body. However, Zopf et al. (2010) found that the illusion was not diminished when there was a lateral translation of the rubber hand away from the real hand, in this case with no rotational component. Again the rubber hand was in a plausible position, and was covered by a cloth to make it seem connected to the body.

In our experiments we have found that all three illusion related questions Q1-Q3 are dependent on synchronous visuo-tactile stimulation. However, Q1 (referral of touch) was also dependent on alignment (i.e., the real and virtual arms being parallel). Q3 (ownership) was dependent on body connectivity, as was time to the illusion. All of our conditions involved the virtual hand in an anatomically plausible position. Our conclusion is that for the illusion of ownership of the virtual hand body connectivity should be considered as an additional important variable. We speculate following (Slater et al. 2010) that seeing the virtual body from a first person perspective is also critical, although this variable was not manipulated in the current experiment. We also conclude from these experiments that proprioceptive drift should be downgraded as a measure of the illusion. When there is first person experience of a whole connected body in immersive virtual reality then this becomes a dominating factor with respect to proprioception and that drift simply records the degree of separation between the real and virtual arms. Perhaps there is a tolerance region where not too much separation results in the virtual and real arm being sensed in the same place with respect to proprioception.

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Figure Legends

Figure 1. The experimental setup. A. The participant wore a head-tracked stereo HMD. The experimenter tapped and stroked the participant's real hand with a 6-degree freedom Wand, the position of which was tracked and used to determine the position of the virtual sphere. **B.** Synchronous vs. asynchronous condition (Experiment 1). Both arms were extended and the left arm was stimulated. The virtual left arm was displaced 20 cm away from real arm. **C.** The virtual left arm was flexed 64° to the right and connected to the body (Experiment 2, connected condition). **D.** The virtual left arm was missing (no body connectivity) with only the hand present (Experiment 2, unconnected condition). Experiment 3 corresponded to C and D, but where the real arms were coincident with the virtual arms.

Figure 2. Synchronous versus asynchronous condition. A. Mean and Standard Errors of raw Questionnaire Responses for the Synchronous-Asynchronous experiment. *** For Q1 $P < 0.0005$, for Q2 $P < 0.00006$ and for Q3 $P < 0.0032$. * For Q5 $P < 0.03$ after removal of two outliers. **B.** Means and Standard Errors of drift. Overall the drift is significantly different from 0, $P < 0.00008$, t-test, $n = 30$. **C.** Means and Standard Errors of time to the illusion. Time was censored at 180s. $P = 0.0006$.

Figure 3. Connected/ Unconnected /Not Aligned. A. Means and standard errors of questionnaire responses for the Unconnected-Connected-Not Aligned experiment. Q2+ $P = 0.053$, Q3* $P = 0.016$, Q7* $P = 0.042$. **B.** Means and standard errors of proprioceptive drift. The hypothesis of zero overall mean ($n=26$) is rejected using the two-tailed t-test, $P < 0.00002$. **C.** Means and standard errors of time for the illusion to occur *$P = 0.024$.

Figure 4. Connected/ Unconnected /Co-located. A. Means and standard errors of questionnaire responses for the Unconnected-Connected-Co-located experiment. Q3* $P = 0.044$. **B.** Means and standard errors of proprioceptive drift. **C.** Means and standard errors of time for the illusion to occur * $P = 0.016$.

Main Manuscript

Table 1

Regression Analyses on Combined Data Using Robust Regression.

Sync = 1 for visuo-tactile synchronous stimulation and 0 for asynchronous

Alignment = 1 when the virtual and real left arms were parallel and 0 otherwise

Displacement is the distance between real and virtual left hands

Connected = 1 when the left hand was connected to the body and 0 otherwise.

	Sync		**Alignment**		**Displacement**		**Connected**	
	Slope	**P**	**Slope**	**P**	**Slope**	**P**	**Slope**	**P**
Q1	**3.38**	0.0000	**1.31**	0.0253	0.01	0.6515	0.26	0.5218
Q2	**3.44**	0.0000	0.44	0.4606	0.01	0.7322	0.27	0.5202
Q3	**2.29**	0.0040	0.79	0.3147	0.00	0.8973	**1.13**	0.0416
Q4	1.23	0.1326	1.24	0.1307	0.04	0.3089	0.20	0.7233
Q5	0.34	0.6079	-1.15	0.0834	0.05	0.1359	0.41	0.3779
Q6	-0.76	0.3235	0.28	0.7210	0.01	0.7784	0.00	0.9988
Q7	0.32	0.6945	0.08	0.9188	-0.02	0.6000	0.96	0.0965
Q8	0.00	1.0000	0.00	1.0000	0.00	1.0000	0.00	1.0000
Q9	0.43	0.5841	1.38	0.0808	0.03	0.3919	0.22	0.6879
Q10	0.00	1.0000	0.00	1.0000	0.00	1.0000	0.00	1.0000
Time	**-89.46**	0.0008	-23.94	0.3556	1.74	0.1438	**-47.18**	0.0110
Drift	5.38	0.6704	-0.08	0.9950	**1.82**	0.0023	8.94	0.3189

