Investigating Bodily Awareness in Adults and Children Using Virtual Reality

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In the Full Body Illusion, adults can embody a virtual body when provided with certain cues. By manipulating variables such as the movement and appearance of a virtual body, experimenters can identify cues needed to build a stable sense of bodily awareness. Such paradigms are also used with children, to build a picture of how bodily awareness changes with development. Here, we used virtual reality and motion capture to provide participants with a first-person perspective of a virtual body to investigate bodily awareness in adults and children. In Experiment 1 we showed adults a virtual body for 5, 30, or 55 seconds, during which it moved synchronously or asynchronously with their movements, or remained static. After 5s, participants reported experiencing embodiment even when movement was asynchronous. These ratings decreased with further exposure to asynchronous movement but remained high in synchronous and no movement conditions, suggesting that adults embody an avatar seen from a first-person perspective by default. In Experiment 2, adults and children viewed bodies which were either 50% or 100% of their own body size. Both groups perceived the virtual environment to have changed size as opposed to their own body, with the exception of children perceiving their body to have grown in the ‘large’ body condition. Therefore body-relative size perception is roughly adult-like from the age of five, with slightly more tolerance to body growth. In Experiment 3, we piloted the use of skin conductance as a measure of embodiment in a group of adults, in response to a ‘child-friendly threat’. Unlike self-reported embodiment, skin conductance did not differ between visuomotor synchrony conditions. Further work is needed to apply psychophysiological measures of embodiment to children. Overall, the work described here contributes to understanding of bodily awareness across ages, as well as having practical applications in virtual reality design.

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Chapter 1
General Introduction

Bodily awareness in adults

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 ‘embodying’ an object (usually one’s own body). Though we tend to take our sense of bodily awareness for granted, the phenomenon is essential for everyday functioning. Without it, one would be unable to interact with others or the environment in a meaningful way. This can be seen in individuals with embodiment disorders, who may not be able to differentiate between their own bodies, those of other people, and objects in the environment (Blanke & Azy, 2005; Pitron & de Vignemont, 2017). Gaining insight of how individuals build a stable sense of bodily awareness is therefore an important step towards better understanding these disorders, as well as being theoretically interesting in itself. In this chapter, current knowledge regarding bodily awareness is outlined, including several important factors which are not yet well understood. These factors will be the focus of the subsequent thesis.

Despite the importance of a stable sense of bodily awareness, it is surprisingly easy to manipulate using body illusions. Using such illusions, researchers can identify the cues we use to build a sense of bodily awareness. The original and 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). Studies have even found adult participants to have a strong physiological reaction in response to a threat to the fake hand, as though their own body was being threatened (Armel & Ramachandran, 2003). 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 (in this case between vision and touch) enables adults to embody external body-like objects.

With advances in technology such as head-mounted displays, researchers have been able to extend 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). These first demonstrations of the FBI used cameras and head-mounted displays to show participants a view of their own body from behind. When visual feedback was played in synchrony with felt touch, participants reported feeling as though they were having 'out of body experiences' and were located outside of their physical body (Ehrsson, 2007). Later demonstrations presented views of mannequin bodies as though seen from a first-person perspective (e.g. Petkova, Khoshnevis, & Ehrsson, 2011). As in the RHI, participants also reported ownership of these bodies, despite them being clearly fake.

Importantly for this work, 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 whose movements were either synchronous (i.e. controlled by the participant) or asynchronous (i.e. random) compared to their own movements. Participants were then asked to rate their levels of ownership (the feeling of the seen body belonging to oneself) and agency (the feeling of being in control of the seen body). Ownership and agency are thought to be separate but related factors which contribute to an overall sense of 'embodiment', and are often measured via self-report to build up a detailed picture of bodily awareness (Kalckert & Ehrsson, 2012; Tsakiris, Prabhu, & Haggard, 2006). Participants who experienced the synchronous condition reported higher levels of both ownership and agency over the virtual body than those who experienced the asynchronous condition, demonstrating that synchronous movement is also an important cue to bodily awareness in adults. Indeed, Kokkinara and Slater (2014) directly compared the influence of visuomotor and visuotactile synchrony on embodiment, and found that participants experienced a strong embodiment illusion when visuomotor cues were synchronous, even when felt and seen touch were asynchronous. Hence, movement cues may be more important to building a stable sense of bodily awareness than touch cues.

The cues described thus far (movement and touch) are based on incoming sensory signals, and are known as 'bottom-up' cues in the literature. This is in contrast to 'top-down' cues, which are based on prior expectations which are not primarily sensory, such as body form (Tsakiris, 2010). Interestingly, it is possible to evoke embodiment of a body part or full body from vision alone, in the absence of any multisensory cues. This could suggest that, although synchronous movement is clearly an important cue to embodiment, visual perspective may be even stronger. 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 visual-tactile incongruency. These results demonstrate the strength of viewing a body 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). The fact that simply viewing a body from a certain perspective can evoke a sense of ownership demonstrates that bodily awareness can be built from a combination of both bottom-up, multisensory cues, and top-down cues of prior expectations. However, it is not clear how long it takes for various cues to take effect. Though experimenters tend to expose participants to various cues for around two minutes, there is no evidence to suggest when in this period ownership is induced, or whether this differs for different cues. A better understanding of this would provide a more complete picture of how a sense of bodily awareness is built, as well as a guide for future research into body illusions.

Since the first demonstration of the RHI, there has been a great deal of research on illusory ownership of body parts and full bodies. From this, we now know a great deal about which cues (both bottom-up and top-down) adults use to build a sense of bodily awareness. However, this is not to say that our understanding of embodiment in adults is complete. Several outstanding questions remain, including those regarding the time course of these body illusions. These issues will be further explored in Chapter 3.

The development of bodily awareness

Though there has been a great deal of research on embodiment in adults, much less is known about how bodily awareness develops throughout childhood. This is an interesting issue as, of course, children’s bodies are constantly changing and growing. Therefore, certain top-down cues on which adults can rely (e.g. some aspects of appearance) are not as reliable. It stands to reason that children would therefore rely on different cues to adults to build a sense of bodily awareness, or may at least weight them differently. Using the same embodiment illusion paradigms as used in adults, researchers can identify how the cues used to build a sense of bodily awareness change through development. The findings of this research do indeed point towards a protracted development of bodily awareness through to late childhood.

Evidence from the RHI suggests that children use vision alone as a cue to embodiment to a greater extent than adults. Specifically, they are more affected by visual capture of a rubber hand in their peripersonal space than are adults (Cowie, Makin, & Bremner, 2013; Cowie, Sterling, & Bremner, 2016). Whilst children as young as four years old showed an adult-like effect of visuotactile synchrony on embodiment of the rubber hand (i.e. reported greater levels of embodiment after synchronous than asynchronous visuotactile input), young children showed a large amount of proprioceptive drift regardless of visuotactile synchrony. This effect reduced with age and did not become adult-like until 10-11 years. This finding suggests that, on some level, young children automatically incorporate body parts placed close to their body into their self-representation, relying on vision more than proprioception (see also Filippetti & Crucianelli, 2019).

Indeed, we have also found this to be the case in the FBI (Keenaghan, Polaskova, Thurlbeck, Kentridge, & Cowie, in prep). We provided both adults and five-year-olds a first-person view of an age-matched virtual body. The body's movements were either random (asynchronous) or controlled by the participant's live movements (synchronous). When asked to rate their feelings of embodiment of the virtual body, adults indicated embodiment in the synchronous condition only, whereas five-year-olds reported feeling embodiment over the virtual body regardless of visuomotor synchrony. We therefore suggest that children rely heavily on seeing a body from a first-person perspective when building a sense of bodily awareness, placing less importance than adults on multisensory synchrony.

Previous research has shown that perspective is an important cue to embodiment for adult participants. It has been repeatedly shown that bodies seen from a first-person perspective are embodied to a greater extent than those seen from various third-person perspectives, as measured by self-report as well as physiological reactions to threat towards the seen body (Debarba et al., 2017; Petkova et al., 2011). These results are fairly intuitive as a first-person perspective is the view one generally has of one's body. Therefore, it may be that a first-person perspective is included in our top-down, prior expectations of bodies which belong to us. Indeed, as described above, a first-person perspective can be a sufficient condition for embodiment (Carey et al., 2019; Maselli & Slater, 2013), demonstrating the strength of the cue in adults.

It may be the case that perspective is even more important in early childhood. Perspective is one of the main stable cues to body ownership at this age, whilst size and appearance change rapidly, likely affecting proprioception and movement (Mowbray & Cowie, 2020). Perspective may therefore be weighed even more heavily than visuomotor synchrony during childhood, allowing children to embody avatars which they have no actual control over. This theory does offer further support to previous findings that children are affected by visual capture of a rubber hand placed congruently in their peripersonal space regardless of multisensory synchrony (Cowie et al., 2016). However, there is much more work to be done in an effort to fully understand how children's bodily awareness changes over development. More background to this issue is provided in Chapters 4 and 5.

Effects of illusory embodiment on perception

Using the various cues outlined so far, it is possible to evoke a sense of embodiment over bodies which look significantly different to one's own (e.g. in terms of age and skin colour; Banakou, Groten, & Slater, 2013; Peck et al., 2013). But embodying such bodies goes beyond skin deep, and can influence one's cognition. There is evidence to suggest that illusory embodiment of bodies which differ from one's own can affect one's view of the world. For example, embodying a dark-skinned avatar has been found to reduce implicit racial bias in light-skinned participants (Peck et al., 2013), and embodying an elderly avatar can reduce ageism (Yee & Bailenson, 2006). However, as well as altering *social* perception and implicit biases, embodiment of different bodies can also affect *visual* perception.

