My body until proven otherwise: Exploring the time course of the Full Body Illusion

Samantha Keenaghan[a], Lucy Bowles[a], Georgina Crawfurd[a], Simon Thurlbeck[a], Robert W. Kentridge[a,b], and Dorothy Cowie[a]

[a] Department of Psychology, University of Durham, Durham, DH1 3LE, UK

[b] Canadian Institute for Advanced Research (CIFAR) Azrieli Programme in Mind, Brain & Consciousness

Keywords: Full Body Illusion, Embodiment, Time course

Corresponding Author: samantha.keenaghan@durham.ac.uk

lucybowles06@gmail.com

crawfurdg@gmail.com

robert.kentridge@durham.ac.uk

simon.thurlbeck@durham.ac.uk

dorothy.cowie@durham.ac.uk

1. Introduction

The term ‘bodily awareness’ refers to the feeling of inhabiting a body which is separate from other objects in the environment (Bermúdez, 2005). In other words, it is the experience of being ‘embodied’ in one’s own body. This phenomenon is essential for everyday functioning as, without it, one would be unable to interact with others or the environment in a meaningful way. Despite the importance of a stable sense of bodily awareness, it is surprisingly easy to manipulate using body illusions. The most well-known case is the Rubber Hand Illusion (RHI; Botvinick & Cohen, 1998). In this illusion, a participant’s own (occluded) hand is stroked at the same time as a fake hand. The sensory conflict caused by the seen and felt touch is resolved by participants feeling as though the fake hand is their own hand, as measured by questionnaire responses and a shift in perceived location of the participant’s own hand towards the fake hand (proprioceptive drift). However, if the stroking on the two hands is asynchronous there is no conflict, and participants do not experience ownership of the fake hand. Hence, multisensory synchrony enables adults to embody external body-like objects.

More recently, researchers have extended the RHI to the Full-Body Illusion (FBI). In the same way as in the RHI, participants can embody mannequins or virtual bodies using synchronous touch (Ehrsson, 2007; Lenggenhager, Tadi, Metzinger, & Blanke, 2007). Importantly for the present study, the FBI can also be induced by synchronous movement of the participant’s own body and a virtual body. For example, Peck, Seinfeld, Aglioti, and Slater (2013) used full-body motion capture and virtual reality to provide participants with a first-person perspective of a body which moved either synchronously or asynchronously with their own movements. Participants who experienced the synchronous condition reported higher levels of ownership and agency (control) over the virtual body than those who experienced the asynchronous condition.

Interestingly, it is also possible to evoke embodiment of a body part or full body in the absence of any multisensory cues. Rohde, Di Luca, and Ernst (2011) compared proprioceptive drift in the classic RHI to a no stroking condition, in which participants passively viewed a fake hand with no tactile cues. They found no significant difference in drift between synchronous stroking and no stroking conditions after two minutes, though both conditions showed significantly higher drift than an asynchronous stroking condition. However, it should be noted that the experimenters did not measure self-reported levels of embodiment in this study, and so we cannot draw strong conclusions regarding embodiment. Carey, Crucianelli, Preston, and Fotopoulou (2019) found that participants reported ownership of a mannequin viewed from a first-person perspective to a greater extent in conditions with no additional multisensory cues than in conditions which included touch to the participant’s own body only. These results demonstrate the strength of viewing a body (part) from a first-person perspective, showing that this can be a sufficient cue to embodiment without additional multisensory cues. Indeed, in some cases viewing a body from a first-person perspective can override asynchronous multisensory input, such that participants can feel ownership of a virtual body which is touched asynchronously to their own, for example (Maselli & Slater, 2013).

Though it is widely accepted that adults can embody external bodies under the correct multisensory and visual conditions, there is not yet any consensus on the time course of these body illusions. In various versions of the RHI, visuotactile/visuomotor stimulation is usually delivered for 1-2 minutes. However, there have been very few investigations of the necessary delivery duration, and those which do exist vary widely in their results. Kalckert and Ehrsson (2017) carried out a visuomotor version of the RHI, in which a fake hand moved either synchronously or asynchronously with the participant's own hand. In addition to the classic questionnaire measures used in the RHI, participants were asked to indicate the time at which they began to feel ownership of the fake hand. The average onset time of the illusion was 23 seconds after synchronous stroking began, with 97% of participants experiencing the illusion within 60 seconds. In a visuotactile version of the RHI, Lane, Yeh, Tseng, and Chang (2017) found the average illusion onset time was over 100 seconds. In contrast, Lloyd (2007) found the average onset of touch referral to the fake hand to be 5 seconds.

According to Kalckert (2018), these drastic inconsistencies in results are likely due to methodological differences between studies. In particular, experimenters measured the onset of different aspects of the illusion; ownership (Kalckert & Ehrsson, 2017), touch referral (Lloyd, 2007), and the presence of 'an illusion' (Lane et al., 2017). Therefore, it may be that individual features of the RHI manifest at different points during the illusion. Indeed, as well as varying findings regarding onset, researchers have also found the illusion, as measured by proprioceptive drift, to increase over time (Tsakiris & Haggard, 2005). In light of these variations, measuring the time course of the RHI may not be as straightforward as asking participants to indicate its onset.

