The development of bodily self-consciousness: Changing responses to the Full Body Illusion in childhood

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Research highlights

1. This study investigates the development of bodily self-consciousness using the ‘full body illusion’.
2. Self-identification with a virtual body is present at 6-7 years, and increases with age.
3. Touch referral to a virtual body develops only by 10 years, while drift in perceived self-location is present only in adults.
4. Therefore, links between multisensory integration and bodily self-consciousness develop significantly across childhood.

Abstract

The present work investigates the development of bodily self-consciousness and its relation to multisensory bodily information, by measuring for the first time the development of responses to the full body illusion in childhood. We tested three age groups of children: 6- to 7-year-olds (n=28); 8- to 9-year-olds (n=21); 10- to 11-year-olds (n=19), and a group of adults (n=31). Each participant wore a head-mounted-display (HMD) which displayed a view from a video camera positioned 2 metres behind their own back. Thus, they could view a virtual body from behind. We manipulated visuo-tactile synchrony by showing the participants a view of their virtual back being stroked with a stick at the same time and same place as their real back (synchronous condition), or at different times and places (asynchronous condition). After each period of stroking, we measured three aspects of bodily self-consciousness: drift in perceived self-location, self-identification with the virtual body, and touch referral to the virtual body. Results show that self-identification with the virtual body was significantly stronger in the synchronous condition than in the asynchronous condition even in the youngest group tested; however, the size of this effect increased with age. Touch referral to the virtual body was greater in the synchronous condition than in the asynchronous condition only for 10- to 11-year-olds and adults. Drift in perceived self-location was greater in the synchronous condition than in the asynchronous condition only for adults. Thus, the youngest age tested can self-identify with a virtual body, but the links between multisensory signals and bodily self-consciousness develop significantly across childhood. This suggests a long period of development of the bodily self and exciting potential for the use of virtual reality technologies with children.

There is growing evidence that the brain basis of self-consciousness is underpinned by the integration of multisensory information about the body – for example, from vision and touch (Blanke, 2012; Blanke & Metzinger, 2009; Gallagher, 2005; Ehrsson, 2007). Modern scientific attempts to understand the self have thus focused on *bodily self-consciousness* - the non-conceptual and pre-reflective representation of body-related sensory information (Legrand, 2006; Lenggenhager, Tadi, Metzinger, & Blanke, 2007) - and have decomposed it further to its component processes of self-location, first person perspective, and body ownership (Serino *et al*., 2013; Dobricki & de la Rosa, 2013). Self-location is the experience that the self is situated in a single, specific spatial location (Alsmith & Longo, 2014), while first-person perspective refers to one's subjective experience being centred on one's body (Vogeley & Fink, 2003). Body ownership is the feeling that one's own physical body and its parts belong to 'me' – that it is 'my' body (Blanke, 2012). When body ownership is applied to the whole body (and not just to a body part) it is frequently termed self-identification (since one identifies one's self with one's whole body, not with a body part; Blanke & Metzinger, 2009),

Experiments using the well-studied rubber hand illusion (RHI; Botvinick & Cohen, 1998; Tsakiris & Haggard, 2005) - showed that visual-tactile conflicts can create illusory shifts in perceived own-hand position, perceived touch location, and illusory ownership for a fake hand. An analogous 'Full Body Illusion' (FBI) can be created for the whole body, which uses visual-tactile stimulation to elicit changes in ownership of the whole body ('self-identification'), self-location, and perceived touch location (Ehrsson, 2007; Lenggenhager *et al*., 2007; Petkova & Ehrsson, 2008; van der hoort, Guterstam &

Ehrsson, 2011). It has been argued that the FBI is more likely than the RHI to lead to insights into the nature of the bodily self because the self is fundamentally associated with one's whole body, rather than single or multiple body parts (Blanke & Metzinger, 2009; Carruthers, 2008; Petkova, Bjornsdotter, Gentile, Jonsson, Li & Ehrsson, 2011). In the present study we examined, for the first time, the development of responses to the FBI in children (6-11 years old), with the aim of understanding how the multisensory basis of bodily self-consciousness develops over childhood.

A number of methods can be used to generate full body illusions; all make use of virtual reality or video-based virtual reality in order to present participants with illusory visual information about their body. Seeing a touch on a virtual body while synchronously feeling it on one's own body evokes the illusory percept that one's self is situated closer to where the touch is seen, i.e., nearer the location of the virtual body. It also induces a stronger feeling of ownership of (self-identification with) the virtual body, and illusory percepts of touch on the virtual body. Recent studies have shown that the FBI affects additional aspects of bodily processing, inducing, e.g., changes in tactile processing (Aspell, Lenggenhager, & Blanke, 2009; Aspell, Palluel, & Blanke, 2012), pain perception (Hänsell, Lenggenhager, Känell, Curatolol, & Blanke, 2011); Pamment & Aspell, in press) and body temperature (Salomon, Lim, Pfeiffer, Gassert, & Blanke, 2013). Neuroimaging studies of full body illusions have demonstrated associated changes in a network of brain areas. This includes premotor areas implementing body ownership (Petkova et al., 2011; Guterstam, Bjornsdotter, Gentile, & Ehrsson, 2015) and the temporoparietal junction implementing self-location (Ionta *et al*., 2011).

The importance of multisensory information for own-body perception has recently been studied in children, and it has been shown that, from an early age, infants combine tactile and visual information arising from their own bodies. Newborns (Filippetti, Johnson, Lloyd-Fox, Dragovic & Farroni, 2013; Filippetti, Lloyd-Fox, Longo, Farroni & Johnson, 2014; Freier, Mason & Bremner, in press) and infants in the first year of life (Zmyj, Jank, Schütz-Bosbach & Daum, 2011) are sensitive to temporal correspondences between visual and tactile information on the face or legs. Likewise, infants in the first year of life are able to detect temporal congruencies between visual and proprioceptive information (Bahrick & Watson, 1985; Schmuckler, 1996; Rochat, 1998). Work on the RHI (Cascio, Foss-Feig, Burnette, Heacock & Cosby, 2012; Cowie, Makin & Bremner, 2013; Cowie, Sterling & Bremner, 2016) has shown that manipulation of visual-tactile cues can also generate bodily illusions in children. Cowie *et al*. (2013, 2016) showed that in 4- to 13-year-olds, synchronous visual-tactile stimulation on real and fake hands causes children to feel a greater sense of ownership for the fake hand than does asynchronous stroking, as well as a larger drift in perceived hand position towards the fake hand.

The current study examines responses to the full-body illusion in children of 6-11 years old, as well as in a comparison adult sample. This age range was chosen for several reasons. There is ample evidence that by 6 years children detect visual-tactile synchrony at least on upper (Cowie *et al*., 2013) and lower limbs (Zmyj *et al*., 2011). Therefore one would expect this source of information to contribute to bodily perception across the age range we tested. Pilot studies showed that a head mounted display was too heavy for use with children below 6 years of age and moreover, it is at 6-11 years old that changes in sensory processing emerge in the RHI. Specifically, across this age range the magnitude of RHI drift responses in both synchronous and asynchronous conditions declines (Cowie *et al.*, 2013, 2016). Thus, from 6-11 years the influence of vision on perceived hand location (Makin, Holmes & Ehrsson, 2008) decreases in the RHI, and may undergo changes in the full body illusion also. This age could therefore be particularly relevant to our understanding of the development of the bodily self.