Previous work has demonstrated that adults are able to easily embody fake bodies and avatars which are much smaller or larger than their own bodies, in the presence of synchronous multisensory cues (Banakou et al., 2013; van der Hoort, Guterstam, & Ehrsson, 2011). Indeed, van der Hoort et al. (2011) suggest that adults' capacity for embodiment is not constrained by top-down representations of body size, and that participants are likely able to embody bodies of any size as long as they are in proportion (i.e. basic body form remains the same). This also appears to be the case in young children. We have previously found that five-year-old children embody virtual avatars of different sizes, though this was regardless of multisensory synchrony (Keenaghan et al., in prep). Both children and adults rated their feelings of embodiment over bodies 50%, 100%, and 150% of their own body size as equally strong. This was consistent with our predictions, as children naturally accept a growing and changing body in their day-to-day lives.

However, there is reason to believe that, during these illusions, adult participants do not perceive their body to be a different size, even when ‘shrunk’ to the size of a Barbie doll (van der Hoort et al., 2011). Instead, participants appear to perceive the size of the environment around them to have changed, whilst their perception of their own body size remains stable. By asking participants to estimate the sizes of objects before and after embodying small or large bodies, researchers have found that participants who embody large bodies perceive the objects as smaller than at baseline, while the opposite is true for those who embody small bodies (Banakou et al., 2013; van der Hoort et al., 2011). This suggests that perception of the environment is a result of the perceived size of one’s body, an effect termed ‘body-relative scaling’ (Linkenauger, Witt, & Proffitt, 2011). Currently, this phenomenon has been investigated by asking participants to estimate sizes of different objects in the environment. However, researchers have not measured (van der Hoort et al., 2011) or reported in detail (Banakou et al., 2013) participants’ subjective experiences of own-body and environment size during these manipulations.

We have attempted to measure whether children also show evidence of body-relative scaling when inhabiting differently sized virtual bodies (Keenaghan et al., in prep). As in previous experiments, we asked participants to estimate the size of objects before and after experiencing illusory embodiment. However, we found no difference in size estimations across body size conditions in either adults or children. This non-replication of a result found several times in adults does not allow us to draw strong conclusions regarding whether young children also experience body-relative scaling. Therefore, the question of whether children are susceptible to body-relative scaling remains unanswered, but is further addressed in Chapter 4.

Measuring embodiment in children

When investigating embodiment in young participants, it may be helpful to develop multiple methods of measuring their experiences. Though we believe that the questionnaire measures we have previously used to measure embodiment in children have accurately reflected perception (especially as they were contrasted with control questions), there is always a possibility that children may not fully understand questionnaire items or scales, or that their answers may be influenced by perceived experimenter expectations (see Lush, 2020 for a discussion of this issue even with adult participants). It would be useful, therefore, to include additional, more objective measures of embodiment in children.

To obtain objective measures of embodiment in adults, researchers have used various physiological techniques. One of the most common techniques used is to measure changes in skin conductance in response to a threat to a virtual body (e.g. Kokkinara & Slater, 2014; Petkova et al., 2011). Skin conductance responses (SCRs) are a measure of electrodermal activity which are used to identify changes in arousal associated to psychological or emotional stress, such as a perceived threat (Boucsein, 2012; Dawson, Schell, & Fillion, 2007). Researchers can 'threaten' an artificial body and record associated SCRs to compare levels of arousal across embodiment conditions. When skin conductance shows a sharp increase in response to threat, it suggests that participants perceive their own body to be threatened. For example, Petkova et al. (2011) compared embodiment of fake bodies seen from different perspectives by providing visuotactile stimulation and subsequently 'slicing' the fake body with a knife. SCRs measured in response to this threat were significantly higher in the first-person perspective condition than any third-person perspective conditions, matching the pattern self-report measures. The physiological measure (SCRs) therefore provided an objective corroboration of subjective questionnaire measures.

This corroboration would be useful when measuring embodiment in children. However, threats used are usually knives or other obviously dangerous stimuli which would be unsuitable for use with children. The development of child-friendly stimuli for measuring physiological responses to embodiment illusions would be extremely helpful. It would be particularly useful to identify stimuli which would be appropriate and effective for use with both adult and child participants, in order to compare embodiment in these groups as has been previously done with self-report measures (Cowie, McKenna, Bremner, & Aspell, 2017; Cowie et al., 2016; Keenaghan et al., in prep). These issues are further discussed in Chapter 5.

Practical implications

The work described here is theoretically important in terms of philosophical and psychological questions regarding our sense of bodily self and how this changes through development. However, the following experiments also aimed to provide useful information regarding how both adults and children react to virtual environments and bodies. As the use of virtual reality extends from entertainment alone to physical rehabilitation (Levin, Weiss, & Keshner, 2015), training (Aggarwal, Black, Hance, Darzi, & Cheshire, 2006), and therapeutic interventions (Carl et al., 2019), it is becoming increasingly important to understand how we interpret various virtual situations in order to fully exploit the benefits (and avoid the pitfalls) of this technology.

Present work

The studies described in this thesis aimed to address several outstanding questions regarding bodily awareness in adults and children. We conducted three experiments, each designed to measure distinct aspects of bodily awareness: a) time course, b) body-relative scaling, and c) measurement.

a) Time course of the FBI. Chapter 3 focuses on embodiment in adults; specifically examining the time course of the FBI. There is currently no clear evidence regarding how long participants need to be exposed to various cues to develop illusory ownership or agency of a virtual body. Therefore, this experiment aimed to compare levels of reported embodiment after varying lengths of exposure to a virtual body. From previous research demonstrating the strength of synchronous movement (Peck et al., 2013) and visual capture (Carey et al., 2019), we predicted that even short exposure to these cues would result in high levels of embodiment. As asynchronous movement rarely provokes significant embodiment, we predicted that this cue would not lead to embodiment regardless of exposure duration.

b) Body-relative scaling. As described above, there is no clear evidence regarding whether children are susceptible to body-relative scaling (Keenaghan et al., in prep). Further, there has been no direct measure of perceived body and environment size during body size illusions in participants of any age. The experiment described in Chapter 4 aimed to identify whether adults and young children perceive changes in body or environment size when inhabiting a virtual body which is smaller or larger than their own. Anecdotally, researchers have reported that adults do not perceive their body to have changed size, but rather their environment (van der Hoort et al., 2011), and so we predicted that we would find a similar pattern. As previous work has shown that young children have a strong bias towards coding space egocentrically (Negen, Heywood-Everett, Roome, & Nardini, 2017), we predicted that we would find a similar, although stronger, pattern in children.

c) Measuring embodiment Finally, Chapter 5 describes a pilot study which aimed to introduce a new measure of embodiment in children: changes in skin conductance in response to a 'threat' to the virtual body. The pilot tested a child-friendly stimulus on adults with the aim of identifying a stimulus which could be used in groups of children and adults. If this stimulus were successful, we would expect to find significantly higher SCRs in response to threat after synchronous movement than after asynchronous movement, as in previous work (e.g. Petkova et al., 2011).

Chapter 2
General Methods

Participants

In all experiments, participants were recruited from the local area. All participants had normal or corrected-to-normal vision, and no motor impairments or limb differences.

a)

b)

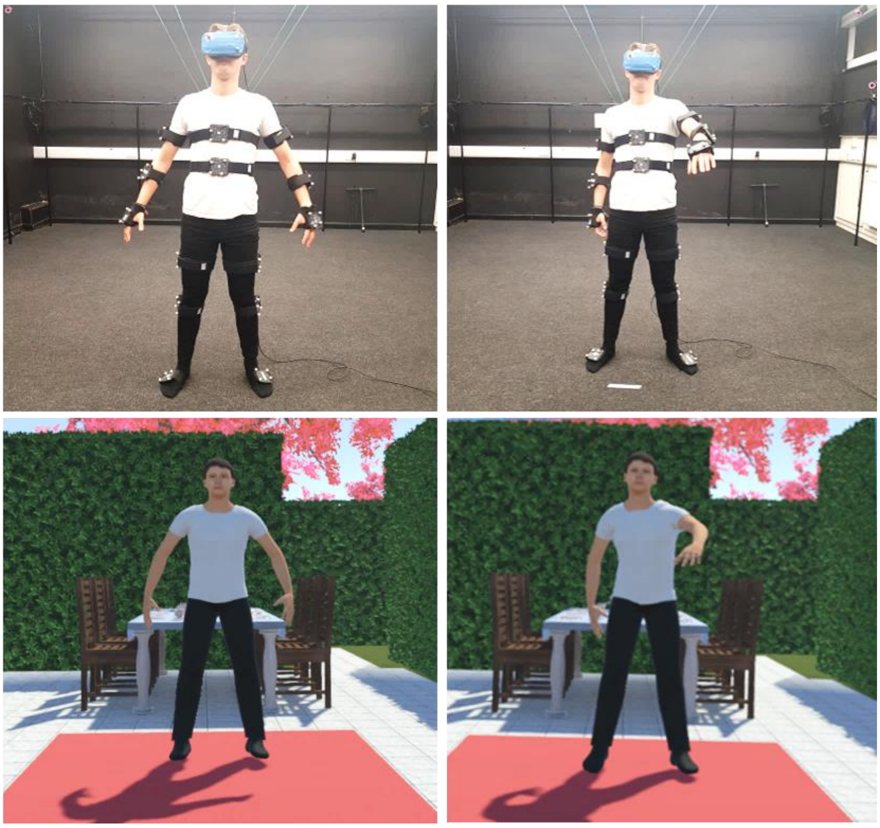

Figure 1. a) Top row: a participant wearing the motion capture clusters in different postures and b) Bottom row: the corresponding virtual body.