Additionally, although asking participants to freely specify the point at which they felt an illusion allows precise onset measurement, it does lend itself to subjective interpretation. Indeed, the very act of asking participants to indicate when they begin to feel an aspect of the illusion likely biases participants towards expecting the illusion to occur. To avoid potential bias when measuring the time course of body illusions, it may be useful to manipulate the length of time for which participants experience the illusion-inducing situation and compare the strength of different aspects of the illusion across durations (as in the present study). Although this method does not allow the experimenter to pinpoint the exact moment of illusion onset, it offers a potentially less confounded technique for assessing how body illusions develop over time.

Though the number of studies which have investigated the onset of the RHI are few, to our knowledge there have so far been no investigations of the onset of the FBI. These two types of illusion may seem very similar, but they are likely caused by different mechanisms. Evidence from the RHI provides valuable information about the embodiment of individual body parts, which may be useful in the design of prosthetic limbs, for example. However, it has been argued that evidence from the FBI is more informative of the nature of global self-consciousness, as our very sense of self is situated in our body (Blanke & Metzinger, 2009). As such, the FBI could be considered more complex, as it not only influences one's sense of limb ownership, but can also effect implicit beliefs about the self (see for example, Banakou, Groten, & Slater, 2013). Additionally, during the FBI participants receive information about a whole body, including all four limbs. Assimilating this information may take longer than processing simple information from the RHI, potentially increasing its time course. Alternatively, the nature of the FBI may make it a faster process than the RHI. Specifically, in the virtual FBI, there is a direct overlap between the position of the participant's own body and the position of the virtual body in space, unlike in the traditional RHI where there is an offset between the participant's hand and the fake hand. The lack of conflict between felt and seen self-location in this version of the FBI may in fact decrease its time course compared to the RHI. In either case, measuring the FBI over time may help us to further understand any differences between embodiment of body parts and of full bodies.

It is also necessary to investigate the course of the FBI over time for practical reasons. As the applications of virtual reality widen, from medicine (Levin, Weiss, & Keshner, 2015), to therapy (Carl et al., 2019), to reducing implicit social biases (Peck et al., 2013), it is increasingly important to investigate user experiences of virtual bodies. Findings from this study will inform procedures for future experiments as well as advising those who design applications of virtual reality as to the length of time it may take users to experience presence in their virtual environments.

Here, for the first time, we measured the time course of the FBI. We used virtual reality and full-body motion capture to provide participants with a moving virtual body which was viewed from a first-person perspective. To allow us to compare the time course of the embodiment illusion with a non-illusion control condition, participants experienced synchronous, asynchronous, or no movement conditions for durations of either 5 seconds, 30 seconds, or 55 seconds. They were subsequently asked to rate their feelings of ownership and agency over the virtual body. Ownership and agency are two related though separable elements of body illusions, which are thought to play a key role in the overall sensation of embodiment (Kalckert & Ehrsson, 2012; Kilteni, Groten, & Slater, 2012). We also asked participants to rate agreement of two control statements so that we could be confident that any effects were specific to embodiment. In addition to examining differences in embodiment ratings between conditions, we were interested in identifying conditions which resulted in particularly high or low levels of ownership and/or agency (defined as ratings which were significantly above or below the midpoint of the questionnaire rating scale).

Previous findings suggest that embodiment illusions take time to develop (Kalckert & Ehrsson, 2017; Lane et al., 2017; Tsakiris & Haggard, 2005), therefore, we hypothesised that embodiment would be low after 5 seconds in all visuomotor synchrony conditions. We predicted that embodiment would increase with longer exposure to the body in the synchronous and no movement conditions as both have previously shown to induce the FBI (Carey et al., 2019; Peck et al., 2013). We predicted that ratings of embodiment would remain low for all durations of asynchronous movement.

2. Materials and methods

2.1. Participants

Power analyses were carried out using G*Power. Based on a predicted medium effect size of f=.5 and a desired power of .8, the total required sample size was calculated to be 30. Participants were 34 (25 female) undergraduate students at Durham University, aged 18-39 years (M=20.8 years, SD=3.7 years). All participants had normal or corrected-to-normal vision, and had no motor impairments. All participants gave informed consent to take part in the study. The project had ethical approval from Durham Psychology Department Ethics Committee. Three participants' data were excluded due to technical issues with motion tracking, leaving 31 participants' data for analysis.

2.2. Apparatus

Testing sessions were carried out in a 5m x 9m lab at Durham University Psychology Department. The lab is fitted with 16 Vicon Bonita cameras (Vicon, Oxford UK). This system uses infrared to track small, reflective markers in real time at 240 Hz, with millimetre accuracy. Movement of body parts was tracked using 'clusters' of reflective markers attached to the arms, legs and trunk using Velcro straps. Participants viewed the virtual environment (which was designed to look like a garden tea party) through an Oculus Rift head-mounted display (HMD) (Oculus, Menlo Park, CA, USA). The HMD was also fitted with a cluster of reflective markers so that participants' head movements could be mapped onto movements of the virtual head. Virtual bodies were created in MakeHuman (a free modelling software used to create 3D human avatars; www.makehumancommunity.org). We used Vicon Pegasus software to map the marker clusters on to the corresponding limbs of the virtual body in order to match the participant's posture (Fig 1). The virtual environment was created and implemented using Unity (Unity Technologies, San Francisco, CA, USA).

Figure 1. a) A participant wearing the motion capture clusters and b) the corresponding virtual body.