To induce an FBI in the present study, we used methods first used in Lenggenhager (2007). This is a widely replicated paradigm (Aspell *et al*., 2009; Aspell *et al.* 2013; Ionta *et al.*, 2011; Lenggenhager *et al*., 2009; Palluel, Aspell & Blanke, 2011; Salomon, Lim, Pfeiffer, Gassert & Blanke, 2013) in which participants, viewing their own body as seen from behind, receive visuo-tactile stimulation (stroking) on their real and virtual bodies. Thus, they see the virtual body while watching a stick stroking its back. During this time, synchronous (same time, same place) or asynchronous (different time, different place) strokes are delivered to the participant's own back. In adults, synchronous stroking induces greater changes (compared with asynchronous stroking) in self-identification with the virtual body and perceived touch location (feeling touch impinging on the virtual body), as indexed by self-report questionnaires. Further, self-location is displaced towards the virtual body. Self-location is measured with a walking measure following stimulation: with eyes closed participants are displaced backwards and asked to return to where they were standing during visuo-tactile stimulation. Following synchronous stroking, they typically walk to a point forward of their own previous position, towards the virtual body. This indicates a forwards drift in self-location. The FBI paradigm is used here to investigate the development in childhood of the multisensory bases of bodily self-consciousness, including tactile perception, self-identification and self-location.

Method

Participants

We tested adults (M = 27.4 years of age, SD = 9.0, n=31), and three age groups of children (6- to 7-year-olds: M = 6.9 years, SD = 0.4, n = 28; 8- to 9-year-olds: M = 9.0 years, SD = 0.2, n=21; 10- to 11-year-olds: M = 11.2 years, SD = 0.5, n = 19). For all participants, vision was normal or corrected-to-normal, and there were no histories of neurological or psychiatric conditions, or developmental disorders. All participants were naïve to the purpose of the study. Written informed consent was given by adult participants and by the children's parents. Children gave verbal consent and were presented with a small reward (e.g. a sticker) at the end of the study. The study was approved by the local ethics research committee at Goldsmiths, University of London. The study was performed in accordance with the ethical standards laid down in the Declaration of Helsinki.

Design

To parallel Lenggenhager *et al.* (2007), a within-subjects design was used. Each participant received one synchronous and one asynchronous trial. The order of these conditions was randomised across participants.

Equipment and procedure

Each participant stood on a 1 x 4 m strip of carpet and completed: (i) a baseline trial, (ii) a recording of the asynchronous trial video, (iii) one synchronous and one asynchronous test trial (order randomised), and (iv) a second baseline trial. After each test trial the participant completed a self-location drift measurement, and answered questionnaire items. An ipod and headphones were used to deliver white noise to the participant throughout. All age groups, including adults, were given the same instructions.

[Insert Figure 1 about here]

In the first baseline trial, the participant standing on the carpet was told that they were standing on the spot of some buried treasure. They were asked to close their eyes and walk backwards while the experimenter guided them 1.5 m backwards from the starting position. While walking backwards, they were asked to make ‘small, penguin steps’ so that they could not use a strategy later in the task which relied on counting the number of steps taken. With eyes still closed, they were asked to return to the starting position using normal-sized steps. Drift was measured as the distance in centimetres between starting position and finishing position in the direction of the virtual body. Thus, positive drifts indicated anterior drift towards the virtual body. Following this, the experimenter moved the participant back to the starting point, using a figure-of-eight walking path to disorient them and thus prevent any feedback from path integration which would allow participants to judge how accurate or not they had been with their estimate. Finally the participant opened their eyes.

Next we recorded the video to be used in the asynchronous test trial, while also training the participant to stand still whilst wearing the head mounted display (HMD, Video Eyewear, 80” screen at 1 m distance). The participant stood at the starting position, with a video camera positioned 2 m behind them. The video camera tripod stand was height-adjusted and where necessary the video camera zoomed in slightly so that each participant was shown a region from the bottom of their back upwards to just above the top of their head (Fig 1). Thus, the same proportion of the body was visible to all participants. The zoom did also have the effect of making the virtual body appear slightly closer for smaller participants than for larger participants. Please see the Discussion section for further comment on these effects.

The participant was asked to stay as still as possible and close their eyes, to 'guard the treasure'. Additional black cloth covered the edges of the HMD so that none of the surrounding environment was visible. The participant's back was then stroked with a metre-long, blunt-tipped wooden stick, and they were told that the stick would 'make them invisible to anybody trying to steal the treasure'. Strokes were delivered at a rate of roughly 1 Hz, on the back only, in all directions. Stroking was recorded for 2 minutes.

In the synchronous test trial, the participant was placed in the starting position wearing the HMD as before, but with eyes open. For two minutes the experimenter stroked the participant's back while the participant watched a live feed of this on the HMD. This provided synchronous visual-tactile information between the real body and the virtual body visible 2 m ahead. Following this period, the participant completed a drift measurement with the same instructions as in the baseline condition (they took small steps backwards for 1.5 m; they were asked to return to start point; and finally they were guided back to the starting point in a figure of eight motion). The asynchronous test trial was identical to the synchronous trial except that the participant watched the pre-recorded tape of stroking rather than the live feed. Therefore, the pattern of touch felt on the back was different to that seen on the virtual body.

As detailed above, the experimenter measured drift following baseline trial 1, synchronous test trial, asynchronous test trial, and baseline trial 2. After each test trial and subsequent drift measurement, the participant's HMD was removed, and they remained at the starting point facing forwards, to answer questions concerning their experience (adapted from those used in Lenggenhagger *et al.*, 2007 and other FBI studies). The questions (see Table 1) addressed: 1. touch referral, 2. sense of ownership, 3. age related differences in affirmative responding (a control question), and 4. explicit awareness of differences between the synchronous and asynchronous conditions. Questions 1-3 were asked in a random order after each test trial, and question 4 was asked only after the second test condition (synchronous or asynchronous depending on the assigned order of conditions). During Questions 1-2 the experimenter pointed in front of the participant to indicate the location of the virtual body.

The answer scale we used has been successfully used with children in the rubber hand illusion (Cowie *et al.*, 2013): “No, definitely not” / “No” / “No, not really” / “In between” / “Yes, a little” / “Yes, a lot” / “Yes, lots and lots”. For analysis, these responses were given equivalent scores from 0 (“No, definitely not”) to 6 (“Yes, lots and lots”).

[Insert Table 1 about here]

Statistical analyses

The measures taken were therefore drift in self-location; and the results of questionnaire items 1-4 for assessing self-identification with, and touch referral to, the virtual body.