Apparatus

All 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 light to track small, reflective markers in real time at 240 Hz, with millimetre accuracy. In these experiments, movement of body parts was tracked using 'clusters' of reflective markers attached to the arms, legs and trunk using Velcro straps (Fig 1a). Participants viewed a virtual environment 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. Note that Figure 1 is included to demonstrate technical set-up, and is not a representation of what participants would see during the procedure.

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 onto the corresponding limbs of the virtual body in order to match the participant's posture (Fig 1b). Participants viewed the virtual body through the HMD from a first-person perspective. They were able to look down at the body as they would their own, and could often see their arms and legs in front of them as they moved. In Experiments 1 and 2 participants also viewed a reflection of the virtual body in a mirror. The virtual environment was designed by the experimenter and subsequently created by a department technician. Across all experiments the environment was designed to look like a garden surrounded by hedges, matching the dimensions of the lab. To appeal to young participants, the virtual environment contained a 'tea party', including a set table surrounded by chairs (Fig 1b). Various objects in the environment were changed by the experimenter across different experiments, as described fully in the following chapters. The virtual environment was both designed and implemented using Unity (Unity Technologies, San Francisco, CA, USA).

Procedure

At the beginning of all testing sessions participants (or parents in the case of child participants) gave informed consent to take part. Participants' height was measured to the nearest centimetre so that the virtual avatar's size closely matched the participant's (or, in Chapter 3, so that avatar size manipulations were consistent across participants). Participants were then fitted with motion-capture clusters and the HMD.

In all studies, participants were asked to give responses to a virtual questionnaire (though the items included varied between experiments). In all instances, questionnaire statements appeared on a large blackboard in the virtual environment above a scale. In the experiments described in Chapters 3 and 4, the scale was visual-analogue, displaying 'NO' on the left and 'YES' on the right. In the third experiment, the scale was presented numerically with markers from 0 (labelled 'not at all') to 10 (labelled 'lots and lots'). The blackboard was shown in an empty 'field' environment approximately two meters in front of the participant, standing at 1.2 meters tall and 1.8 meters wide. Participants were asked to move a virtual marker on the scale by moving their hand, in order to indicate their level of agreement with each statement. The programme transformed questionnaire responses to a number between 0-100. The next statement would then appear. The order in which statements appeared was randomised for each participant. The virtual body was not visible whilst participants responded to questionnaires.

At the end of the testing session, adult participants received course credit and child participants were given a small toy. All studies received ethical approval from Durham Psychology Department Ethics Committee.

Analyses

All analyses were carried out in either 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. All figures were created in R studio.

Chapter 3

Experiment 1:
Exploring the time course of the Full Body Illusion

The details of this study have been published as a journal article: Keenaghan et al. (2020). My body until proven otherwise: Exploring the time course of the full body illusion. *Consciousness and Cognition, 78,* 102882. A modified version of this article is presented below.

Introduction

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 affect 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 et al., 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.

Methods

Participants. Power analyses were carried out using G*Power. Calculations were carried out based on between-subjects and within-subjects factors as well as within-between interactions. Based on a predicted medium effect size of f=.5 and a desired power of .8, the largest total required sample size (based on the main between-subjects effect of exposure time) was calculated to be 30. Participants were 34 (25 female) undergraduate students at Durham University, aged 18-39 years (M_{age}=20.8 years, SD_{age}=3.7 years). Three participants' data were excluded due to technical issues with motion tracking, leaving 31 participants' data for analysis.

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 a virtual questionnaire. Statements are shown in Table 1.

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 (Tail)
At the tea party, I felt like my hair was turning blue.	Control (Hair)

Procedure. 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, which was designed to resemble an outdoor tea party. There was also a virtual full-length mirror situated in front of the participant so that their virtual body could be seen both in their reflection and from a first-person perspective. 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. In the synchronous condition 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, 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.

Results

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 (ownership, agency, and two controls) 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 ($p<.001$, $BF_{10}=173946.167$).

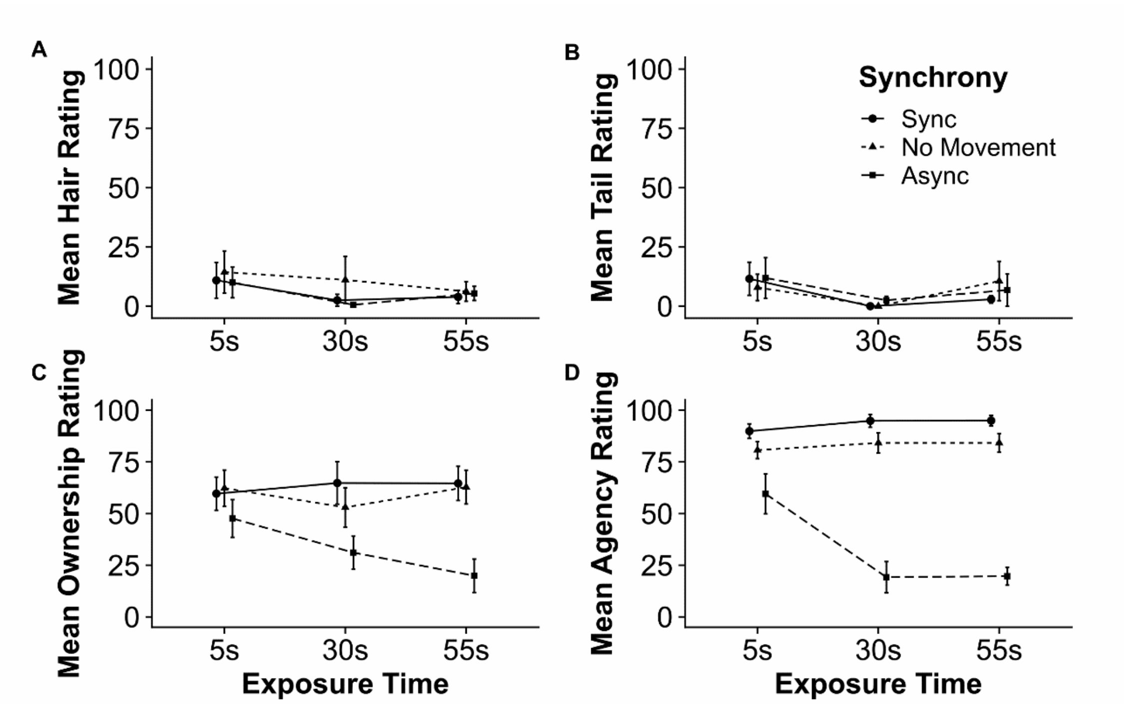

Figure 2. Mean ratings of control (a and b), ownership (c), and agency (d) statements for each synchrony and exposure time condition. Error bars represent standard error.

Participants' ratings were significantly affected by synchrony condition ($F(1.63,45.68)=72.01$, $p<.001$, $\eta_p^2=.720$, $BF_{10}=8784.677$). 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. To investigate this interaction, we ran three two-way ANOVAs of the effects of statement and exposure time on mean ratings for each synchrony condition separately. These ANOVAs were chosen so that hypotheses regarding embodiment levels over time for each synchrony condition could be properly tested.

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.

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).

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 seconds 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 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 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.

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. Differences in movement between the synchronous and asynchronous conditions may be indicative of differences in attention during the two conditions. It may be that viewing an asynchronously-moving body is more distracting for participants than the everyday experience of viewing a body which moves in synchrony with oneself. In future it may be useful to use eye-tracking in conjunction with virtual reality to determine differences in attention across conditions.

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.

Chapter 4

Experiment 2:
Size perception in the Full Body Illusion

Introduction

As previously shown, adults and children can embody virtual bodies of different sizes (Banakou, Groten, & Slater, 2013; Keenaghan, Polaskova, Thurlbeck, Kentridge, & Cowie, in prep; van der Hoort, Guterstam, & Ehrsson, 2011). When the relative size between one's body and environment changes, the observer can interpret this in one of two ways: either the environment has changed size and one's body is the same size, or the environment has stayed the same and one's body has changed. Previous investigations have found that adult participants tend towards the former. van der Hoort et al. (2011) induced illusory ownership of either very large or very small bodies using synchronous visuotactile stimulation. After this, participants inhabiting a large body perceived objects in the environment as smaller, and those inhabiting a small body judged objects to be larger. Importantly, participants anecdotally reported being unaware that the body they inhabited was a different size to their own. Instead, they felt as though they were surrounded by a differently sized world. Banakou et al. (2013), using fully-immersive virtual reality to deliver visuomotor stimulation, have replicated this finding: after synchronous experiences in a small body, their participants perceived objects to be larger than at baseline. This effect of body size on size perception has been labelled "body-relative scaling" (Linkenauger, Ramenzoni, & Proffitt, 2010). It is important to note that, despite anecdotal and indirect evidence that adults perceive their body size as constant but the environment to change size during these illusions, to our knowledge previous studies have not directly measured or reported in detail on participants' subjective perception of own-body size during these experiences.