2.3. Design

Visuomotor synchrony (synchronous, asynchronous, no movement) was manipulated within-subjects and was counter-balanced to avoid order effects. Piloting had indicated that the order of synchrony condition did not affect embodiment ratings (i.e. there was no carry-over from the synchronous condition to the asynchronous condition). Exposure time had three conditions (5s, 30s, 55s) and was manipulated between-subjects. Five seconds was chosen as, according to our observations, it is the shortest amount of time that a participant could move all four limbs in sequence. Thirty seconds and 55 seconds were chosen so that all exposure times were at equal intervals within one minute, within which the vast majority of participants experience the moving hand illusion (Kalckert & Ehrsson, 2017). Overall, each participant experienced three synchrony conditions for one of three exposure time conditions. Eleven participants experienced each synchrony condition for 5s, 10 for 30s, and 10 for 55s.

Embodiment was measured using self-report. In the virtual environment in which they had just experience the virtual body, participants were shown a large blackboard displaying one of four statements (shown in Table 1). The four statements were presented in succession. Participants indicated their agreement with a statement on a continuous scale, using a marker which they could move with their hand. The response scale ranged from 'NO' (0% agreement) to 'YES' (100% agreement). Statements were also simultaneously read aloud by the experimenter. The next statement was presented after the participant had made a response. The order of presentation was randomised for each participant.

Table 1. Questionnaire statements and categories.

Statement	Category
At the tea party, I felt as if the virtual body I saw was my own body or belonged to me.	Embodiment (Ownership)
At the tea party, I felt like I was controlling the movements of the virtual body.	Embodiment (Agency)
At the tea party, I felt like I had a tail.	Control
At the tea party, I felt like my hair was turning blue.	Control

2.4. Procedure

Participants were fitted with reflective motion-tracking markers on their limbs and trunk, and a HMD. Their height was measured to the nearest centimetre so that their virtual avatar matched their own body size as closely as possible. Before entering the virtual environment, participants were taught a series of movements in which they sequentially raised and lowered each limb (i.e. left arm raised and lowered, right arm raised and lowered, left leg raised and lowered, right leg raised and lowered). A pre-recording of participants carrying out these movements these movements lasting roughly 60s was taken, for use in the asynchronous visuomotor condition.

Participants then entered the virtual environment. The environment was an outdoor garden party scene, with a mirror located in front of the participant. Therefore, participants could see a gender-matched virtual body from both a first-person perspective and in the mirror reflection. In both the synchronous and asynchronous visuomotor conditions, participants were asked to perform the same movements they were taught at the beginning of the experiment. Tracking was done by the highly accurate Vicon Tracker motion capture system operating at 240 Hz, and movement was mapped to the avatar's movements via gold standard Vicon Pegasus software. In the synchronous condition, therefore, the virtual body's movements were driven by the participant's live movements with no perceivable lag. In the asynchronous condition, the pre-recording of the participant's earlier movements drove the avatar's movements so that the participant had no control over the movements of the avatar. Indeed, to ensure that there was no question that the movements in this condition were seen as being driven by the participant's current actions, the recording was played from halfway through so that, as the participant moved their arms, they could usually see the avatar moving its legs (although, again, there was no causal relationship between the two). In the no movement condition, participants were asked to stand still with their arms slightly extended in front of them, and to look towards the floor so that they had a partial view of the body from a first-person perspective and in the mirror. Although participants were asked to stand as still as possible, any tiny movements they made were still reflected in the avatar. Once they had experienced the scene for their specified exposure time (5s, 30s, or 55s) they completed the embodiment questionnaire detailed in section 2.3. and then the experiment automatically moved on to the next visuomotor condition (for the same exposure time). This procedure was repeated three times so every subject experienced each visuomotor synchrony condition. Participants were then debriefed and awarded course credits for their participation. The full procedure took roughly 30 minutes per participant.

3. Results

We carried out all analyses using IBM SPSS 22 or JASP. Bayes factor (BF_{10}) is reported for all parametric tests, indicating the likelihood of H_1 compared to H_0. In accordance with Kass and Raftery (1995), BF_{10} of 3.2 or lower is considered extremely weak evidence against H_0, whilst BF_{10} of 10 or above is considered strong evidence against H_0.

Firstly, for the purpose of this study we wished to be able to distinguish conditions in which ratings indicated 'high' or 'low' levels of embodiment as opposed to those with middling embodiment levels. We operationalised 'high' and 'low' ratings as those which were significantly higher or lower than 50% respectively, as tested by one-sample t-test (it is worth noting that this method of categorisation is rather conservative, as arguably any rating above zero indicates some level of embodiment). Mean ratings which significantly differed from 50% are indicated in Table 2. Notably, ownership ratings were consistently middling – never significantly higher or lower than 50% after synchronous (5s: $t(10)=1.20$, $p=.258$, $BF_{10}=.534$; 30s: $t(9)=1.44$, $p=.183$, $BF_{10}=.693$; 55s: $t(9)=1.77$, $p=.111$, $BF_{10}=.979$) or no movement (5s: $t(10)=1.40$, $p=.191$, $BF_{10}=.648$; 30s: $t(9)=.32$, $p=.760$, $BF_{10}=.322$; 55s: $t(9)=1.57$, $p=.151$, $BF_{10}=.789$) conditions. Agency ratings were always significantly higher than 50% after synchronous (5s: $t(10)=11.26$, $p=<.001$, $BF_{10}=28253.927$; 30s: $t(9)=14.47$, $p=<.001$, $BF_{10}=79283.742$; 55s: $t(9)=17.88$, $p=<.001$, $BF_{10}=404120.494$) and no movement (5s: $t(10)=7.47$, $p=<.001$, $BF_{10}=1093.041$; 30s: $t(9)=7.06$, $p=<.001$, $BF_{10}=448.6$; 55s: $t(9)=7.59$, $p=<.001$, $BF_{10}=726.289$) conditions. After 5s exposure to asynchronous movement, neither ownership ($t(10)=-.26$, $p=.801$, $BF_{10}=.648$) nor agency ($t(10)=1.0$, $p=.343$, $BF_{10}=.448$) ratings were significantly different to 50%. These scores were significantly lower than 50% after 30s (ownership: $t(9)=-2.37$, $p=.042$, $BF_{10}=2.016$; agency: $t(9)=-4.06$, $p=.003$, $BF_{10}=17.262$) and 55s (ownership: $t(9)=-3.73$, $p=.005$, $BF_{10}=11.421$; agency: $t(9)=-7.04$, $p<.001$, $BF_{10}=441.305$) of asynchronous movement.