To assess effects of Synchrony and Age on drift data we used standard parametric statistics (ANOVA and t-tests). We note that questionnaire items give ordinal data, and therefore present medians and interquartile ranges for these rather than means and standard deviations. Further, for our main analyses of the questionnaire data, prior to submitting the data to parametric testing, we first applied an Aligned Rank Transformation (Wobbrock, Findlater, Gergle, Higgins, 2011). This procedure produces ranks of nonparametric data (Conover & Iman, 1981), while also including an alignment step which, importantly for the present study, allows for the correct assessment of interaction effects. This aligned ranked data was then submitted to standard mixed ANOVA to enable us to examine effects of Age and Synchrony. Follow-up comparisons were conducted using the appropriate non-parametric tests on the untransformed questionnaire data (e.g. Kruskal-Wallis H tests; Wilcoxon tests). On the basis of previous literature, we have a strong *a priori* expectation that questionnaire items and drift measures will be higher in the synchronous than in the asynchronous stroking mode (Tsakiris, 2010). Therefore, paired comparisons between synchronous and asynchronous conditions were one-tailed. Reported p-values reflect this, as well as Bonferroni correction for multiple comparisons (described throughout); α remains at .05.

Results

While all questionnaire results presented are for the transformed data, we also note that all main effects and interactions reported below were present also in ANOVA of the untransformed data.

[Insert Figure 2 about here]

Q3 (control question) and data correction for response bias

We will first present the results of Q3, a control question ("When I was stroking with the magic wand, did it feel like your nose was growing?"). Fig 2a shows that children and adults responded somewhat differently to this question. ANOVA confirmed that while there was no significant effect of Synchrony, $F(1,95)=0.02$, $p=.89$, $\eta^2_p < 0.001$, and no interaction between Synchrony and Age, $F(3,95)=1.2$, $p=.31$, $\eta^2_p = 0.04$, there was a significant effect of Age, $F(3,95)=8.7$, $p<.001$, $\eta^2_p = 0.22$. This included significant linear (p=.001) and quadratic (p=.001) components. Children tended to agree with statements more positively than adults: median ratings were 6-to 7-year-olds (Mdn=1), 8- to 9-year-olds (Mdn=1.75), 10-to 11-year-olds (Mdn=1), and adults (Mdn=0). While these age-related differences in response style would not affect the crucial synchronous *vs.* asynchronous comparisons, they could contribute to effects of age.

Therefore, on the assumption that children's tendency to agree likely affected responses to other questions, we compensated for this in subsequent analyses by calculating for each child scores for Q1, Q2 and Q4 which have been corrected for response bias. To do this, we subtracted for each child their average score on Q3 from their score for Q1, Q2, and Q4. This was initially done for all participants. However, while for most participants ratings on Q3 (control) were low (0-2), for some participants the responses to Q3 (control) were actually *higher* than responses to one or more of the other questions. This would have made corrected values negative. We suspect that this is because Q3 asked about the nose, and some participants reported that they were very aware of the HMD weighing down on their nose. In these cases we think that Q3 responses reflected a genuine attempt to indicate some feeling about one's nose, rather than a propensity to use the answer scale in a particular way. However, to be cautious, we removed participants for whom Q3 responses were higher than Q1, Q2 or Q4 responses (6-7 year olds n=6; 8-9 year olds n=9; 10-11 year olds n=6).

The remaining sample was as follows: 6- to 7-year-olds (n=22); 8- to 9-year-olds (n=12); 10- to 11-year-olds (n=13); adults (n=31). The low sample sizes in the middle two age groups resulted in a significant loss of statistical power compared with the younger (6-7 years) and older (adult) groups. The following analyses therefore combine the 8- to 9-year-old and 10- to 11-year-old groups, giving a sample as follows: 6- to 7-year-olds (M=6.9y, SD=0.4y, n=22); 8- to 11-year-olds (M=10.2y, SD=1.2y, n=25); adults (M=27.4y, SD=9.0y, n=31).

The correction for response bias affected results only slightly: all ANOVA results remained the same as for the raw data (see footnotes, and Fig S1). Nevertheless it provides a more valid measure of children's experience of the FBI. These data are shown in Figs 2b-d, and presented in our main analyses below.

Q1 (Touch Referral)

ANOVA on Q1 scores (Fig 2b) showed a main effect of Age, $F(2,75)=4.3$, $p=.016$, $\eta^2_p = 0.10$, a main effect of Synchrony, $F(1,75)=78.9$, $p<.001$, $\eta^2_p = 0.51$; and a significant interaction, $F(2,75)=6.3$, $p=.003$, $\eta^2_p = 0.14$.[1] Synchronous stroking (Mdn=5) produced stronger feelings of referred touch than asynchronous stroking (Mdn=3). Age showed a significant quadratic contrast (p=.025): averaged across stroking conditions, 8- to 11-year-olds had a lower median rating (Mdn=3.25) than 6-to 7-year-olds (Mdn=4) or adults (Mdn=4.75).

[1] ANOVA of the full sample's raw scores, in their original four age groups (Fig S1), shows a main effect of Age, $F(3,95)=4.3$, $p=.007$, $\eta^2_p = 0.12$; a main effect of Synchrony, $F(1,95)=73.2$, $p<.001$, $\eta^2_p = 0.44$; and a significant Age x Synchrony interaction, $F(3,95)=16.2$, $p<.001$, $\eta^2_p = 0.34$.

To explore the Age by Synchrony interaction, we first measured the effects of Synchrony at each age with Wilcoxon-Signed Rank tests (one-tailed, corrected for three multiple comparisons). Synchronous stroking produced stronger feelings of referred touch than asynchronous stroking for adults (Z=-4.7, p<.001, r = .84), and at 8-11 years (Z=-2.9, p=.006, r = -.58), but not at 6-7 years (Z=-1.7, p=.135, r = -.36). Thus, the effects of Synchrony on illusory touch referral to the virtual body increase with age, becoming fully apparent at 8-11 years of age.

To explore the Age by Synchrony interaction further, we measured the effects of age in each stroking condition with a Kruskal-Wallis H test, followed up with Dunn's (1964) post-hoc tests corrected using the Bonferroni method. The synchronous condition showed a significant effect of Age, $\chi^2(2)=18.9$, p<.001, with scores for adults higher than both 6- to 7-year-olds (p=.001) and 8- to 11-year-olds (p=.001) but no difference between the two child groups (p=1.0). In the asynchronous condition, there was no effect of Age, $\chi^2(2)=0.2$, p=.197. Thus, the development of touch referral with age emerged largely from age-related strengthening of responses to the synchronous condition, rather than weakening of responses to the asynchronous condition.

Q2 (self-identification)

ANOVA on Q2 scores (Fig. 2c) showed a main effect of Age, F(2,75)=4.5, p=.014, η^2_p = 0.11; a main effect of Synchrony, F(1,75)=91.3, p<.001, η^2_p = 0.55; and a significant interaction, F(2,75)=9.1, p<.001, η^2_p = 0.20.[2] Synchronous stroking (Mdn=5) produced stronger agreement than asynchronous stroking

[2] ANOVA on the full sample's raw scores (Fig. S1), in four age groups, showed a main effect of Age, F(3,95)=7.1, p<.001, η^2_p =0.183; a main effect of Synchrony, F(1,95)=105.6, p<.001, η^2_p =0.53; and a significant interaction, F(3,95)=14.2, p<.001, η^2_p =0.31.

(Mdn=3). There was a significant quadratic effect of age (p=.005) such that that 6- to 7-year-olds (Mdn=4.5) and adults (Mdn=4.75) scored most highly, with 8- to 11-year-olds (Mdn=3.5) scoring more moderately.