Supplementary Table 1

Supplementary Table 1

Within Groups ANOVA for Synchronous-Asynchronous Experiment 1

	AS				SA				P		
	Async		Sync		Async		Sync				
Variable	**Mean**	SD	**Mean**	SD	**Mean**	SD	**Mean**	SD	Main Effect [1]	Order Effect [2]	Interaction [3]
Q1	**4.43**	2.70	**6.57**	0.53	**3.50**	2.33	**6.63**	0.74	0.001	0.562	0.427
Q2	**3.86**	2.73	**6.14**	0.90	**2.63**	2.07	**6.38**	1.06	0.000	0.539	0.184
Q3	**4.14**	2.67	**6.00**	1.83	**3.25**	2.25	**5.13**	2.47	0.005	0.426	0.987
Q4	**4.29**	2.56	**5.57**	2.15	**4.13**	2.03	**5.00**	2.27	0.116	0.714	0.752
Q5	**2.43**	1.51	**3.29**	2.06	**2.13**	1.81	**2.25**	2.05	0.381	0.430	0.491
Q6	**3.14**	1.68	**3.43**	1.81	**3.13**	2.36	**1.75**	1.75	0.312	0.320	0.170
Q7	**4.00**	1.91	**4.00**	2.58	**2.75**	2.43	**3.38**	2.39	0.463	0.423	0.492
Q8	**2.29**	1.89	**2.29**	1.50	**1.13**	0.35	**1.50**	0.76	0.390	0.128	0.421
Q9	**4.14**	2.04	**5.00**	1.63	**4.13**	2.42	**4.13**	2.47	0.494	0.656	0.465
Q10	**2.00**	1.29	**1.71**	1.25	**2.38**	2.20	**1.25**	0.46	0.086	0.945	0.307
Time (s)	**103.00**	77.37	**53.43**	61.04	**180.00**	0.00	**80.63**	70.93	0.001	0.069	0.153
Drift (mm)	**25.86**	36.68	**48.29**	39.02	**48.75**	31.02	**20.63**	58.40	0.804	0.858	0.183

[1] Difference between synchronous and asynchronous

[2] Difference between the groups AS and SA

[3] Interaction between synchronous /asynchronous and group.

Supplementary Table 2

Supplementary Table 2

Within Group ANOVA for Connected-Unconnected - Not Aligned Experiment

	UC				CU				P		
	Unconnected		Connected		Unconnected		Connected				
Variable	**Mean**	SD	**Mean**	SD	**Mean**	SD	**Mean**	SD	Main Effect[1]	Order Effect[2]	Interaction[3]
Q1	**3.86**	2.04	**5.14**	2.19	**5.00**	2.10	**5.00**	1.67	0.129	0.640	0.158
Q2	**5.29**	2.21	**5.86**	1.77	**5.17**	1.72	**5.50**	1.87	0.062	0.823	0.603
Q3	**3.29**	1.38	**5.14**	1.77	**4.67**	1.86	**4.67**	2.07	0.002	0.644	0.003
Q4	**4.14**	2.27	**4.71**	2.21	**3.83**	1.72	**3.83**	2.32	0.527	0.599	0.558
Q5	**2.29**	1.50	**4.43**	2.07	**3.83**	2.79	**3.50**	2.43	0.133	0.776	0.071
Q6	**3.29**	2.21	**3.29**	2.56	**1.33**	0.82	**1.33**	0.82	1.000	0.072	1.000
Q7	**2.86**	1.57	**4.00**	1.73	**2.17**	2.04	**3.17**	2.71	0.052	0.468	0.888
Q8	**1.43**	0.53	**2.43**	1.27	**1.50**	1.22	**1.67**	1.03	0.183	0.396	0.358
Q9	**3.43**	1.99	**3.71**	1.50	**2.33**	1.97	**3.17**	2.56	0.267	0.438	0.565
Q10	**1.57**	0.98	**2.00**	1.29	**2.17**	2.40	**2.67**	2.58	0.234	0.533	0.924
Time (s)	**145.29**	61.09	**68.14**	60.58	**121.17**	59.68	**115.17**	75.63	0.011	0.733	0.031
Drift (mm)	**27.43**	35.46	**59.86**	49.01	**62.50**	59.22	**54.50**	54.22	0.283	0.561	0.126

[1] Difference between connected and unconnected

[2] Difference between the groups UC and CU

[3] Interaction between connected/unconnected and group.