We then investigated the effects of exposure time and visuomotor synchrony on embodiment using a mixed ANOVA with between-subjects factor: exposure time (5s, 30s, 55s), and within-subjects factors: synchrony (synchronous, asynchronous, no movement), and statement (ownership, agency, hair, tail). Statement was included as a factor to assess any differences between ownership and agency between conditions. Interactions were examined by carrying out follow-up ANOVAs. For any analyses in which the assumption of sphericity was violated, a Greenhouse-Geisser correction was applied to the corresponding F-test. We conducted additional analysis of our data to check for further deviations from the assumptions of ANOVA. The residuals could be considered borderline in terms of normality. This is unlikely to have affected the conclusions we drew from the analyses (Keppel, 1991). Nevertheless, we ran complementary non-parametric tests, which returned results entirely consistent with the findings of our initial parametric analyses. Means and standard deviations are presented in Table 2, and a visual summary of results is shown in Figure 2.

Table 2. Means and standard deviations for each condition. + indicates values significantly higher than 50%. − indicated values significantly lower than 50%.

Exposure time	VM synchrony	Ownership		Agency		Hair (Control)		Tail (Control)	
		M	SD	M	SD	M	SD	M	SD
5s	Sync	59.6	26.6	89.9^{+}	11.8	10.9^{-}	24.9	11.5^{-}	23.1
	Async	47.6	30.3	59.5	31.8	10.0^{-}	21.5	11.9^{-}	28.3
	No movement	62.3	29.0	80.7^{+}	13.6	14.4^{-}	29.5	7.9^{-}	18.5
	Overall	**56.5**	**28.5**	**76.7**	**24.2**	**11.8^{-}**	**24.8**	**10.5^{-}**	**23.0**
30s	Sync	64.8	32.4	94.9^{+}	9.8	2.5^{-}	7.9	0.0^{-}	0.0
	Async	31.1^{-}	25.2	19.2^{-}	24.0	0.6^{-}	1.1	2.5^{-}	5.3
	No movement	53.0	30.1	84.2^{+}	15.3	11.1^{-}	31.3	0.0^{-}	0.0
	Overall	**49.6**	**31.7**	**66.1**	**37.9**	**4.7^{-}**	**18.6**	**0.8^{-}**	**3.2**
55s	Sync	64.6	26.1	95.0^{+}	8.0	3.9^{-}	8.8	2.9^{-}	5.1
	Async	19.9^{-}	25.5	19.7^{-}	13.6	5.4^{-}	9.5	6.8^{-}	21.5
	No movement	62.8	25.8	84.2^{+}	14.3	6.2^{-}	13.1	10.6^{-}	26.2
	Overall	**49.1**	**32.6**	**66.3**	**35.8**	**5.2^{-}**	**10.3**	**6.8^{-}**	**19.4**

The four statements were rated significantly differently ($F(1.61,45.03)=123.43$, $p<.001$, $\eta_p^2=.815$, $BF_{10}=3.876e+61$). Mean ratings of the two control statements were not significantly different from each other ($p=1.0$, $BF_{10}=.141$), but were significantly lower than mean ratings of both embodiment statements (Hair lower than Ownership: $p<.001$, $BF_{10}=1.753e+16$, and Agency: $p<.001$, $BF_{10}=1.062e+25$; Tail lower than Ownership: $p<.001$, $BF_{10}=2.739e+18$, and Agency: $p<.001$, $BF_{10}=5.421e+25$). Overall the mean agency rating was significantly higher than the mean ownership rating ($p<.001$, $BF_{10}=173946.167$).