To explore the Age by Synchrony interaction, we first measured the effects of synchrony at each age with paired samples t-tests (one-tailed, corrected for three multiple comparisons). These showed that synchronous stroking produced stronger agreement than asynchronous at 6-7 years (Z=-2.2, p=.042, r = -.47); 8-11 years, (Z=-3.3, p=.002, r = -.66); and adult, (Z=-4.3, p<.001, r = -.77).

Using analyses to explore the Age by Synchrony interaction further (as per Q1), we tested the effects of age in each stroking condition. There was an effect of Age in the synchronous condition, $\chi^2(2)=11.9$, p=.003. Bonferroni-corrected post-hoc Dunn's tests showed no difference between the two child groups (p=.63) or between 6- to 7-year-olds and adults (p=.15), but adults scored significantly higher than 8- to 11-year-olds (p=.002). There was also a significant effect of Age in the asynchronous condition, $\chi^2(2)=9.6$, p=.008. Here, scores were highest in the youngest group, with a significant reduction at 8- to 11-years (p=.016) and adult (p=.023). There was no difference between the two older groups (p=1.0). Thus, feelings of self-identification in the synchronous condition broadly increased with age while in the asynchronous condition they declined.

Q4 (awareness)

To ask whether participants were aware of a difference between the synchronous and asynchronous conditions, we used a Kruskal-Wallis H test to examine the effect of Age on responses to question 4 (Fig 2d). This analysis showed a main effect of Age, $\chi^2(2)=14.9$, p=.001.[3] Post-hoc Bonferroni-corrected Dunn's tests showed a significant difference between 6- to 7-year-olds and adults (p=.000) but not between the two child groups (p=.27) or between 8- to 11-year-olds and adults (p=.10). Thus, the extent to which participants noticed the difference between stroking conditions broadly increased with age.

Drift measures

Since we did not need to exclude any participants as for the questionnaire data, these analyses are presented for the full sample of participants in four age groups. Self-location was measured by the 'drift' from the participant's actual starting position to the perceived own-body location following visuo-tactile stimulation, with positive values indicating anterior drift (towards the virtual body). To estimate the perceived own-body location, participants were displaced backwards and asked to return to their starting point.

[Insert Table 2 about here]

We first took two baseline trials of the walking estimate, with no visuo-tactile stimulation. An accurate response would be when the participant walked back exactly to their starting point. For each trial, we calculated the distance between this point ('zero') and the actual point that the participant walked to. Positive errors indicated that the participant walked too far forwards; negative errors indicated that they did not walk far enough. The constant error for each participant was calculated by taking the mean of these two trials. Baseline constant error (Table 2) showed a main effect of Age, F(3,95)=3.4, p=.021, η^2 = 0.10. Neither linear nor quadratic trends were significant. Baseline variable error

[3] Analysis of the full sample's uncorrected scores (Fig S1), in four age groups, showed a main effect of Age, $\chi^2(3)$= 18.0, p<.001.

was calculated by taking the unsigned difference between the two walking estimates (given the low number of points, standard deviation was an inappropriate measure). Baseline variable error (Table 2) showed a main effect of Age, $F(3,95)=3.9$, $p=.011$, $\eta^2 = 0.11$, with a strong linear component ($p=.001$). Importantly therefore, these baseline estimates were subtracted from post-stimulation estimates to give a measure of drift following stroking that is corrected for any baseline age differences in the distance estimation task.

[Insert Figure 3 about here]

This baseline-corrected drift (Fig. 3) showed a main effect of Age, $F(3,95)=3.3$, $p=.025$, $\eta^2_p = 0.09$, and an interaction between Synchrony and Age, $F(3,95)=5.5$, $p=.002$, $\eta^2_p = 0.15$, but no effect of Synchrony, $F(1,95)=0.002$, $p=.961$, $\eta^2_p < 0.001$. The effect of Age had a significant linear component ($p=.008$), with average drift increasing across age groups (6-7 years M=-0.1; 8-9 years M=0.04; 10-11 years M=0.05; Adult M=0.07). One-tailed paired samples t-tests, corrected for four multiple comparisons, showed that synchronous stroking produced larger drift than asynchronous stroking for adults, $t(30)=4.8$, $p<.001$, $d = 0.9$, but not for 6- to 7-year-olds, $t(27)=-0.8$, $p=0.79$, $d = -0.2$, 8- to 9-year-olds, $t(20)=1.0$, $p=0.16$, $d = 0.2$, or 10- to 11-year-olds, $t(18)=-2.3$, $p=0.98$, $d = -0.5$. One-sample t-tests comparing drift with zero showed a difference only for adults in the synchronous condition (Table 3).

[Insert Table 3 about here]

Discussion

The present study investigated whether we could experimentally induce a ‘full body illusion’ in children, as found in adult participants (e.g., Lenggenhager *et al*., 2007). We found that synchronous visuo-tactile stimulation of the participant's body and the virtual body produced self-identification with the virtual body in both children (6-7 and 10-11 years of age) and adults; and a perceived referral of touch to the virtual body in 10- to 11-year-olds and adults. Synchronous stimulation also produced an anterior drift in perceived self-location (towards the virtual body) in adults, although not in children of any age. Thus, for children as for adults, visuo-tactile synchrony modulated self-identification, and we note that self-identification with the virtual body can be induced at the earliest ages tested (6-7 years). However, the full complement of adult-like responses to the full body illusion appears to take some years to develop, with substantial developmental change across childhood in the extent to which visuo-tactile synchrony modulates self-identification, touch referral, and self-location. This work substantially advances our knowledge of how bodily self-consciousness develops, moving beyond what is known both of multisensory perception (Filippetti *et al*., 2013, 2014; Freier et al., in press; Bahrick & Watson, 1985; Rigato *et al.*, 2014; Rochat, 1998; Zmyj *et al*., 2011) and a sense of ownership relating to body parts (Cowie *et al*., 2013, 2016). It shows significant development across childhood in the sensory bases of whole body ownership, which is arguably more fundamentally tied to the sense of self (Blanke & Metzinger, 2009).

Self-identification

At 6-7 years, 10-11 years and in adults, synchronous visuo-tactile stimulation elicited greater self-identification with the virtual body than did asynchronous stimulation. Questionnaire ratings in the synchronous condition were higher than scores in asynchronous condition. These results demonstrate for the first time that visuo-tactile synchrony contributes to identification of the whole body in children as young as 6-7 years.

The current study accords well with the findings of adult studies using the same FBI paradigm (e.g., Aspell *et al*., 2009, 2012; Lenggenhager, Mouthon & Blanke, 2009; Lenggenhager *et al*., 2007). In our set-up, participants viewed the body from a third person perspective – that is, as if seen by someone else, and not from a first person perspective, in the visual reference frame of one's own body. The third person perspective version of the FBI produces a weaker illusion than a first person perspective version (Petkova, Kohshnevis & Ehrsson, 2011; Maselli & Slater, 2013; Pomés & Slater, 2013), and some authors have claimed that self-identification ratings in third person perspective set-ups merely demonstrate self-recognition as one would recognize oneself in a mirror (Petkova *et al*., 2011). However, this does not explain why in our dataset and those of others (e.g., Aspell *et al*., 2009; Lenggenhager, 2007) synchronous stroking produces stronger self-identification than asynchronous stroking. We therefore suggest that the current results show a genuine manipulation of self-identification with the virtual body in young children as well as in adults. This illusion of viewing one's body in extrapersonal space is a striking demonstration of the power of multisensory cues in own-body perception, and accords with naturally-occurring (if rare) neurological disorders, known as autoscopic phenomena (out of body experiences, heautoscopy and autoscopic hallucinations) in which one's illusory double is seen from a third person perspective (Heydrich & Blanke, 2013). Indeed, in one published case of heautoscopy a patient has reported seeing her double from behind (Blanke *et al.*, 2004).