There has been little previous investigation of how body size affects size perception in children. This question is of particular interest as children's bodies are constantly changing size, but we do not know how this affects the way they perceive the world around them. It has been consistently shown that children around 2 years of age show errors in their own perceived body size – namely 'scale errors', in which toddlers attempt to use very small objects in the same way as normal sized objects (e.g. attempting to sit on a tiny doll's chair; Brownell, Zerwas, & Ramani, 2007; DeLoache, Uttal, & Rosengren, 2004). These errors are thought to occur due to an inability to inhibit automatic actions associated with the sight of certain objects. Beyond infancy, we have shown that 5-year-olds can embody avatars of different sizes (Keenaghan et al., in prep), though we did not find any solid evidence of body-relative scaling in this age group through implicit measures. Previously we predicted that young children's size perceptions would be affected by perceived body size to an even greater extent than those of adults as they tend to encode their environment egocentrically (Negen et al., 2017). Further investigation is required to test this hypothesis thoroughly.

The present study was designed to directly address whether changes in body size lead to changes in the perceived size of the environment, or of the body itself, in both adults and children. Based on previous work (van der Hoort et al., 2011), we predicted that adults would perceive changes in their virtual body size as changes to the size of the environment – such that the environment would seem smaller after inhabiting a large body and vice versa – and would not perceive their body size to have changed. Due to the tendency of young children to code external space with an egocentric bias (Negen et al., 2017), we predicted that children would also report the environment to have changed size in accordance to body-relative scaling, as opposed to changes in their own body size, and this may be to an even greater extent than in adults. We used fully-immersive virtual reality to manipulate the size of a virtual body in a group of five-year-olds and adults. Five-year-olds were chosen as we have previously found them to respond well to full-body motion capture and virtual reality (Keenaghan et al., in prep). The effect of body size on size perception was assessed using a four-item questionnaire probing subjective perception of body and environment sizes.

Method

Participants. Power analyses were carried out using G*Power. Calculations were carried out based on between-subjects and within-subjects factors as well as within-between interactions. Based on a predicted medium effect size of f=.5 and a desired power of .8, the largest total required sample size (based on the main between-subjects effect of body size) was calculated to be 24. Participants were 12 undergraduate students (M_{age} = 19.9 years, SD_{age} = 1.3 years, 10 female) and 12 five-year-old children (M_{age} = 5.4 years, SD_{age} = 0.3 years, 2 female).

Design. Virtual body size had two levels (small, large; operationalised as 50% and 150% of participant's body height respectively) and was manipulated within-subjects. The order in which body size conditions were presented was counter-balanced to avoid order effects. Age also had two levels: adults and children (5-year-olds). Subjective size estimations were measured using a virtual questionnaire, as described in Chapter 2.

This experiment was designed as a direct follow-up to our previous work which demonstrated that adults and children embody synchronously-moving bodies of different sizes (Keenaghan et al., in prep). Embodiment was therefore not manipulated here. Rather, the experiment described here aimed to explicitly address the question of how inhabiting a smaller/larger virtual body affects size perception.

Procedure. Before participants entered the virtual environment, they were taught a well-known, standardised set of full-body movements which therefore placed minimal demands on attention and memory (the children's dance 'the hokey cokey'), which they would carry out whilst inhabiting a virtual body. They then entered the virtual environment. In each body size condition participants performed the movements taught to them by the experimenter, which lasted approximately two minutes. After this phase, participants were shown a large blackboard which sequentially showed one of four statements in a random order (statements are shown in Table 3). Participants rated their agreement with each statement as outlined in Chapter 2. These steps were then repeated for the second body size condition.

Table 3. Size questionnaire statements.

Statement	**Category**
When I was at the tea party it felt as though the body I saw was smaller than my own body	Body smaller
When I was at the tea party it felt as though the body I saw was bigger than my own body	Body bigger
When I was at the tea party it felt as though objects around me were smaller than normal	Objects smaller
When I was at the tea party it felt as though objects around me were bigger than normal	Objects bigger

Results

Ratings were examined for each statement separately using four mixed ANOVAs, with each having within-subjects factor body size (small, large) and between-subjects factor age (adult, child). Mean ratings for each question are shown in Figure 3**.**

For the ‘body smaller’ question, there was no effect of body size (F(1,22)=.08, p=.787, η_p^2=.003, BF_{10}=.30) or age (F(1,22)=.55, p=.464, η_p^2=.025, BF_{10}=.41) on agreement ratings, and no interaction (F(1, 22)=.09, p=.767, η_p^2=.004, BF_{10}=.05).

‘Body bigger’ agreement ratings were significantly affected by body size (F(1,22)=9.55, p=.005, η_p^2=.303, BF_{10}=7.79) with ratings higher in the large body condition than the small body condition. Ratings were not significantly affected by age (F(1,22)=1.88, p=.184, η_p^2=.079, BF_{10}=.60), but there was a significant interaction of body size and age (F(1,22)=7.36, p=.013, η_p^2=.251, BF_{10}=30.07). Paired t-tests reveal that children rated ‘body bigger’ higher in the large body condition than the small body condition (t(11)=3.73, p=.003, BF_{10}=14.72), whereas adults did not (t(11)=.30, p=.770, BF_{10}=.30).

‘Object smaller’ ratings were significantly higher in the large body condition than the small body condition (F(1,22)=23.29, p<.001, η_p^2=.514, BF_{10}=2194.41), but were not significantly affected by age (F(1,22)=1.19, p=.287, η_p^2=.051, BF_{10}=.44). There was no significant interaction of body size and age for this question according to the p-value, though Bayes factor indicated some evidence of an interaction (F(1,22)=1.54, p=.228, η_p^2=.065, BF_{10}=809.23). Investigating this further, adults’ ratings were significantly higher in the large body condition than the small body condition (p<.001, BF_{10}=136.50), whereas this difference was marginal for children (p=.052, BF_{10}=1.61).

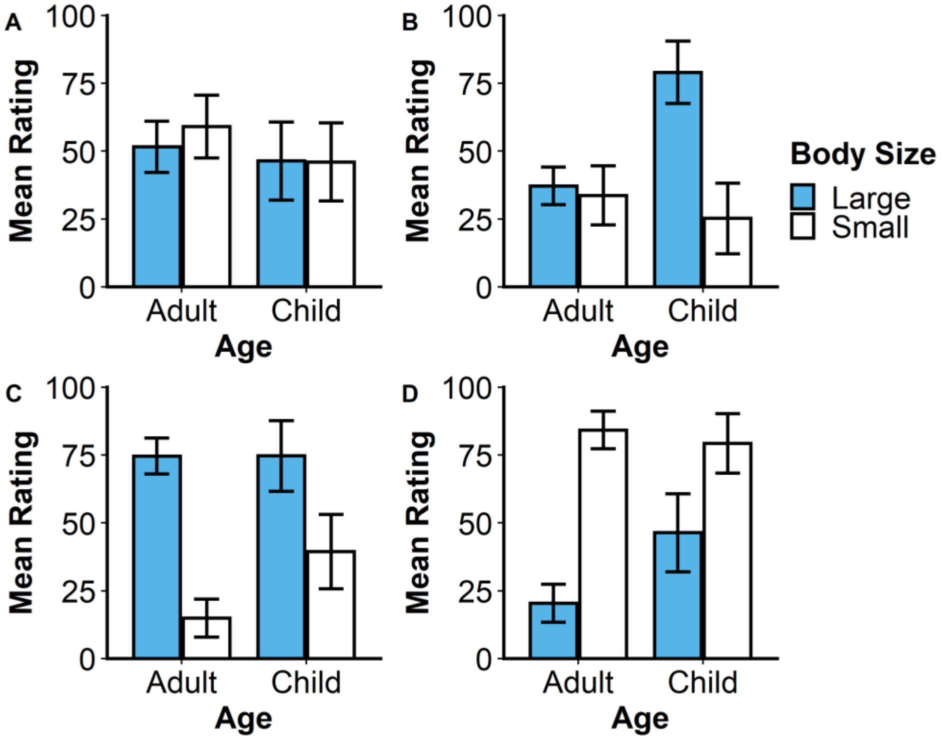

Figure 3. Mean ratings for a) 'Body smaller'; b) 'Body larger'; c) 'Object smaller'; d) 'Object larger'

Finally, 'object bigger' agreement ratings were also significantly affected by body size (F(1,22)=20.17, p<.001, η_p^2=.478, BF_{10}=1976.56), with ratings higher in the small body condition than the large body condition. There was no significant effect of age on this question (F(1,22)=1.14, p=.297, η_p^2=.049, BF_{10}=.42). Again, although the p-value indicated that there was no significant interaction, Bayes factor suggested otherwise (F(1,22)=2.05, p=.166, η_p^2=.085, BF_{10}=850.59). Again, adults rated this question higher in the small body condition, and the difference was marginal in children (p=.095, BF_{10}=1.03).