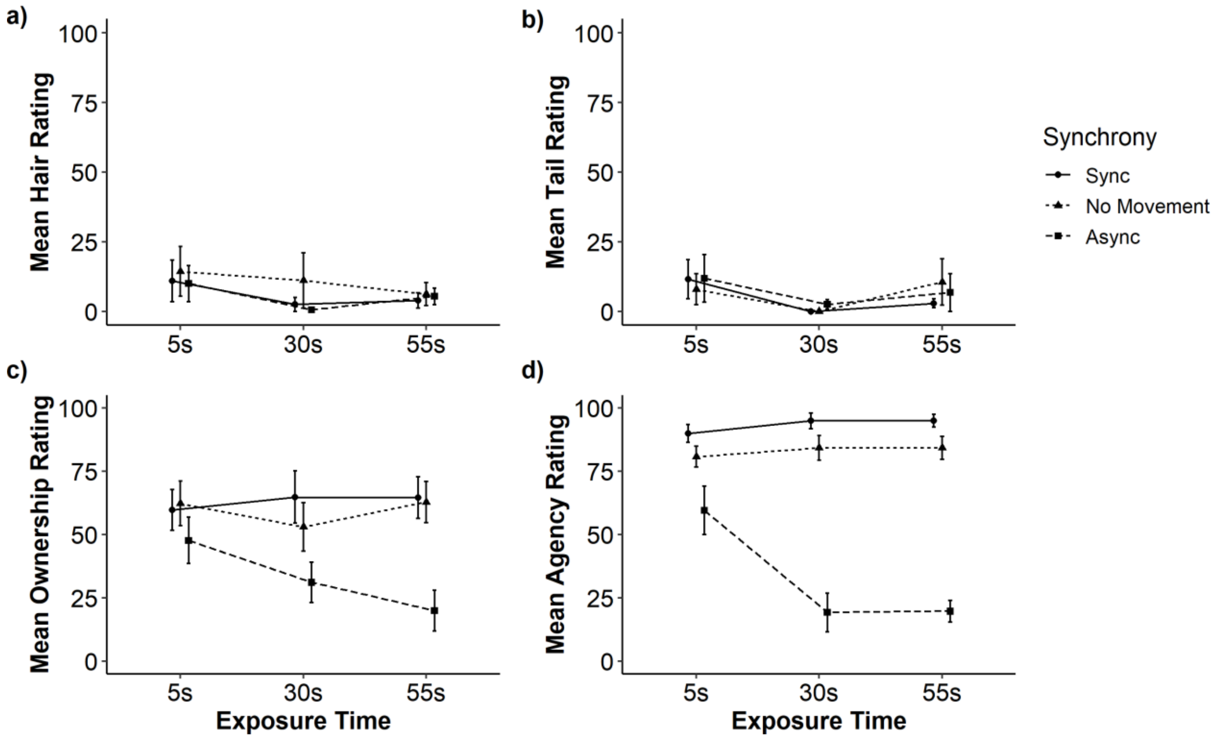

Figure 2. Mean ratings of control (a and b), ownership (c), and agency (d) statements for each synchrony and exposure time condition. Error bars represent standard error.

Synchrony significantly affected ratings (F(1.63,45.68)=72.01, p<.001, η_p^2=.720, BF_{10}=8784.677). While there was no significant difference between the synchronous and no movement conditions (p=.774, BF_{10}=.178), the mean rating in the asynchronous condition was significantly lower than both (Synchronous: p<.001, BF_{10}=8.564e+7; No Movement: p<.001, BF_{10}=1.466e+7). The significant two-way interaction of statement and synchrony (F(4.14,115.87)=33.50, p<.001, η_p^2=.545, BF_{10}=6.921e+89) showed that this pattern of lower ratings in the asynchronous condition was found for the two embodiment statements only (Ownership: F(2,92)=10.27, p<.001, η^2=.186, BF_{10}=120237.733; Agency: F(2,92)=75.77, p<.001, η^2=.627, BF_{10}=8.769e+17), but not the two control statements (Hair: F(2,92)=.70, p=.502, η^2=.015, BF_{10}=.297; Tail: F(2,92)=.11, p=.892, η^2=.003, BF_{10}=.147).

Exposure time did not produce a main effect (F(1,28)=2.17, p=.133, η_p^2=.134, BF_{10}=.125), but there was a significant three-way interaction between synchrony, statement, and exposure time. Statement and exposure time did not interact in either the synchronous (F(3.56,49.86)=.73, p=.623, η_p^2=.050, BF_{10}=.019) or no movement conditions (F(4.03,56.43)=.39, p=.816, η_p^2=.027, BF_{10}=.011), but rather in the asynchronous condition (F(3.71,51.92)=2.68, p=.045, η_p^2=.161, BF_{10}=1.674e+8). Here, there was no effect of exposure time for either control statement (Hair: F(2,30)=1.20, p=.318, η^2=.079, BF_{10}=.449; Tail: F(2,30)=.53, p=.597, η^2=.036, BF_{10}=.293; Figs 2a-b), and only a weak trend for the ownership statement (F(2,30)=2.77, p=.080, η^2=.165, BF_{10}=1.189; Fig 2c). However, there was a significant effect of exposure time on mean agency ratings in the asynchronous condition (F(2,30)=9.41, p=.001, η^2=.402, BF_{10}=45.477; Fig 2d), where ratings were higher in the 5s condition than in the 30s (p=.002, BF_{10}=9.902) or 55s (p=.003, BF_{10}=20.136) conditions.

We then carried out Kruskal Wallis tests to further examine the effect of exposure time on ownership and agency ratings for each synchrony condition. Due to the lack of clear guidelines for calculation Bayes factors from non-parametric tests, we cannot report Bayes factors here. These analyses confirmed that ratings did not differ with exposure time in either the synchronous (ownership: H(2)=.41, p=.815; agency: H(2)=1.28, p=.528) or no movement conditions (ownership: H(2)=.91, p=.634; agency: H(2)=.42, p=.812). In the asynchronous condition, ownership ratings showed a weak trend towards decreasing with increased exposure time (H(2)=5.40, p=.067). Agency ratings showed a highly significant decrease with increased exposure time (H(2)=10.13, p=.006).

In summary, we found that feelings of agency of a virtual body were rated highly after both synchronous and no movement conditions regardless of exposure time. After asynchronous movement, participants rated their feelings of agency of the body as middling after 5 seconds, but these ratings decreased significantly with increased exposure to the asynchronously-moving body. This pattern could be seen to a lesser extent for ownership ratings, which were also lower than agency ratings overall. Possible reasons for this difference between the two embodiment ratings are discussed in the following section.