Here we show both a significant contribution of multisensory information to self-identification with a virtual body at 6 years, and a significant increase in the extent to which visuo-tactile synchrony modulates self-identification from 6 years to adulthood. Interestingly, the youngest children did not explicitly notice a difference between stroking conditions. Our strict correction for response bias also means that the findings were not an artifact of young children's propensity to agree with the experimenter. We also note that this occurred despite the fact that increased zoom for smaller participants may have given them an illusion of a slightly closer body. This kind of self-identification is apparent and modulated by visuo-tactile synchrony at the youngest age we tested in the current paradigm.

The current view of developing bodily self-consciousness is that an implicit awareness of the body, a kind of postural schema directed towards action control, is present in the 3-month-old infant, who is able to identify for example whether limbs in a display move contingently with her own (Rochat & Morgan 1995, Bahrick & Watson 1985; Rochat, 2010; although see Bremner, 2016). Two years of age marks a transition from this online, action-driven bodily awareness to a more conceptual understanding of the self. Thus, by this age, most children pass the 'rouge' test, checking for a mark on their own body when they see one on the body in the mirror (Lewis & Brooks_Gunn, 1979; Povinelli, 1995). They also demonstrate increasing understanding that the self is both distinct from, and observed by, other selves - for example by showing embarrassment at a mirror image (Rochat, 2009), or using personal pronouns like ‘mine’ (Lewis & Ramsay, 2004) .

This view rather overlooks the possibility of significant sensory developments occurring beyond infancy. However, there is good reason to believe that these do occur. Both we (Bremner, Hill, Pratt, Rigato & Spence, 2013; Cowie, Sterling & Bremner, 2016) and others (Contreras-Vidal, Bo, Boudreau, & Clark, 2005; Nardini, Begus & Mareschal, 2012) have shown that the relations between sensory information and body-part localisation develop right through childhood. The present study provides a striking demonstration of protracted development in the sensory foundations of the bodily self: As age increased, so too did the link between visuo-tactile synchrony and self-identification with the body. Further, the current data suggest additional work at this age is merited, both to unpick development within the 8-11-year age bracket and to understand how the non-linearities we find in body identification during mid-childhood (e.g., lower response to the synchronous condition at 8-11 years, Fig 2c) parallel what it known of hand localization. What is manipulated in the Full Body Illusion is the experience of owning a single, whole body situated in space and providing a standpoint for perception and action (‘minimal phenomenal selfhood’, Blanke & Metzinger, 2009). The current data emphasize that not only does a cognitive, reflective sense of self develop in childhood, but so too do these lower-level sensory foundations of self-consciousness.

This is in contrast to the much earlier-developing ownership of a fake hand using similar techniques: in the RHI paradigm there is no change in the effect of synchrony on ownership between 4 years and adulthood (Cowie *et al.*, 2013). One explanation of this discrepancy is that full-body representations take longer to develop to maturity than do body-part representations. This may reflect their dependence on slightly different neural mechanisms (Blanke, 2012). Thus, bimodal visual-tactile neurons in parietal cortex may contribute to both illusions, but those subserving the RHI would have tactile receptive fields on the hand whereas those subserving the FBI may have tactile fields centred on the trunk. These neural populations differ in their response properties (Sakata, Taira, Murata & Milne, 1995; Serino et al., 2013), and may well differ in their development. This is because congruent visual tactile input is extremely common for the hand but less so for the trunk. Therefore it is very likely that trunk-centred fields receive less input during childhood, causing the later development of responses to the FBI. Later development of responses to our 'third-person-perspective full-body illusion' may also result because this requires some conception of one's own body as an object situated in external space, whereas the first-person-perspective rubber hand illusion merely requires the representation of a hand in PPS. Thus, for young children who can demonstrate marked difficulty with perspective taking (Piaget & Inhelder, 1967), the full body illusion may be a much more demanding task for which adult-like responses take some time to develop. In order to test this, it would be useful to develop first-person versions (e.g. van der Hoort *et al*., 2011) of the FBI in young children. The necessary developmental foundations for establishing self-identification with a virtual body should be explored in future work.

Touch referral

The phenomenon of mislocalizing (or mis-referring) touch to a virtual body is present in adults (e.g., Lenggenhager *et al*., 2007; 2009; Pomés & Slater, 2013). It can be measured by questionnaires, and is further evident in implicit measures, i.e., changes in crossmodal congruency effects (Aspell *et al*., 2009) and somatosensory evoked potentials (Aspell *et al*., 2012) during the illusion. The present study assessed the development of touch referral, and we found that the magnitude of difference between baseline-corrected questionnaire responses in the synchronous condition and the asynchronous condition increased strikingly with age. At 6-7 years, there were no significant differences between responses to synchronous and asynchronous stroking. In contrast, for 10- to 11-year-olds and adults, synchronous cues elicited significantly stronger feelings of touch referral than asynchronous cues. Further, at these ages, only synchronous stroking elicited ratings above neutral. Thus, we show that from 6-11 years there is increased referral of touch to a virtual body.

It is interesting to note that the 6-7 years group may have experienced touch referral illusion in both conditions, since asynchronous ratings are rather high in this youngest group, later declining with age. As such referral of touch in this group may have been driven by viewing a body only (irrespective of visual-tactile synchrony or asynchrony). To determine separately the effects of viewing a body and experiencing visual-tactile synchrony, an interesting follow-up would be the introduction of a no-stroking condition. Indeed some authors suggest that under certain conditions an FBI can occur simply by seeing the body, irrespective of touch (Maselli & Slater, 2013). It has also been shown that referral of touch can be elicited (measured by changes in the crossmodal congruency effect) simply by showing participants their own body, from the back, via an HMD (Aspell et al. 2009). Nevertheless, the widening gap between stroking conditions across ages suggests that younger children have a rather less specific interpretation of body cues than older children. With age comes an increased ability to use multisensory visuo-tactile synchrony as a marker of body ownership, and to use asynchronous visuo-tactile stimulation as a cue indicating that one is not viewing one's own body.

The development of touch referral to the virtual body has interesting parallels to what we know of touch localization on hands across the same developmental period. In studies of the Rubber Hand Illusion, there is a widening gap between responses in the synchronous and asynchronous conditions from 4-11 years (Cowie *et al*., 2013; Cowie *et al*., submitted). This accords with the present findings and may suggest that the integration of tactile information into body-defined reference frames improves across this period. Developmental changes in the role of vision for touch localization are also seen in other studies (Pagel, Heed & Röder, 2009; Begum Ali, Cowie & Bremner, 2014; Begum Ali, Spence & Bremner, 2015; Bremner, Mareschal, Lloyd-Fox & Spence, 2008).