Supplementary Table 3

Supplementary Table 3

Within Group ANOVA for Connected-Unconnected - Coincident Experiment

	UC				CU				P		
	Unconnected		Connected		Unconnected		Connected				
Variable	**Mean**	SD	**Mean**	SD	**Mean**	SD	**Mean**	SD	Main Effect[1]	Order Effect[2]	Interaction[3]
Q1	**6.44**	0.53	**6.00**	1.00	**5.50**	1.85	**6.50**	0.76	0.542	0.585	0.075
Q2	**5.56**	1.74	**5.78**	1.64	**5.88**	1.73	**6.13**	0.64	0.465	0.626	0.965
Q3	**4.78**	1.92	**5.56**	1.67	**4.25**	2.38	**5.88**	1.25	0.047	0.886	0.449
Q4	**5.11**	1.54	**4.67**	2.40	**3.88**	2.17	**4.50**	1.51	0.881	0.429	0.188
Q5	**1.67**	1.41	**1.33**	0.71	**1.38**	1.06	**1.25**	0.71	0.227	0.690	0.586
Q6	**2.00**	1.58	**2.11**	1.69	**2.50**	1.60	**3.00**	2.39	0.574	0.356	0.710
Q7	**3.33**	1.80	**3.67**	2.06	**3.00**	2.00	**4.25**	1.83	0.078	0.884	0.275
Q8	**1.33**	0.71	**1.33**	0.71	**1.38**	0.74	**1.25**	0.71	0.331	0.952	0.304
Q9	**4.33**	1.73	**3.67**	2.06	**3.38**	2.07	**4.00**	1.77	0.889	0.712	0.141
Q10	**1.33**	0.50	**1.67**	1.41	**2.13**	1.25	**1.38**	0.74	0.511	0.574	0.057
Time (s)	**58.44**	72.75	**36.33**	55.68	**98.38**	81.13	**36.50**	60.84	0.015	0.509	0.199
Drift (mm)	**-2.78**	31.53	**2.78**	19.06	**1.88**	23.75	**7.50**	11.02	0.415	0.605	0.996

[1] Difference between connected and unconnected

[2] Difference between the groups UC and CU

[3] Interaction between connected/unconnected and group.