4. Discussion

In the present study, we investigated the role of visuomotor synchrony on embodiment over time. We compared the time course of the full-body illusion (FBI) when participants were presented with a virtual body which moved synchronously or asynchronously with their own movements, or did not move at all. With regards to visuomotor synchrony, we replicated previous findings that synchronous and no movement induce embodiment to a greater extent than asynchronous movement (Carey et al., 2019;

Kokkinara & Slater, 2014; Peck et al., 2013). It could be argued that embodiment ratings were high in the 'no movement' condition as participants may have experienced some visuomotor synchrony. Despite being instructed to remain as still as possible, any small movements made by participants would have been reflected in the movements of the virtual body. Though any such movements would be much smaller than those made in the synchronous condition, it is possible that they could have induced a similar sense of agency and ownership of the virtual body. However, such movements were seldom observed by the experimenters. Plus, even in the presence of small movements in the no movement condition, the extent of body movement still differed greatly between synchronous and no movement conditions. Therefore it is still notable that participants rated their feelings of embodiment similarly in these conditions, despite the differing movement experiences. Additionally, as our results replicate previous findings from 'pure' no movement conditions (Carey et al., 2019), we can be reasonably confident in our interpretation. Despite this, future work should aim to eliminate the possibility of small amounts of synchronous movements, perhaps by freezing the view of the body which the participant views through the HMD.

Interestingly, even in the synchronous condition, ownership ratings were not particularly high (around 60%), in comparison to agency ratings (around 90%). This may be the result of participants reporting their believed – i.e. cognitively mediated – levels of ownership, as opposed to their felt levels. Previous findings suggest that participants rate their feelings of ownership of a fake hand as higher than their believed ownership, as adults of course consciously know that a fake hand does not belong to them (Tamè, Linkenauger, & Longo, 2018). Though the questionnaire statements in the present study were worded to relate to participants' feelings, future studies may wish to give more explicit instructions to participants regarding such rating scales. Alternatively, it may be the case that participant's ratings *did* reflect their felt levels of ownership of the virtual body, which were in fact not as high as their felt agency. One possible reason for these relatively low ownership ratings is that participants could see the virtual body's face in the mirror in front of them. As, in most cases, the virtual face did not resemble the participant's own face any further than being gender-matched, and did not move with participants' changes in expression etc., the presence of the visible face may have negatively affected participants' feelings of ownership. Certain previous studies in which participants view a virtual face in a mirror also show middling ownership ratings (Banakou et al., 2013; Slater, Spanlang, Sanchez-Vives, & Blanke, 2010). There may be reason, therefore, to further investigate whether viewing the face of a virtual body can reduce feelings of ownership over it.

Contrary to our predictions, we also found that participants experienced middling-to-high levels of agency over the avatar after 5 seconds regardless of visuomotor synchrony. Agency ratings remained high with increased exposure to the body (30 second and 55 seconds) in the synchronous and no movement conditions, but decreased dramatically in the asynchronous condition. There was weaker evidence of this pattern for ownership ratings, where it did not reach significance. This may be due to the overall lower ratings given for the ownership statement, which have already been discussed. Overall, these findings directly oppose our hypotheses. Based on previous findings, we had predicted that embodiment would be low after a short exposure to a virtual body, and would increase in the synchronous and no movement conditions.

Particularly striking is our finding that reported agency was middling-to-high after 5 seconds of exposure to the virtual body, regardless of visuomotor synchrony. For the most part, this is in contrast to previous work. Lloyd (2007) did suggest that participants experienced touch referral on a rubber hand after 5 seconds of synchronous stroking, however they did not compare this to an asynchronous stroking condition. Additionally, though touch referral is one key aspect of the Rubber Hand Illusion (RHI), its onset cannot necessarily be generalised to the onset of illusory ownership or agency. When Kalckert and Ehrsson (2017) asked participants to indicate the onset of ownership of a rubber hand, they found the average onset to be after 23 seconds of synchronous movement. Again, this was not compared to an asynchronous movement condition. Of course, the methods used in previous studies differed to the ones that we employed. Whilst other researchers asked participants to indicate the exact point at which they began to feel part of the illusion, we asked participants to rate embodiment levels on a 0-100 scale after pre-determined 'doses' of visuomotor experience. Measuring the onset of an illusion is an 'all or nothing' method, as participants must decide between not feeling the illusion at all and feeling it entirely. Allowing participants to rate their experience on a scale may have allowed us to pick up on evidence of embodiment earlier than in previous studies. Future work could confirm whether this is the case by asking participants to identify the onset of the FBI as in previous work on the onset of the RHI. It may be that this method would produce findings comparable to previous work. Alternatively, there may be something specific about full bodies which elicits embodiment more quickly than body parts.

Indeed, whilst all previous work to our knowledge has focused on the onset of the Rubber Hand Illusion (RHI), we were particularly interested in the time course of the FBI. It is plausible that the embodiment of a single body part may follow a different time course than the embodiment of a full body. Previous studies in which participants were asked to indicate the onset of the illusion work under the assumption that body illusions start from zero and build to feelings of embodiment with additional information. That is, the default state of participants is to not embody an external object until the evidence builds to suggest that it should be embodied. This may be true in the case of individual body parts, at least for subjective ratings of their embodiment. The contrary has been suggested regarding proprioceptive drift, where it seems that synchronous stroking does not enhance the drift, but rather that extended asynchronous stroking reduces it (Rohde et al., 2011; see also Makin, Holmes, & Ehrsson, 2008). However, our results lend support to the idea that at least some level of embodiment may be the default for full bodies, which can be broken by asynchronous movement.