However, touch referral is experienced at 4 years in the RHI but only at 10 years in the FBI. Again this may to some degree reflect developing multisensory mechanisms of body representation. A further consideration is that, in the RHI (Lloyd, 2007), drift is only induced when the body is within peripersonal space (PPS). If whole-body PPS is body-scaled (as for manual PPS space; Gabbard, Cordova & Ammar, 2007), then in absolute terms children's whole-body PPS will not extend as far as adults'. The size of PPS varies widely between adult participants but has been measured to be in the region of ~60-80cm from the body in (static) adults (Longo & Lourenco, 2007; Ferri *et al.*, 2015). In walking adults, the PPS extends to ~165 cm from the body (Noel *et al*., 2014)), although interestingly, it has recently been shown that the FBI enlarges the PPS in front-space by ~15-30cm (Noel *et al.*, 2015). In our task, when self-location is measured, participants first walk 150 cm backwards and typically end up <25 cm forwards of their start position (e.g., Lenggenhager *et al.*, 2007; Aspell *et al.*, 2009). While this would be inside the 'PPS boundary' for adults, it may fall outside it for children. This could make touch localization difficult and it may also explain why we did not find any drift in self-location in children. The interesting question of how whole-body peripersonal space develops in childhood should be investigated in future work.

Interestingly, we find earlier development of self-identification than touch referral: at 6-7 years, self-identification, but not touch referral, was significantly moderated by synchrony. This supports the growing understanding that different aspects of bodily illusions are dissociable (Longo *et al.*, 2008; Rohde & Ernst, 2011; Maselli & Slater, 2014; Serino *et al.*, 2013). In particular, it is clear that the experience of ownership involves a wide network of brain areas processing not only visuo-tactile synchronies but also, for example, visuo-proprioceptive synchronies and interoceptive sensations. The difference in developmental trajectories we find here suggests that future work should explore further the links between touch referral and ownership (self-identification) in the full body illusion.

Self-location

Self-location was measured as drift in perceived self-location following visuo-tactile stimulation. In adults, following synchronous stroking self-location was perceived to be forwards of the real body position, towards the virtual body. In contrast, we found no difference in drift measures between synchronous and asynchronous stroking in children. This suggests that synchronous visuo-tactile stimulation of one's own and a virtual body cannot induce a drift in self-location towards the virtual body until adulthood, and contrasts with the RHI, in which there is reliable drift for children from 4 years old (Cowie *et al*., 2013).

As for the questionnaire responses we gathered, developing neural systems, spatial factors, or a smaller peripersonal space might explain the lack of drift towards the virtual body in children. The developmental dissociation we find between self-location and other aspects of the illusion is entirely consistent with the adult data discussed above which shows that changes in body ownership can occur in the absence of changes in self-location (e.g., Maselli & Slater, 2014; Serino *et al.*, 2013; Petkova *et al.*, 2011). It further supports the developmental finding from the rubber hand illusion that ownership and drift are dissociable in body illusions (Cowie *et al*., 2013). In line with that data, we find here a later development of self-location than self-identification, suggesting that spatial representation of the self is a more difficult skill to develop than a sense of body-part ownership or self-identification. Although this is highly speculative at this stage, our data would be consistent with a later development of the temporoparietal junction, which is specifically associated with self-location, than the premotor cortex, which is more associated with ownership/identification (Serino *et al.*, 2013).

It is also possible that aspects of our design affected the drift variable. Walking back to the target requires more steps for younger children because of their shorter stride lengths, and these added steps might introduce more noise, masking differences between synchronous and asynchronous conditions. In support of this, baseline variable error was higher in our youngest groups. The drift task also taxes working memory, which has limited capacity in young children (Gathercole, Pickering, Ambridge & Wearing, 2004) - in order for drift to occur, the participant must remember both the perceived location of their own body during visuo-tactile stimulation, and how far backwards they moved during the displacement phase. These demands are not present in the single, arm-length scaled reaching response used in the RHI. The slightly zoomed images presented to young children may have made the virtual body feel closer to them than for older children, resulting in less drift at those ages.

In summary, the lack of significant drift in the FBI suggests a relative immaturity of full-body representation in children, in terms of the ability to represent the body as an object in external space and the ability to derive a sense of body ownership from visuo-tactile correlations. It raises the interesting question of how PPS develops in childhood, and underlines the motor and memory demands that may constrain children engaging in virtual experiences.

Practical implications

The results of the present study strongly suggest that virtual "out-of-body experiences" can be experimentally elicited in the same way for children as for adults. With a very simple setup (no stereoscopic display, stimulation delivered for only 2 minutes), we were able to induce of ownership for and touch referral towards a virtual body. These results suggest the promise of using virtual technologies with children. Through commercially available systems such as the *Oculus Rift*, virtual reality is becoming increasingly available both for computer games and education. Recent work with adults has shown in particular that virtual environments can be useful tools for understanding social interactions, for example in reducing implicit racial bias (Peck, Seinfeld, Aglioti & Slater, 2013) or simulating dangerous situations (Slater *et al.,* 2013). Yet while we know that adults can be convincingly embodied in (and have self-identification for) a child's body (Banakou, Groten & Slater, 2013), we still need to understand the limits of viable virtual bodies for children. This will include understanding the roles of visual-proprioceptive congruency (Sanchez-Vives, Spanlang, Frisoli, Bergamasco & Slater, 2010) and interoceptive signals (Aspell *et al*., 2013) in body ownership; as well as the importance of first-person perspective. Further, it will be necessary to measure the extent to which the form of the body matters for children, as it does for adults (Lenggenhager *et al*., 2007; Salomon, van Elk, Aspell & Blanke, 2012; Steptoe, Steed & Slater, 2013). However, the present data provide a good starting point from which to begin this process of tailoring virtual bodies for use with children.

Summary

Using the Full Body Illusion, we found synchrony-dependent changes in self-identification, touch referral, as well as an anterior drift in perceived self-location for adults. These findings are all in keeping with previous studies. For the first time we showed that, for children, the effects of the FBI on self-identification are present from 6-7 years. However, effects on both self-identification and touch referral became stronger with age. These findings suggest that links between multisensory integration and bodily self-consciousness develop significantly across childhood.

References

Adolph, K. E., Cole, W. G., Komati, M., Garciaguirre, J. S., Badaly, D., Lingeman, J. M., ... & Sotsky, R. B. (2012). How do you learn to walk? Thousands of steps and dozens of falls per day. *Psychological Science*, *23* 1387-1394.

Alsmith, A. J., & Longo, M. R. (2014). Where exactly am I? Self-location judgements distribute between head and torso. *Consciousness and Cognition*, *24*, 70-74.

Aspell, J. E., Lenggenhager, B., & Blanke, O. (2009). Keeping in touch with one's self: multisensory mechanisms of self-consciousness. *PLoS ONE 4*, e6488.

Aspell, J. E., Palluel, E., & Blanke, O. (2012). Early and late activity in somatosensory cortex reflects changes in bodily self-consciousness: An evoked potential study. *Neuroscience, 216*, 110-122.