Figure 1
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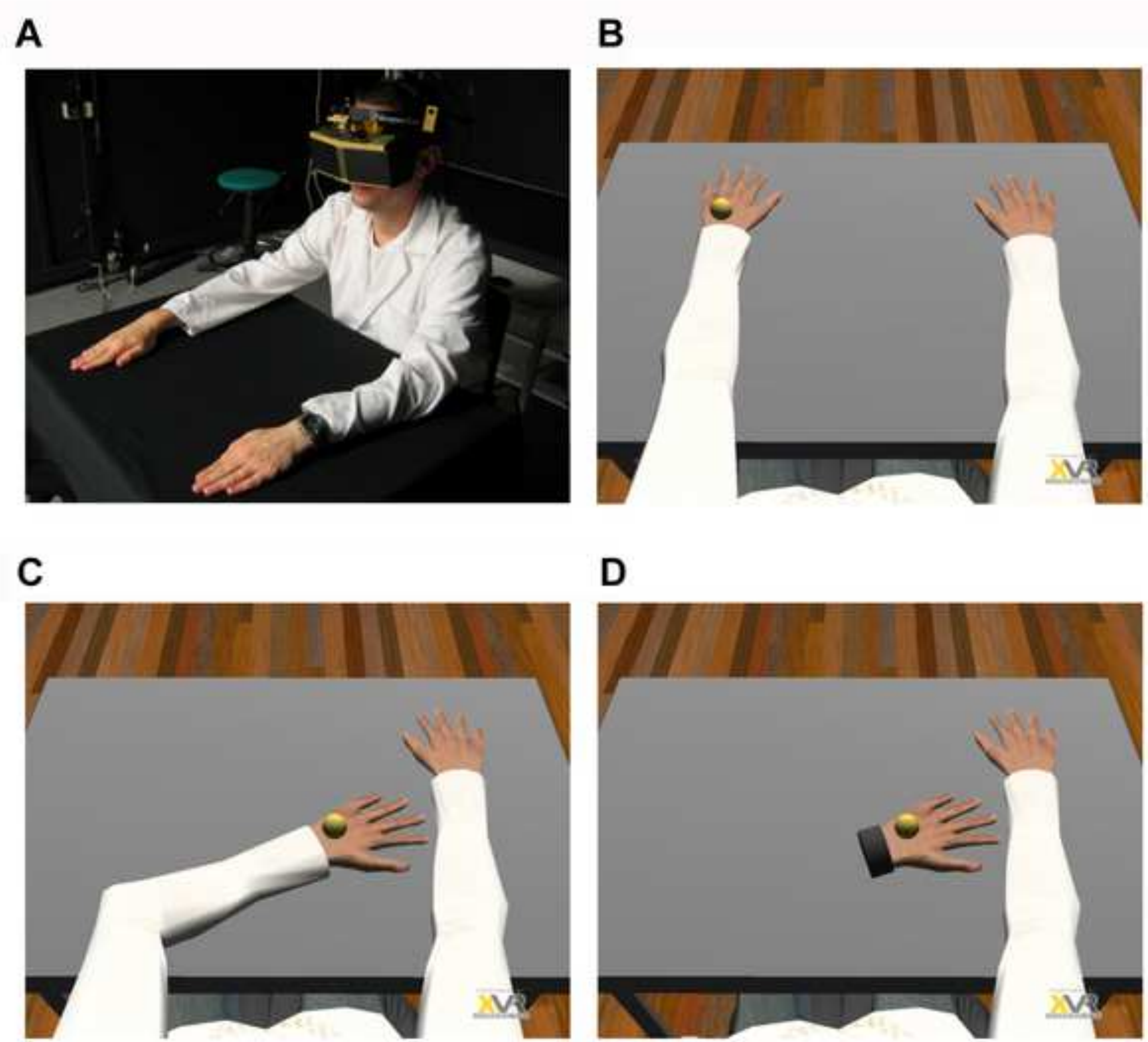