Discussion

In this study we aimed to better understand the perceptual experience of participants when inhabiting a virtual body that was a different size to their own. Specifically, do adults and children perceive their body to have changed size, or rather their environment? We therefore provided a group of adults and five-year-olds with a body smaller or larger than their own. After a period of embodiment, we asked participants to report the perceived size of the body they saw as well as the virtual environment. We found that in the small body condition, neither adults nor children reported a change in perceived body size – rather, both reported that the environment appeared larger (though this effect was somewhat weaker in children than in adults). However, in the large body condition, adults did not report a change in perceived body size, whereas children did report perceiving their body as larger. Both age groups also reported that the environment seemed smaller than usual (though again, this was slightly more apparent in adults than children).

These results support previous findings on size perception based on implicit measures (i.e. size estimation) in adults (Banakou et al., 2013; Linkenauger et al., 2010; van der Hoort et al., 2011). In these previous experiments, adults were asked to estimate the size of objects in the environment, either by holding out their hands or by verbally estimations. Objects were perceived to be smaller after inhabiting a larger body than usual, and vice versa. To our knowledge, however, this is the first study to have explicitly asked participants about their perception of size during such an illusion. Therefore, we show that body-relative scaling can be thought of consciously and explicitly measured.

Importantly, this was also the first study to have examined the effect of body size on size perception in children. This question was of theoretical interest as, of course, children's bodies are continuously changing size, as opposed to adult bodies whose sizes stay mostly constant. This could feasibly mean that children would not use their body size as a reference for the size of their environment due its lack of reliability. However, we did not find this to be the case. The five-year-old group responded in much the same manner as the adults, suggesting that they do in fact use body size as a cue to size perception in the environment. However, notably, in the large body condition children did report their body to have grown where adults did not. We suggest that this could be due to young children being more 'tuned-in' to their body growth, as this is something they must account for as they develop, therefore they may be more likely than adults to notice such a change. Further work should test a broader age range in order to confirm whether this effect does diminish as body growth slows. This finding was also complemented by the fact that neither adults nor children reported their body to have shrunk in the small body condition. Participants may be less sensitive to changes in body size in this direction as it does not normally occur naturally during the lifespan.

It is worth noting that, for some analyses, reported p-values and Bayes' Factors were somewhat contradictory. Specifically, for both questions concerning the size of the environment (as opposed to the virtual body), p-values indicated that ratings were not significantly affected by an interaction between age and body size, however Bayes' Factors were extremely large, indicating evidence of a significant interaction. It is difficult to know how to interpret such seemingly contradictory statistics. From examining the raw data, it may be the case that the effect of body size on the perceived size of the environment may be slightly greater in adults than in children. This could be driven by a valid psychological difference, or merely children's slightly noisier response patterns. In either case, it would likely be useful to repeat this experiment with a larger sample size to thoroughly examine whether this effect is comparable in adults and young children.

Our previous findings have demonstrated that around two minutes of synchronous movement allows both adults and five-year-old children to embody a body larger or smaller than their own (Keenaghan et al., in prep). We were therefore confident that, on the whole, participants embodied their virtual avatars and therefore findings regarding size perception were related to the experience of inhabiting a differently-sized body. However, it could be argued that embodiment should be manipulated (in this case, through the use of an additional asynchronous movement condition) so that differences in size perception could be compared between the experimental condition and a control condition. Indeed, the lack of such a condition in the present study could be considered a limitation. It would be useful for further investigations of body-relative scaling to make this comparison to be able to explicitly link changes in size perception to embodying a small or large virtual avatar rather than any other factors which may have influenced our findings.

Overall, we have found evidence that both five-year-olds and adults are susceptible to body-relative scaling, whereby their perception of the size of their environment is affected by the size of the avatar which they control. These findings alone add a great deal to our theoretical understanding of the development of size perception, though they also provide the starting-point for many avenues of further investigation. Practically, we have also confirmed once again that full-body motion tracking and immersive virtual reality can be used successfully in young children. Such technology is being widely used in adults to investigate social interactions (e.g. Peck et al., 2013), and may be useful in physical rehabilitation (Levin et al., 2015). Based on the present findings, it is plausible that these important areas could be applied with children as young as five years old.

Chapter 5

Experiment 3:
Psychophysiology in the Full Body Illusion: A pilot study

Introduction

In the vast majority of studies on bodily awareness using body illusions, embodiment levels are measured using self-report questionnaires which ask participants to rate their feelings of ownership and agency over a fake body (or body part) during the illusion. This method does offer a valuable insight into participants' subjective feelings of embodiment. However, as with all self-report measures, there are limitations to using questionnaires when measuring bodily awareness. For example, participants may be consciously or subconsciously influenced by their beliefs about the aim of the experiment and may answer accordingly (Lush, 2020).

Due to these limitations, researchers often combine self-reports with psychophysiological measures for more objective quantifications of stimulus intensity and autonomic arousal. Skin conductance responses (SCRs) are part of the electrodermal activity (EDA) complex, and are frequently used to identify changes in arousal that are associated with psychological or emotional stress, such as perceived threat (Boucsein, 2012; Dawson et al., 2007). SCRs are typically taken by attaching two electrodes to the body (usually the fingers) and measuring the skin's changes in electrical properties between them. This activity can fluctuate depending on the amount of physiological change occurring within the body, i.e. due to changes in levels of sweat gland secretion on the skin, which is driven by activity in the sympathetic branch of the autonomic nervous system.

In the context of bodily awareness research, skin conductance is usually measured in response to a 'threat' towards the fake body, such as being hit or cut (Ehrsson, 2007; Petkova et al., 2011). The logic is that, if a participant really does feel the fake body (or body part) to be their own (e.g. under synchronous multisensory conditions), their arousal levels (as measured by skin conductance) will show a heightened response to the threat compared to when they have not embodied the fake body. The main advantages of SCR measures are that they are inexpensive, non-invasive and, crucially, can be measured without the individual's awareness or control. Therefore, it provides an objective measure of emotional arousal to threat and consequently, the degree of perceived embodiment for the fake body part being threatened

(Boucsein, 2012). It has also been argued that use of affective measures such as SCR are more informative of true ‘embodiment’ (de Vignemont, 2010). Though ‘tools’ (such as spoons and rakes) can be incorporated into one’s body schema when used extensively (see, for example Witt, Proffitt, & Epstein, 2005), it is the affective response one has when a fake body part is threatened that sets the two phenomena apart.

SCRs in response to threats have been repeatedly used as an index of embodiment for adults, with results often reflecting those from questionnaire measures. For example, Armel and Ramachandran (2003) exposed participants to either synchronous or asynchronous stroking of their own (hidden) hand and a fake hand, then bent back a finger of the fake hand and measured SCR. Participants’ SCRs were significantly higher after the synchronous condition than after the asynchronous condition, a pattern which was also found in self-reported feelings of embodiment. Extending this paradigm to the FBI, Ehrsson (2007) found that participants showed significantly higher SCRs to a hammer threat to a fake body after experiencing synchronous stroking compared to when the stroking was asynchronous. Extending these findings, SCRs have demonstrated that participants embody bodies seen from a first-person perspective to a greater extent than those seen from third-person perspectives (Petkova et al., 2011), and that bodies which maintain a typical form are embodied to a greater extent than those with altered forms, such as with arrows in place of hands (Yuan & Steed, 2010). Hence, SCR is a useful tool in objectively measuring embodiment, and is a helpful method of supporting subjective self-reports.

Previous studies have explored embodiment and SCRs toward a threat in adult participants only, whereas studies with children have used questionnaires and proprioceptive drift (Cowie et al., 2017; Cowie et al., 2016; Keenaghan et al., in prep). Using psychophysiological measures of embodiment and emotional arousal in children, particularly young children, would be extremely beneficial, perhaps even more so than in adults. Whilst experimenters can attempt to ensure that young children understand what is being asked of them by giving them lots of practice and asking control questions, there is a higher chance that children could misunderstand questionnaire items or scales than adults, and they are likely more prone to answer in accordance with what they think the experimenter wants to hear. As mentioned previously, participants cannot control their SCRs, and so this would be an ideal measure to corroborate young participants’ self-reports.

Previously, we have found that five-year-old children reported similarly high levels of embodiment over a virtual body, regardless of whether its movements were synchronous or asynchronous with their own (Keenaghan et al., in prep). The children who participated in this study were trained on the response scale of the self-report measure until the experimenter was satisfied that they understood the task sufficiently, and their responses to control questions compared to embodiment questions did indicate that their responses did vary depending on the question asked. Therefore, we interpreted our findings to mean that young children embody a body seen from a first-person perspective regardless of movement cues. However, due to the subjective nature of self-report, there remains a possibility that children's responses were biased by other factors. Repeating this study with the addition of psychophysiological measures would help to either support our previous finding, or to suggest alternative explanations.

The main hurdle in using SCR measures in children is that previous research has often analysed SCRs toward negative threat behaviours delivered to a fake body (or body part). Whilst such measures are valid and suitable for adult participants (Braithwaite, Watson, & Dewe, 2020), they would be entirely inappropriate to use with children. It is therefore necessary to identify 'threats' to a virtual body which can be used safely with young participants yet are potent enough to elicit changes in emotional arousal. Of course, in many developmental studies of this kind, measures are compared between children and adults. In this case, it would be necessary to identify a threat which is not only suitable for children but is also sufficient to prompt a reaction in adults. Because of this, it would be necessary for a potential stimulus to be piloted in a group of adults, as well as children.