Aspell, J. E., Heydrich, L., Marillier, G., Lavanchy, T., Herbelin, B., & Blanke, O. (2013). Turning body and self inside out: visualized heartbeats alter bodily self-consciousness and tactile perception. *Psychological Science*, *24*, 2445-2453

Bahrick, L. E., & Watson, J. S. (1985). Detection of intermodal proprioceptive–visual contingency as a potential basis of self-perception in infancy. *Developmental Psychology*, *21*, 963.

Banakou, D., Groten, R., & Slater, M. (2013). Illusory ownership of a virtual child body causes overestimation of object sizes and implicit attitude changes. *Proceedings of the National Academy of Sciences*, *110*, 12846-12851.

Begum Ali, J., Cowie, D., & Bremner, A. J. (2014). Effects of posture on tactile localization by 4 years of age are modulated by sight of the hands:

evidence for an early acquired external spatial frame of reference for touch. *Developmental Science*, *17*, 935-943.

Begum Ali, J., Spence, C., & Bremner, A. J. (2015). Human infants' ability to perceive touch in external space develops postnatally. *Current Biology, 25,* R978-R979.

Blanke, O. (2012). Multisensory brain mechanisms of bodily self-consciousness. *Nature Reviews Neuroscience, 13*, 556-571.

Blanke, O., Landis, T., Spinelli, L., & Seeck, M. (2004). Out-of-body experience and autoscopy of neurological origin. *Brain, 127*, 243-258.

Blanke, O., & Metzinger, T. (2009). Full-body illusions and minimal phenomenal selfhood. *Trends in Cognitive Sciences, 13*, 7-13.

Blanke, O., Mohr, C., Michel, C., Pascual-Leone, A., Brugger, P., Seeck, M., . . . Thut, G. (2005). Linking Out-of-Body Experience and Self Processing to Mental Own-Body Imagery at the Temporoparietal Junction. *Journal of Neuroscience, 25*, 550-557.

Botvinick, M., & Cohen, J. (1998). Rubber hands `feel' touch that eyes see. *Nature, 391*(6669), 756-756.

Bremner, A.J. (2016). Developing body representations in early life: Combining somatosensation and vision to perceive the interface between the body and the world. *Developmental Medicine and Child Neurology,* ***58****(Suppl. 4)*, 12-16.

Bremner, A.J., Hill, E.L., Pratt, E., Rigato, S., & Spence, C. (2013). Bodily illusions in young children: Developmental change in the contribution of vision to perceived hand position in early childhood. *PLoS ONE, 8*, e51887.

Bremner, A. J., Mareschal, D., Lloyd-Fox, S., & Spence, C. (2008). Spatial localization of touch in the first year of life: Early influence of a visual spatial code and the development of remapping across changes in limb position. *Journal of Experimental Psychology: General*, *137,* 149-162.

Carruthers, G. (2008). Types of body representation and the sense of embodiment. *Consciousness and Cognition*, *17*, 1302-1316.

Cascio, C. J., Foss-Feig, J. H., Burnette, C. P., Heacock, J. L., & Cosby, A. A. (2012). The rubber hand illusion in children with autism spectrum disorders: delayed influence of combined tactile and visual input on proprioception. *Autism*, *16,* 406-419.

Contreras-Vidal, J. L., Bo, J., Boudreau, J. P., & Clark, J. E. (2005). Development of visuomotor representations for hand movement in young children. *Experimental Brain Research*, *162*, 155-164.

Cowie, D., Makin, T. R., & Bremner, A. J. (2013). Children's responses to the rubber-hand illusion reveal dissociable pathways in body representation. *Psychological Science, 24*, 762-769.

Cowie, D., Sterling, S., & Bremner, A.J. (2016). Multisensory processes in own-hand localisation develop by 10 years: Evidence from the rubber hand illusion, *142,* 230-238.

Dobricki, M., & de la Rosa, S. (2013). The Structure of Conscious Bodily Self-Perception during Full-Body Illusions. *PLoS ONE, 8*, e83840.

Ehrsson, H. (2007). The Experimental Induction of Out-of-Body Experiences. *Science, 317*(5841), 1048.

Ferri, F., Costantini, M., Huang, Z., Perrucci, M. G., Ferretti, A., Romani, G. L., & Northoff, G. (2015). Intertrial variability in the premotor cortex accounts for individual differences in peripersonal space. *The Journal of Neuroscience*, 35 16328-16339.

Filippetti, M. L., Johnson, M. H., Lloyd-Fox, S., Dragovic, D., & Farroni, T. (2013). Body perception in newborns. *Current Biology*, 23, 2413-2416.

Filippetti, M. L., Lloyd-Fox, S., Longo, M. R., Farroni, T., & Johnson, M. H. (2014). Neural mechanisms of body awareness in infants. *Cerebral Cortex*, bhu261.

Freier, L., Mason, L., & Bremner, A. J. (in press). Perception of visual-tactile co-location in the first year of life. *Developmental Psychology.*

Gabbard, C., Cordova, A., & Ammar, D. (2007). Estimation of reach in peripersonal and extrapersonal space: A developmental view. *Developmental Neuropsychology*, 32, 749-756.

Gallagher, S. (2005). *How the body shapes the mind*. Oxford: Clarendon Press.

Gathercole, S. E., Pickering, S. J., Ambridge, B., & Wearing, H. (2004). The structure of working memory from 4 to 15 years of age. Developmental Psychology, *40*, 177-???.

Godoi, D., & Barela, J. A. (2008). Body sway and sensory motor coupling adaptation in children: effects of distance manipulation. *Developmental Psychobiology*, 50(1), 77-87.

Guterstam, A., Björnsdotter, M., Gentile, G., & Ehrsson, H. H. (2015). Posterior cingulate cortex integrates the senses of self-location and body ownership. *Current Biology*, 25(11), 1416-1425.

Hänsell, A., Lenggenhager, B., Känell, R., Curatolol, M., & Blankel, O. (2011). Seeing and identifying with a virtual body decreases pain perception. *European Journal of Pain, 15,* 874-879.

Heydrich, L., & Blanke, O. (2013). Distinct illusory own-body perceptions caused by damage to posterior insula and extrastriate cortex. *Brain*, *136*, 790-803.

Ionta, S., Heydrich, L., Lenggenhager, B., Mouthon, M., Fornari, E., Chapuis, D., . . . Blanke, O. (2011). Multisensory mechanisms in temporo-parietal cortex support self-location and first-person perspective. *Neuron, 70*, 363-374.

Legrand, D. (2006). The bodily self: The sensori-motor roots of pre-reflective self-consciousness. *Phenomenology and the Cognitive Sciences, 5*, 89-118.

Lenggenhager, B., Mouthon, M., & Blanke, O. (2009). Spatial aspects of bodily self-consciousness. *Consciousness and Cognition, 18*, 110-117.

Lenggenhager, B., Tadi, T., Metzinger, T., & Blanke, O. (2007). Video Ergo Sum: Manipulating Bodily Self-Consciousness. *Science, 317*(5841), 1096-1099.

Lewis, M., & Brooks-Gunn, J. (1979). Toward a theory of social cognition: The development of self. *New directions for child and adolescent development*, 1979(4), 1-20.

Lewis, M., & Ramsay, D. (2004). Development of Self-Recognition, Personal Pronoun Use, and Pretend Play During the 2nd Year. *Child Development*, 75(6), 1821-1831.