Blanke and Metzinger (2009) refer to the idea of 'minimal phenomenal selfhood' (MPS), which is made up of the minimum conditions necessary to experience a global self-consciousness or sense of self. In this view, embodiment of a full body may be different to that of a single limb not just in terms of size, but in its philosophical implications for our sense of self. For example, embodying virtual avatars of different races reduces participants' implicit racial bias (Farmer, Tajadura-Jiménez, & Tsakiris, 2012; Peck et al., 2013), and embodying a virtual child body led participants to self-identify with child-like attributes more quickly (Banakou et al., 2013). Therefore, MPS is a different and more global phenomenon to embodying individual body parts. Blanke and Metzinger argue that a visual first-person perspective, self-localisation, and self-identification are necessary for a sense of MPS, all of which were available to participants in the present study in even the shortest exposure time under asynchronous visuomotor conditions. Indeed, holding a first-person perspective of a body is a unique experience reserved only for one's own body under normal circumstances, making it a particularly salient cue to body ownership (de Vignemont, 2018). This may explain why participants can embody a virtual body seen from this perspective, even in the presence of some asynchronous multisensory feedback (Maselli & Slater, 2013). Due to the presence of this factor, MPS may have been instantly induced in this study.

Interestingly, agency is not thought to be a necessary condition for MPS, as a sense of agency involves *consciously* directing attention towards the body whilst MPS is subconscious. When the body is the object of direct attention, MPS develops into what Blanke and Metzinger refer to as a "strong first-person perspective", or a more conscious form of bodily awareness. We argue that in the 5-second exposure time condition, participants experienced some level of MPS in all visuomotor synchrony conditions. Their whole-body movements may have activated a global motor representation which were not affected by local visuomotor synchrony. In other words, "I feel myself making full body movements, and see a body making full body movements. Therefore, I am controlling the movements of the body I see". Though local aspects of motor representations would have been mismatched, 5 seconds may not have been a sufficient amount of time to detect this and draw explicit attention to it. However, after 30 seconds and longer, participants may have developed a strong first-person perspective of the virtual body, wherein they consciously attended to the local aspects of the virtual body's movements, as well as the global aspects. This may explain why, in conditions longer than 5 seconds, participants' embodiment (particularly agency) ratings of the asynchronously moving virtual body decreased significantly.

A potential limitation of the present study, is that we did not control for the frequency of body movements during the different exposure times. Therefore, as the length of time spent in the virtual body increased, so did the number of limb movements made by participants. From this, we cannot definitively separate the effect of exposure duration from the effect of number of limb movements on perceived embodiment. Future investigations of the time course of the FBI may wish to control for these factors in order to pinpoint the exact factors which influence changes in embodiment over time. Related to this point, in this study we did not record tracking data of participants' movements across synchrony conditions. Therefore it is impossible to know whether participants moved differently in terms of speed, for example, between synchronous and asynchronous movement conditions. If participants did indeed move more slowly in the asynchronous condition, it could be argued that this reduced movement drove the effect of synchrony on embodiment ratings. In future it may be useful to record tracking data of participants' movements during the experiment.

The findings of this study have provided valuable insight into MPS and provided evidence in support of the idea that this global self-consciousness may differ from local embodiment of individual body parts. In particular, full-body illusions may induce MPS immediately, whereas single body part illusions may take more time to develop. Our findings could also have practical applications in virtual reality and particularly virtual body design. We have shown that adult participants are able to embody a virtual avatar seen from a first-person perspective despite experiencing short doses of asynchronous movement. Therefore, in virtual body exposure lasting only a few seconds, avatar movements may not have to be completely in synchrony with the user's movements. Arguably, this first-person perspective may be a key factor in embodiment such that users could embody forms other than human as long as there is a first-person perspective. Future work should aim to identify the limits of the power of first-person perspective in embodiment of virtual bodies.

5. Conclusions

In this study, we aimed to understand the time course of the Full Body Illusion. We found that participants rated ownership and agency of a virtual body as middling-to-high after 5 seconds of exposure, regardless of visuomotor synchrony. Visuomotor synchrony affected embodiment ratings differently over time. In particular, agency ratings remained high after 30 and 55s of synchronous or no movement, but decreased after the same duration of asynchronous movement. We take this to show that minimal phenomenal selfhood can be immediately induced when viewing a full body from a first-person perspective, even when that body is moving asynchronously to one's own. Further deliberate attention towards the body for longer durations may then lead to embodiment in synchronous/no movement conditions alone. These results have both theoretical implications and practical applications in virtual reality design and user experience.

Acknowledgements

This work was supported by an Economic and Social Research Council-funded studentship awarded to SK. RWK is supported by fellowship of the Canadian Institute for Advanced Research (CIFAR) Azrieli Program in Mind, Brain, and Consciousness. The authors declare that they had no conflicts of interest with respect to their authorship or the publication of this article.

References

Banakou, D., Groten, R., & Slater, M. (2013). Illusory ownership of a virtual child body causes overestimation of object sizes and implicit attitude changes. *Proceedings of the National Academy of Sciences*, *110*(31), 12846–12851. https://doi.org/10.1073/pnas.1306779110

Bermúdez, J. L. (2005). The phenomenology of bodily awareness. In D. Woodruff Smith & A. L. Thomasson (Eds.), *Phenomenology and Philosophy of Mind* (pp. 295–316). New York: Oxford University Press.