Therefore, the aim of this study was to test a 'threat', which could potentially be used with children, on a group of adult participants. We designed a threat which we believed matched these criteria: a cloud of virtual red dots which moved through the virtual body. This stimulus was chosen as, although it is not explicitly threatening, the idea of an object passing through one's body would be unsettling. We recorded changes in SCRs to the presentation of this threat after participants experienced a period of movement in VR. In this movement period, participants saw the virtual body move either synchronously or asynchronously with their own, or the virtual body was replaced with a static, prism-shaped object. We compared participants' responses to threat across these three conditions. If the threat worked properly, we would replicate results from previous studies with adults; SCRs would be higher in the synchronous condition than either the asynchronous or object conditions. The object condition was particularly important for when the experiment progressed to be applied to children, as it would help us to identify whether children embodied any object seen from a first-person perspective, or whether the object had to have a body-like form. We also measured self-reported levels of embodiment after each condition to identify whether self-reports matched differences in SCRs.

The stimulus was first piloted in a group of adults as the aim was to eventually use the same stimulus to compare responses between adult and child participants. It was therefore necessary to confirm that our designed threat was salient enough to provoke the predicted response pattern in adult participants (based on previous findings) before trialling the stimulus with children. Based on previous findings, we predicted that both SCRs and questionnaire ratings would be higher in the synchronous movement condition than either the asynchronous movement or object conditions, and that the latter two conditions would not significantly differ from each other. If we found this to be the case, we could be confident that our stimulus worked as expected, and could therefore move on to applying the paradigm with children.

Method

Participants. Participants were 23 adults (10 male) recruited from Durham University Psychology Department. As this was a pilot study, participant ages were not recorded. Approximately, participants ranged in age from 19 to 60 years, with most participants being undergraduate students.

Design. Body type (synchronous, asynchronous, object) was manipulated within subjects and counter-balanced to avoid order effects. In the synchronous condition, the virtual body's movements were driven by those of the participant. In the asynchronous condition, the virtual body's movements did not match those of the participant, but were instead driven by an earlier recording of the participant's movements. In the object condition, participants viewed a static, blue translucent prism (labelled as "the glass box" to participants) in place of the virtual body. To measure emotional arousal and embodiment levels, we recorded SCRs to the mild threat approaching the virtual body/object after each movement condition, and asked participants to complete an embodiment questionnaire after each condition.

Apparatus. Apparatus was the same as described in Chapter 2, with the addition of SCR equipment. Skin conductance measures were acquired using a Biopac MP150 data-acquisition unit. The unit was connected to a Dell Latitude E5550 laptop (4GB RAM, 500GB memory) with Intel Core i5-5200U Dual Core processor and integrated Intel HD Graphics

5500. The data-acquisition rate was 2000 samples per second. Signals were recorded via Ag-AgCL pre-gelled 1cm disposable electrodes (EL507) attached to the distal phalanges of the index and middle fingers on the left hand. These electrodes were connected to the data-acquisition unit via EDA sensor leads. Data were analysed using Biopac's AcqKnowledge software. Here, phasic fluctuations that crossed a threshold of 0.03µs (microsiemens) from the background signal were recorded in each movement condition to calculate event-related SCRs to observed threats.

Procedure. Participants sat on a chair in front of a wooden box (30cm height x 120cm length x 30cm width) with three coloured circles attached to the top. The distance between the chair and box was adjusted for each participant so that they could comfortably reach the box with their feet. Participants were told that the coloured circles were buttons, which they would be asked to push with their feet in a random order specified by the experimenter. They then practiced pressing the buttons for approximately one minute, whilst the experimenter took a recording of their movements for use in the asynchronous condition.

Participants then put on the HMD and SCR recording began. The virtual environment was an outdoor garden scene, which included the participant's chair and a box with buttons, which closely resembled the real box in appearance and position. Participants were asked to sit still for one minute to ensure sensors had acclimatized; electrodermal activity was recorded during this minute as a baseline SCR measure. After the baseline recording was complete, participants were asked to press the coloured buttons on the box with their feet. Whilst pressing the buttons, participants experienced one of three body-type conditions – synchronous, asynchronous, or object – from a first-person perspective. In the synchronous condition, participants viewed a virtual body whose movements were driven by their own. In the asynchronous conditions, participants viewed a virtual body whose movements were controlled by an earlier pre-recording and so were not controlled by the participant's live movements. In the object condition, participants viewed a 'glass box' in placed of a virtual body, which did not move at all.

After approximately one minute of movement (pressing the coloured buttons), participants were asked to sit still. They then viewed a 'cloud' of red virtual orbs emerge from a virtual hedge approximately 4 metres in front of them. The cloud slowly floated towards and then through the virtual body, and was designed to act as a mild threat. The 'threat' period lasted seven seconds. The onset of baseline, movement, and threat periods were manually indicated by the experimenter on the SCR signal to help with later interpretation.

After the threat had passed, participants were ‘transported’ to a new virtual environment. This was another outdoor scene with a blackboard, which displayed one of four questionnaire statements (shown in Table 4), and a scale from 0-10. On the scale was a yellow marker, which participants could move up and down with their hand to rate their agreement with each statement, from 0 (not at all) to 10 (lots and lots). After the participant had rated each statement, the next question was shown on the blackboard in a randomised order for each participant.

Table 4. Questionnaire statements and categories.

Statement	**Category**
While I was pressing the buttons, I felt as if the virtual body/glass box I saw was my own body or belonged to me.	Embodiment (Ownership)
While I was pressing the buttons, I felt like I was controlling the movements of the virtual body/glass box.	Embodiment (Agency)
While I was pressing the buttons, I felt like I had a tail.	Control (Tail)
While I was pressing the buttons, I felt like my hair was turning blue.	Control (Hair)

Once all four statements had been rated, participants completed the next body type condition until all three conditions had been completed.

Results

Embodiment questionnaire. Questionnaire data were available for 17/23 participants. We examined the effect of body type on agreement ratings using a repeated measures ANOVA with within-subjects factors of body type (synchronous, asynchronous, object) and statement (hair, tail, ownership, agency). Statement was included as a factor in order to assess differences between different aspects of embodiment.

Agreement ratings differed significantly across body type conditions ($F(2,20)=97.11$, $p<.001$, $\eta_p^2=.86$, $BF_{10}=1.37e+11$), and were significantly higher in the synchronous condition than either the asynchronous ($p<.001$, $BF_{10}=899{,}914.26$) or block conditions ($p<.001$, $BF_{10}=2.34e+6$). Ratings did not differ significantly between asynchronous and block conditions ($p=1.0$, $BF_{10}=.13$).

Statement also had a significant effect on agreement ratings (*F*(3,48)=77.32, *p*<.001, η_p^2=.83, BF_{10}=4.319e+9). Whilst ratings of control questions did not significantly differ from each other (*p*=1.0, BF_{10}=.19), they were significantly lower than both embodiment questions (*p*s<.001, BF_{10}>2757.07).

Finally, body type significantly interacted with statement (*F*(6,96)=54.0, *p*<.001, η_p^2=.77, BF_{10}=5.964e+58), such that ratings for control questions did not differ across body type conditions (hair: *F*(2,32)=.45, *p*=.64, η_p^2=.03, BF_{10}=.22; tail: *F*(2,32)=.25, *p*=.78, η_p^2=.02, BF_{10}=.18) but ratings of embodiment questions did (ownership: *F*(2,32)=23.77, *p*<.001, η_p^2=.60, BF_{10}=840,455.27; agency: *F*(2,32)=167.48, *p*<.001, η_p^2=.91, BF_{10}=2.89e+20). Participants rated feelings of ownership and agency as higher after synchronous movement than asynchronous movement (ownership: *t*(16)=4.69, *p*<.001, *d*=1.14, BF_{10}=128.86; agency: *t*(16)=167.48, *p*<.001, *d*=3.97, BF_{10}=3.755e+8) or the object condition (ownership: *t*(16)=5.62, *p*<.001, *d*=1.36, BF_{10}=666.53; agency: t(16)=16.46, *p*<.001, *d*=3.99, BF_{10}=4.045e+8; Figure 4).

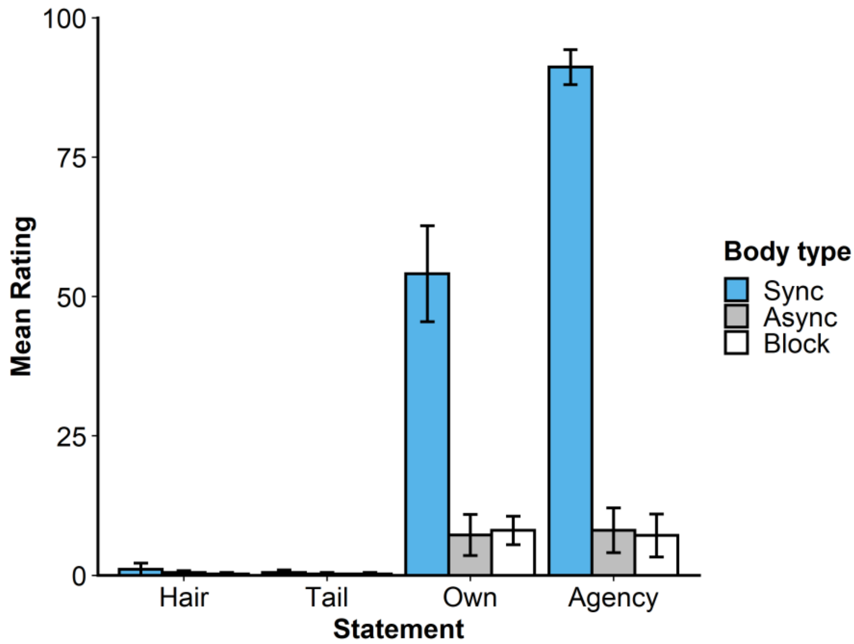

Figure 4. Mean ratings of control (hair, tail) and embodiment (ownership, agency) statements for each body type condition (synchronous, asynchronous, block). Error bars represent standard error.