Figure 2

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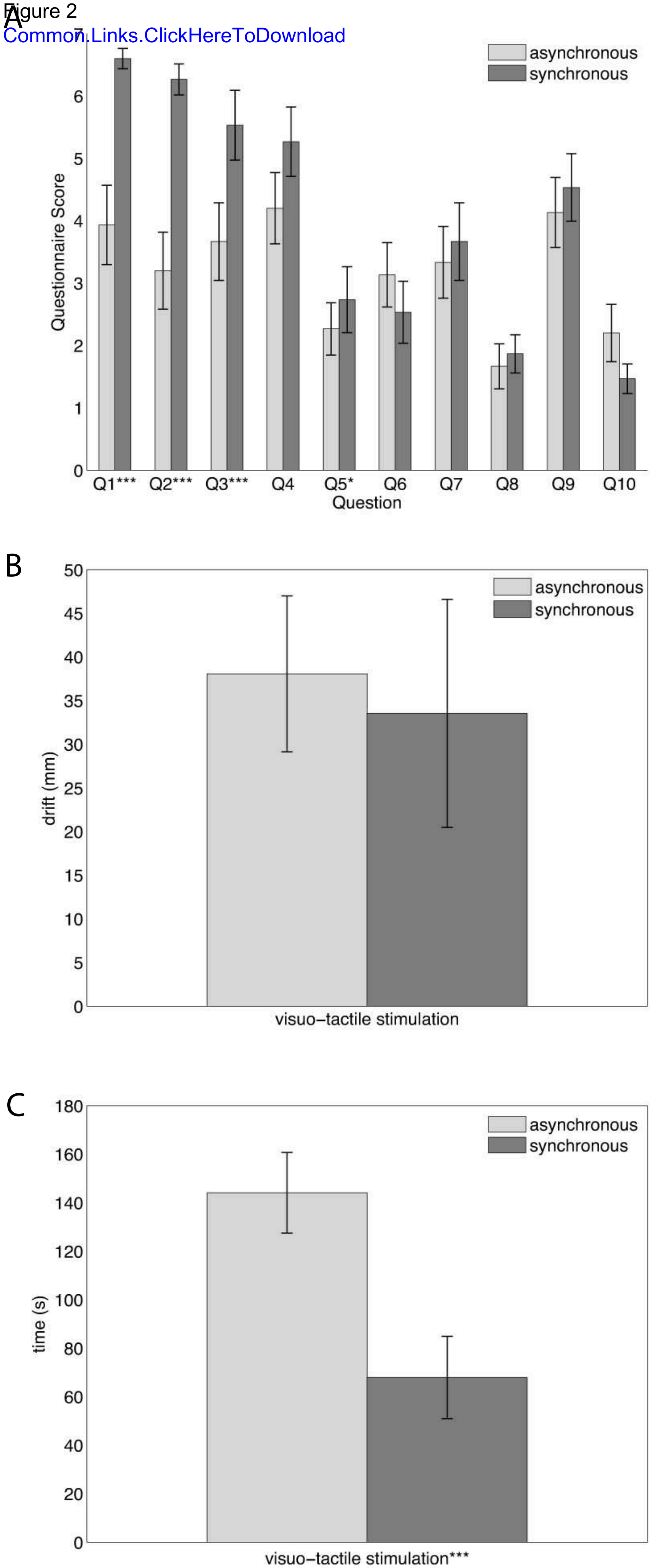
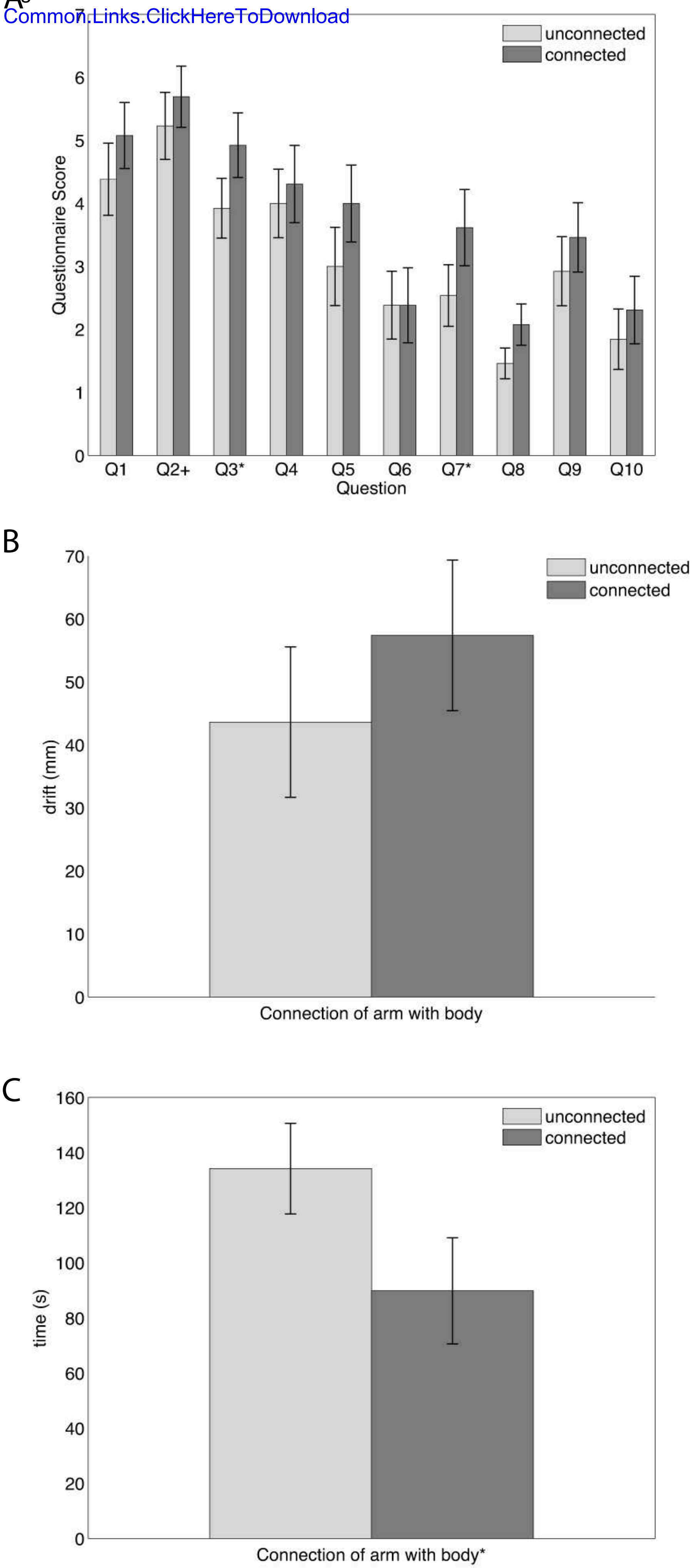


Figure 3


A
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Connection of arm with body
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Connection of arm with body*

Figure 4
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