Blanke, O., & Metzinger, T. (2009). Full-body illusions and minimal phenomenal selfhood. *Trends in Cognitive Sciences*, *13*(1), 7–13. https://doi.org/10.1016/j.tics.2008.10.003

Botvinick, M., & Cohen, J. (1998). Rubber hands “feel” the touch that eyes see. *Nature*, *391*(6669), 756.

Carey, M., Crucianelli, L., Preston, C., & Fotopoulou, A. (2019). The effect of visual capture towards subjective embodiment within the full body illusion. *Scientific Reports*, *9*, 2889. https://doi.org/10.1101/397943

Carl, E., Stein, A. T., Levihn-Coon, A., Pogue, J. R., Rothbaum, B., Emmelkamp, P., … Powers, M. B. (2019). Virtual reality exposure therapy for anxiety and related disorders: A meta-analysis of randomized controlled trials. *Journal of Anxiety Disorders*, *61*, 27–36. https://doi.org/10.1016/j.janxdis.2018.08.003

de Vignemont, F. (2018). *Mind the Body*. New York: Oxford University Press.

Ehrsson, H. H. (2007). The experimental induction of out-of-body experiences. *Science*, *317*(5841), 1048. https://doi.org/10.1126/science.1142175

Farmer, H., Tajadura-Jiménez, A., & Tsakiris, M. (2012). Beyond the colour of my skin: How skin colour affects the sense of body-ownership. *Consciousness and Cognition*, *21*(3), 1242–1256. https://doi.org/10.1016/J.CONCOG.2012.04.011

Kalckert, A. (2018). Commentary: Switching to the rubber hand. *Frontiers in Psychology*, *9*, 588. https://doi.org/10.3389/fpsyg.2018.00588

Kalckert, A., & Ehrsson, H. H. (2012). Moving a rubber hand that feels like your own: A dissociation of ownership and agency. *Frontiers in Human Neuroscience*, *6*, 40. https://doi.org/10.3389/fnhum.2012.00040

Kalckert, A., & Ehrsson, H. H. (2017). The onset time of the ownership sensation in the moving rubber hand illusion. *Frontiers in Psychology*, *8*, 344. https://doi.org/10.3389/fpsyg.2017.00344

Kass, R. E., & Raftery, A. E. (1995). Bayes factors. *Journal of the American Statistical Association*, *90*(430), 773–795.

Keppel, G. (1991). *Design and analysis: A researcher’s handbook*. New York: Prentice Hall.

Kilteni, K., Groten, R., & Slater, M. (2012). The sense of embodiment in virtual reality. *Presence*, *21*(4), 373–387.

Kokkinara, E., & Slater, M. (2014). Measuring the effects through time of the influence of visuomotor and visuotactile synchronous stimulation on a virtual body ownership illusion. *Perception*, *43*(1), 43–58. https://doi.org/10.1068/p7545

Lane, T., Yeh, S.-L., Tseng, P., & Chang, A.-Y. (2017). Timing disownership experiences in the rubber hand illusion. *Cognitive Research: Principles and Implications*, *2*(4). https://doi.org/10.1186/s41235-016-0041-4

Lenggenhager, B., Tadi, T., Metzinger, T., & Blanke, O. (2007). Video ergo sum: Manipulating bodily self-consciousness. *Science*, *317*(5841), 1096–1099. https://doi.org/10.1126/science.1144876

Levin, M. F., Weiss, P. L., & Keshner, E. A. (2015). Emergence of virtual reality as a tool for upper limb rehabilitation: Incorporation of motor control and motor learning principles. *Physical Therapy*, *95*(3), 415–425. https://doi.org/https://doi.org/10.2522/ptj.20130579

Lloyd, D. M. (2007). Spatial limits on referred touch to an alien limb may reflect boundaries of visuo-tactile peripersonal space surrounding the hand. *Brain and Cognition*, *64*(1), 104–109. https://doi.org/10.1016/J.BANDC.2006.09.013

Makin, T. R., Holmes, N. P., & Ehrsson, H. H. (2008). On the other hand: Dummy hands and peripersonal space. *Behavioural Brain Research*, *191*, 1–10. https://doi.org/10.1016/j.bbr.2008.02.041

Maselli, A., & Slater, M. (2013). The building blocks of the full body ownership illusion. *Frontiers in Human Neuroscience*, *7*(83). https://doi.org/10.3389/fnhum.2013.00083

Peck, T. C., Seinfeld, S., Aglioti, S. M., & Slater, M. (2013). Putting yourself in the skin of a black avatar reduces implicit racial bias. *Consciousness and Cognition*, *22*(3), 779–787. https://doi.org/https://doi.org/10.1016/j.concog.2013.04.016

Rohde, M., Di Luca, M., & Ernst, M. O. (2011). The rubber hand illusion: Feeling of ownership and proprioceptive drift do not go hand in hand. *PLoS ONE*, *6*(6), e21659. https://doi.org/10.1371/journal.pone.0021659

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

Tamè, L., Linkenauger, S. A., & Longo, M. R. (2018). Dissociation of feeling and belief in the rubber hand illusion. *PLOS ONE*, *13*(10), e0206367. https://doi.org/10.1371/journal.pone.0206367

Tsakiris, M., & Haggard, P. (2005). The rubber hand illusion revisited: Visuotactile integration and self-attribution. *Journal of Experimental Psychology*, *31*(1), 80–91. https://doi.org/10.1037/0096-1523.31.1.80