SCR data. SCR data were available for 16/23 participants (12 of whom also had questionnaire data available), which was a lower sample size than desired. Analysis was conducted in Biopac's AcqKnowledge software following recommended guidelines (Braithwaite, Watson, Jones, & Rowe, 2013) and procedure as described in Brathwaite, Watson, and Dewe (2017). Signal data were initially assessed visually. If present, artefacts were removed by applying a baseline smoothing algorithm which down-sampled the signal in steps of 200 samples per second. A custom 'Find Cycles' routine was run on the data, which identified SCR peaks deviating more than .03 µs (microsiemens) from the background signal. SCRs were defined as the difference between the SCR onset and the maximum (peak) amplitude for that SCR. Given the dynamic nature of the threat stimulus, which lasted approximately seven seconds, and the potential for slow/ongoing responses, the largest peak SCR within a 15-second time window after threat onset was identified as the threat-SCR for each body type condition, for each participant (for similar see Armel & Ramachandran, 2003; Dewe, Watson, & Braithwaite, 2016; Dewe, Watson, Kessler, & Braithwaite, 2018). To make the data suitable for parametric analysis, all SCR data were normalised using the Log (SCR+1) correction. Z-scores were calculated for each participant in order to correct for individual differences, allowing comparisons across participants despite individual differences in background signal levels. This resulted in three Z-scores for each participant, one for each body type condition.

We investigated the effect of body type on SCR with repeated measures ANOVA. Skin conductance responses did not significantly differ across body type conditions ($F(2,26)=3.0$, $p=.067$, $\eta_p^2=.19$, $BF_{10}=1.46$; Table 5). The p-value here indicated a marginally significant difference between conditions such that responses were higher in the synchronous condition than in the asynchronous or block conditions. However, due to the small effect size and low B_{10} value, strong conclusions cannot be drawn.

Table 5. Means and standard errors of standardised SCR z-scores across body type conditions.

Sync		**Async**		**Block**	
M	**SE**	**M**	**SE**	**M**	**SE**
.83	1.03	-1.04	0.09	0.32	0.44

In order to assess whether autonomic response was related to subjective illusion experience, we ran Spearman's correlations between ownership and agency responses and SCR in each condition. SCRs did not significantly correlate with questionnaire ratings in the synchronous condition (ownership: $r=-.060$, $p=.854$; agency: $r=.075$, $p=.817$), asynchronous condition (ownership: *r*=-.383, *p*=.219; agency: *r*=-.507, *p*=.093), or block condition (ownership: *r*=-.036, *p*=.911; agency: *r*=.205, *p*=.525).

Discussion

In this study, we aimed to test the effectiveness of a child-friendly virtual 'threat' in evoking changes in arousal in adults, as measured by skin conductance response across three embodiment conditions (synchronous movement, asynchronous movement, and object). If the threat was effective, we would see larger threat-related SCRs in the synchronous movement condition than in either the asynchronous movement or object conditions, as in previous studies (Ehrsson, 2007; Petkova et al., 2011; Yuan & Steed, 2010). If we did replicate these findings, we planned to use our threat to compare responses across multisensory conditions in adults and children in a future study. We also used a questionnaire measure to compare subjective feelings of embodiment of a virtual body to psychophysiological responses when it was threatened, predicting that embodiment ratings would also be highest in the synchronous condition.

Our findings from the questionnaire measure were as predicted. While participants rated control questions as low regardless of body type condition, this was not the case for ownership and agency ratings. Participants felt much higher levels of ownership and agency in the synchronous movement condition than either the asynchronous movement or object conditions. Indeed, embodiment levels in the asynchronous and object conditions were comparably low. Therefore, as found in multiple previous studies, participants embody a virtual body which moves synchronously with their own, but not one which moves asynchronously to them, or which does not have a basic body-like form (Lenggenhager et al., 2007; Peck et al., 2013). These findings serve to confirm that our paradigm was successful in evoking differing levels of subjective embodiment across different virtual bodies, as expected. Therefore we can be confident that the embodiment paradigm itself was not responsible for any unexpected SCR findings.

The findings from our SCR measure were not quite as predicted. We hypothesised that participants' SCR would change more in response to a threat in the synchronous movement condition than either the asynchronous or object conditions. Though we did find some evidence of this trend, it did not reach significance. This is in contrast to previous findings, where SCR was significantly higher in synchronous multisensory conditions than asynchronous conditions (Armel & Ramachandran, 2003; Ehrsson, 2007; Petkova et al., 2011), and conditions with objects in the place of normal body form (Yuan & Steed, 2010). The reason for this discrepancy is likely the vast difference in the threat used and the low sample size here. Previous studies with adults have used highly aversive threats such as knives or objects falling on the body. Here, our aim was to identify a threat stimulus which was less severe, so could be used with child participants, but also provoked psychophysiological reactions in adult participants. It is likely the case that the threat used in the present study was not strong enough to show differences across conditions. Though anecdotally several participants did note that the cloud threat "felt weird" when it went through the virtual body, many others reported not feeling anything in response to the stimulus. In hindsight, it would have been useful to include a questionnaire item which specifically asked participants to rate how threatening they found the stimulus. From this, it would have been possible to quantify the perceived threat of the stimulus, which would have allowed more concrete interpretations of our findings.

Despite this limitation, we conclude that the particular stimulus used in this study was not sufficiently salient as a 'threatening' behaviour toward the virtual body to provoke a difference in emotional arousal across the body type conditions. This was in contrast to questionnaire responses, which did indicate a stronger sensation of embodiment under synchronous conditions. Further investigations will need to be carried out in order to identify a threat stimulus which does provoke a difference in SCR according to body type, so that this stimulus can then be applied to child participants. Once this particular problem in the field has been solved, researchers will be able to make stronger conclusions regarding the development of bodily awareness.

Chapter 6
General Discussion

The studies described in this thesis were designed to address three outstanding questions regarding bodily awareness and its development: Firstly, how does embodiment over a virtual body change over time? Secondly, is children's perception altered in line with the body they inhabit, as in adults? And thirdly, can embodiment be compared across adults and children using a physiological measure? Each of these questions was addressed in a separate study, the results of which have contributed to our understanding of embodiment.

Time-course of the Full Body Illusion in adults

The aim of Experiment 1 was to identify how feelings of embodiment alter over the time course of the FBI in adults. Participants experienced a first-person perspective of a virtual body in blocks of 5, 30, or 55 seconds. During these blocks, their virtual body moved either synchronously or asynchronously with their own movements, or in a third condition, both the participant and virtual body remained still. After each block, participants were asked to rate their feelings of ownership and agency over the virtual body they saw.

Contrary to our expectations, we found that embodiment ratings were high after a short exposure to a virtual body, regardless of whether the body moved synchronously, asynchronously, or not at all. While embodiment remained high with increased exposure to a synchronously-moving or stationary body, the longer participants were exposed to asynchronous movement, the more their embodiment ratings decreased. Therefore, embodiment is not built over time based on evidence. In the contrary, participants appear to automatically embody an avatar seen from a first-person perspective, only 'disembodying' it when exposed to enough information to this effect. This further reinforces the idea that perspective is a highly important aspect of embodiment.

It is worth noting that this pattern was more evident when participants were reporting feelings of agency than when they reported their levels of ownership over the virtual body. Agency and ownership are considered to be related but separate elements of embodiment (Kalckert & Ehrsson, 2012; Tsakiris et al., 2006), and therefore may be felt to different degrees in different circumstances. Here, overall ownership ratings were lower than agency ratings, suggesting that participants felt that they were in control of the virtual body's movements to a greater extent than they felt the body to belong to them. Indeed, ownership ratings were middling overall, hovering at around 50/100, which suggests no strong feelings of either ownership or disownership of the virtual body. In contrast, agency ratings tended further towards the higher end of the response scale. These findings confirm the distinct nature of these elements of embodiment, indicating that one can experience agency over a body without strong feelings of ownership. The question of whether agency in the absence of ownership constitutes 'true' embodiment still remains, and is being explored somewhat by researchers interested in whether 'embodying' a tool is comparable to embodying a body part (see, for example de Vignemont & Farnè, 2010). Despite these considerations, our findings still demonstrate interesting patterns in (at least elements of) embodiment across time, leading to interesting questions regarding the importance of visual perspective in bodily awareness.

In relation to this point, 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 leads 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.

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. This provides useful information for Experiment 2 and 3 where we induce the illusion in both adults and children.

Development of size perception in the Full Body Illusion

Experiment 2 was designed to answer our second question: Is children’s perception altered in line with the body they inhabit? In other words, are children susceptible to body-relative scaling in the same way as adults? Participants (a group of five-year-olds and a group of adults) were shown a virtual body from a first-person perspective, which was either 50%

larger or smaller than their own body. After a period of embodiment, participants were asked to report their subjective experience of the size of their own body, and that of their environment.

Our findings showed that both adults and children report the environment to appear smaller when inhabiting a large body, and larger when inhabiting a small body. This supports previous results found with adults (Banakou et al., 2013; Linkenauger et al., 2011; van der Hoort et al., 2011), and extends them to show the same effect in young children. While adults did not report their body to have changed size in either condition, five-year-olds only reported a change in body size after inhabiting a large body, reporting their body to be larger than usual. Therefore, perception is affected by body size in a somewhat adult-like way from as early as five years.

To our knowledge, this was the first study to measure body-relative scaling by asking participants to report their subjective experiences, rather than measuring perception indirectly (e.g. through size estimation measures). This was important as, while previous studies have reported findings on participants' perception of the environment, they have not directly measured or reported participants' explicit perception of their own body size during illusory embodiment of a small or large body. Anecdotally, van der Hoort et al. (2011) reported that participants did not perceive their body to have changed size, but rather reported the experience of inhabiting a giant world. However, this was based on the comments of participants during the experiment and was not directly measured. Our results confirm these anecdotal findings and somewhat extend them to children as young as five years old. However, as children did report their body to seem bigger than usual in the large body condition, it seems that children are more likely than adults to accept that their body has grown (but equally as unlikely to perceive their body to have shrunk).

Broadly, our findings from Experiment 2 help to explain previous findings that adults and children can readily embody fake bodies which are much larger or smaller than their own, providing that basic body layout and proportions remain intact (Banakou et al., 2013; Keenaghan et al., in prep; van der Hoort et al., 2011). This seeming acceptance of different-sized bodies may in fact merely reflect the fact that participants do not generally perceive the fake body to be any different from their usual body size. As, according to these participants, it is the environment around them that has changed size rather than their body, it stands to reason that this would have no effect on their feelings of embodiment over the body. Hence, rather than saying that adults and children accept bodies of different sizes as their own, it would be more accurate to state that participants embody bodies even when situated in unusually small or large environments.

Psychophysiology in the Full Body Illusion

Experiment 3 was a pilot study which aimed to identify a method of measuring embodiment physiologically in both adults and children. Specifically, we aimed to test a non-violent ‘threat’ to a virtual body which would be suitable for children but sufficient to elicit a response in adults. We designed such a stimulus: a cloud of flickering red dots which passed through the virtual body. We measured skin conductance responses to this stimulus after a period during which the virtual body moved synchronously or asynchronously with participants, or was replaced with a static object. We also measured participants’ reports of embodiment after each condition.

The results of the self-report measure indicated that the paradigm had worked as expected in terms of subjective levels of embodiment across the different conditions. Participants rated feelings of ownership and agency as high in the synchronous condition, and low in both the asynchronous and object conditions. These results reflected those which have been found previously: participants generally do not embody asynchronously-moving bodies (Peck et al., 2013) or objects which do not have a body-like form (Lenggenhager et al., 2007).

However, there was no difference in SCR across the three conditions, which was in contrast with multiple previous findings (e.g. Ehrsson, 2007; Yuan & Steed, 2010). From this we concluded that the stimulus used was too weak to elicit strong enough skin conductance signals to be compared between conditions. It is likely to be challenging to identify a stimulus which can be used effectively and safely with both adults and children. However, the addition of a physiological measure would greatly improve the validity of bodily awareness research in children. Though self-report measures can be used with young children provided they are given enough instruction, objective measures of embodiment could help to strengthen findings relating to embodiment in young children.

Theoretical implications

The findings of these three experiments have made a valuable contribution to our understanding of bodily awareness in both adults and children. In particular, we have expanded knowledge regarding the contribution of movement to the FBI over time and how embodying a virtual body of a different size to one's own may affect perception. In both Experiments 1 and 3, the synchrony between seen and felt movement was manipulated such that participants experienced visuomotor synchrony and asynchrony, as well as passively viewing a stationary virtual body (Experiment 1) or non-corporeal object (Experiment 3). Our findings regarding differing levels of embodiment evoked by these conditions were consistent with the literature in that periods of synchronous and no movement lead to subjective feelings of embodiment, whereas asynchronous movement of a virtual body and a view of a non-corporeal object generally do not (Carey et al., 2019; Lenggenhager et al., 2007; Peck et al., 2013).

Experiment 1 also showed that these patterns of full-body embodiment related to movement synchrony change over time. We found that, when exposed to an asynchronously-moving virtual body for a short period of time, participants did feel senses of both ownership and agency, which were contradictory to the general understanding of the importance of visuomotor synchrony. With further exposure to asynchronous movement, the pattern of embodiment returns to 'normal', suggesting that visuomotor synchrony (or, rather, the absence of asynchronous visuomotor cues) is an essential cue to embodiment only when exposure time is greater than a few seconds. These findings indicate that embodiment is not built up over time, but is rather a default state when viewing a body from a first-person perspective.

It is widely accepted in the literature that, when adult participants experience the FBI in a body which is larger or smaller than their own body, this affects how they perceive the size of their environment (Banakou et al., 2013; van der Hoort et al., 2011). Experiment 2 built upon this understanding, showing that this effect can be found in children as young as five years old. Moreover, findings of Experiment 2 explicitly show that both children and adults explicitly believe the size of their environment to have changed during these illusions, as opposed to the size of their own body (with the exception of illusions where children embody an avatar larger than their own body, in which they do report perceiving their body to be larger than usual). We have therefore provided further evidence that illusory embodiment has a significant impact upon perception. We now also suggest that previous findings showing that adults and children can embody avatars of different sizes (Banakou et al., 2013; Keenaghan et al., in prep; van der Hoort et al., 2011) are unsurprising, as it is likely that participants do not experience these illusions as any different to those in which they embody fake bodies of a similar size to their own.

Overall, the findings described here have answered several outstanding questions regarding bodily awareness and its development, whilst also providing starting-points for further avenues of investigation.

Practical applications for virtual environments

The studies included in this thesis have all made valuable contributions to our understanding of bodily awareness and perception in children and adults, or at least been a key step towards developing more thorough experimental methods. However, they also provide practical information which is invaluable in the development of virtual environments for use in research, entertainment, rehabilitation, and training. As the accessibility and applications of VR are constantly widening, it is important to ensure that the design of virtual environments is based on research regarding how such environments are perceived, and how users react to them. Plus, research findings can help developers to know where they can 'cut corners', and where accuracy is important.

For example, Experiment 1 provided helpful information in the development of virtual applications. Our findings appear to demonstrate that adults embody an avatar seen from a first-person perspective automatically, regardless of how it moves (over a short period of time). Not only does this mean that avatars seen for a short amount of time do not have to move perfectly in sync with a user to be embodied, it also hints at the power of perspective. It may be the case that perspective can override other top-down cues such as appearance, allowing users to embody forms which deviate from a typical body. Indeed, to a lesser extent, it has been shown that participants can embody avatars of a different age or race to their own, or even those with extra limbs in the presence of cues such as multisensory synchrony and/or first-person perspective (Banakou et al., 2013; Peck et al., 2013; Steptoe, Steed, & Slater, 2013; Tajadura-Jiménez, Banakou, Bianchi-Berthouze, & Slater, 2017). Here we have added to the mounting evidence that perspective is a majorly important cue for building a sense of bodily awareness.

Experiment 2 demonstrated that both adults and children tend to perceive body size as stable, and so changes in body size result in perceived changes in environment size. Therefore, developers could present a large or small environment by 'shrinking' or 'growing' the avatars which users inhabit, without having to alter the size of all objects in the environment. On the other hand, if the goal is to demonstrate that an avatar is abnormally large or small, additional cues would have to be provided.

Experiment 3 was a pilot of a new paradigm which could be used in adults and children to better measure embodiment in even young participants. Whilst our stimulus was not sufficiently salient for use in adults (and therefore we did not attempt to use it with children), we acknowledge the importance of finding objective ways of measuring embodiment in children and are striving to achieve this goal. As virtual applications extend to use in children (Asl Aminabadi, Erfanparast, Sohrabi, Ghertasi Oskouei, & Naghili, 2012), it is increasingly important to be able to thoroughly measure children's embodiment in different environments and properly design environments which they can engage with.

Previously, researchers in psychology, neuroscience, and computer science have been interested in how participants perceive virtual bodies and environments. However, these disciplines have remained somewhat separate, with findings not often shared across groups. Going forward it is essential that this work is interdisciplinary and shared, so that virtual environments used in practical applications can be based off the most up-to-date research.

Conclusions

The research reported in this thesis was designed with the aim of increasing understanding of three distinct aspects of bodily awareness research: time course, body size and perception, and physiological measurement. The methods used in these studies expanded established paradigms used in virtual reality to include new designs, such as the direct measurement of size perception, and a block design in measuring the time course of the FBI. We also began work on identifying methods of comparing physiological measures of embodiment between adults and children. All of this work has provided a starting point for new avenues of research in bodily awareness and its development, such as the presence body-relative scaling throughout development as the body grows at different rates, the strength of a first-person perspective as a cue to embodiment, and of course, the continued aim of measuring embodiment using objective physiological methods in children. Not only has the work described here contributed to our theoretical understanding of bodily awareness, but it can also be used to inform the design of virtual environments for use in adults and children across different settings, from entertainment to physical rehabilitation.

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