Lloyd, D.M. (2007). Spatial limits on referred touch to an alien limb may reflect boundaries of visuo-tactile peripersonal space surrounding the hand. *Brain and Cognition*, *64,* 104–109.

Longo, M. R., & Lourenco, S. F. (2007). Space perception and body morphology: extent of near space scales with arm length. *Experimental brain research, 177*, 285-290.

Makin, T. R., Holmes, N. P., & Ehrsson, H. H. (2008). On the other hand: dummy hands and peripersonal space. *Behavioural Brain Research*, *191*, 1-10.

Maselli, A., & Slater, M. (2013). The building blocks of the full body ownership illusion. *Frontiers in Human Neuroscience*, 7.

Maselli, A., & Slater, M. (2014). Maselli, A., & Slater, M. (2014). Sliding perspectives: dissociating ownership from self-location during full body illusions in virtual reality. *Frontiers in Human Neuroscience*, *8*.

Nardini, M., Begus, K., & Mareschal, D. (2013). Multisensory uncertainty reduction for hand localization in children and adults. *Journal of Experimental Psychology: Human Perception and Performance*, *39*, 773-???.

Noel, J. P., Grivaz, P., Marmaroli, P., Lissek, H., Blanke, O., & Serino, A. (2014). Full body action remapping of peripersonal space: The case of walking. *Neuropsychologia*, *70*, 375-384.

Noel, J. P., Pfeiffer, C., Blanke, O., & Serino, A. (2015). Peripersonal space as the space of the bodily self. *Cognition*, *144*, 49-57.

Pagel, B., Heed, T., & Röder, B. (2009). Change of reference frame for tactile localization during child development. *Developmental Science*, *12*, 929-937.

Palluel, E., Aspell, J. E. and Blanke, O. (2011). Leg muscle vibration modulates bodily self-consciousness: integration of proprioceptive, visual, and tactile signals. *Journal of Neurophysiology*, *105*, 2239-2247.

Pamment, J. & Aspell, J.E. (in press). Putting pain out of mind with an 'out of body' illusion. *European Journal of Pain*

Peck, T. C., Seinfeld, S., Aglioti, S. M., & Slater, M. (2013). Putting yourself in the skin of a black avatar reduces implicit racial bias. *Consciousness and Cognition*, *22*, 779-787.

Petkova, V. I., & Ehrsson, H. H. (2008). If I were you: perceptual illusion of body swapping. *PloS ONE*, *3*, e3832.

Petkova, V. I., Khoshnevis, M., & Ehrsson, H. H. (2011). The perspective matters! Multisensory integration in ego-centric reference frames determines full-body ownership. *Cognition, 2 [THIS CAN'T BE RIGHT]*, 35-xx?.

Petkova, V. I., Björnsdotter, M., Gentile, G., Jonsson, T., Li, T. Q., & Ehrsson, H. H. (2011). From part-to whole-body ownership in the multisensory brain. Current Biology, *21* 1118-1122.

Piaget, J., & Inhelder, B. (1967). The child's conception of space. New York: W. W.

Pomés, A., & Slater, M. (2013). Drift and ownership toward a distant virtual body. *Frontiers in Human Neuroscience, 7.*

Povinelli, D.J. (1995). The unduplicated self. IN P. Rochat (Ed.), *The self in infancy* (pp 161 - 192). Amsterdam: North-Holland/Elsevier.

Rigato, S., Begum Ali, J., Van Velzen, J. L., & Bremner, A. J. (2014). The neural basis of somatosensory remapping develops in human infancy. *Current Biology, 24,* 1222-1226.

Rochat, P. (1998). Self-perception and action in infancy. *Experimental Brain Research*, *123*, 102-109.

Rochat, P. (2003). Five levels of self-awareness as they unfold early in life. *Consciousness and Cognition*, *12*, 717-731.

Rochat, P., & Morgan, R. (1995). Spatial determinants in the perception of self-produced leg movements in 3-to 5-month-old infants. *Developmental Psychology, 31,* 626-xxx?.

Rochat, P. (2009). Others in mind: Social origins of self-consciousness. Cambridge University Press.

Rochat, P. (2010). The innate sense of the body develops to become a public affair by 2–3 years. *Neuropsychologia, 48*, 738-745.

Salomon, R., van Elk, M., Aspell, J. E., & Blanke, O. (2012). I feel who I see: visual body identity affects visual–tactile integration in peripersonal space. *Consciousness and Cognition*, *21*, 1355-1364.

Salomon, R., Lim, M., Pfeiffer, C., Gassert, R., & Blanke, O. (2013). Full body illusion is associated with widespread skin temperature reduction. *Frontiers in Behavioral Neuroscience, 7*.

Sakata, H., Taira, M., Murata, A., & Mine, S. (1995). Neural mechanisms of visual guidance of hand action in the parietal cortex of the monkey. *Cerebral Cortex*, *5*, 429-438.

Sanchez-Vives, M. V., Spanlang, B., Frisoli, A., Bergamasco, M., & Slater, M. (2010). Virtual hand illusion induced by visuomotor correlations. *PloS ONE*, 5, e10381.

Schmuckler, M. A. (1996). Visual-proprioceptive intermodal perception in infancy. *Infant Behavior and Development*, *19*, 221-232.

Serino, A., Alsmith, A., Costantini, M., Mandrigin, A., Tajadura-Jimenez, A., & Lopez, C. (2013). Bodily ownership and self-location: Components of bodily self-consciousness. *Consciousness and Cognition, 22*, 1239-1252.

Slater, M., Rovira, A., Southern, R., Swapp, D., Zhang, J. J., Campbell, C., & Levine, M. (2013). Bystander responses to a violent incident in an immersive virtual environment. *PLoS ONE, 8*, e52766.

Steptoe, W., Steed, A., & Slater, M. (2013). Human tails: ownership and control of extended humanoid avatars. *IEEE Transactions on Visualization and Computer Graphics, 19*, 583-590.

Tsakiris, M., & Haggard, P. (2005). The rubber hand illusion revisited: visuo-tactile integration and self-attribution. *Journal of Experimental Psychology: Human Perception and Performance*, *31*, 80-xx??.

Tsakiris, M. (2010). My body in the brain: a neurocognitive model of body-ownership. Neuropsychologia, *48*, 703-712.

van der Hoort, B., Guterstam, A., & Ehrsson, H. H. (2011). Being Barbie: the size of one's own body determines the perceived size of the world. *PLoS ONE, 6*, e20195.

Vogeley, K., & Fink, G. R. (2003). Neural correlates of the first-person-perspective. *Trends in Cognitive Sciences*, *7*, 38-42.

Zmyj, N., Jank, J., Schütz-Bosbach, S., & Daum, M. M. (2011). Detection of visual–tactile contingency in the first year after birth. *Cognition*, *120*, 82-89.

Table 1. Self-identification Questionnaire.

1 When I was stroking with the magic wand, did it sometimes seem as if you could feel the touch of the stick on the body you saw over there?
2 When I was stroking with the magic wand, did you sometimes feel like the body you saw over there was your body?
3 When I was stroking with the magic wand, did it feel like your nose was growing?
4 Did you notice any difference between the first and second times I did the stroking?

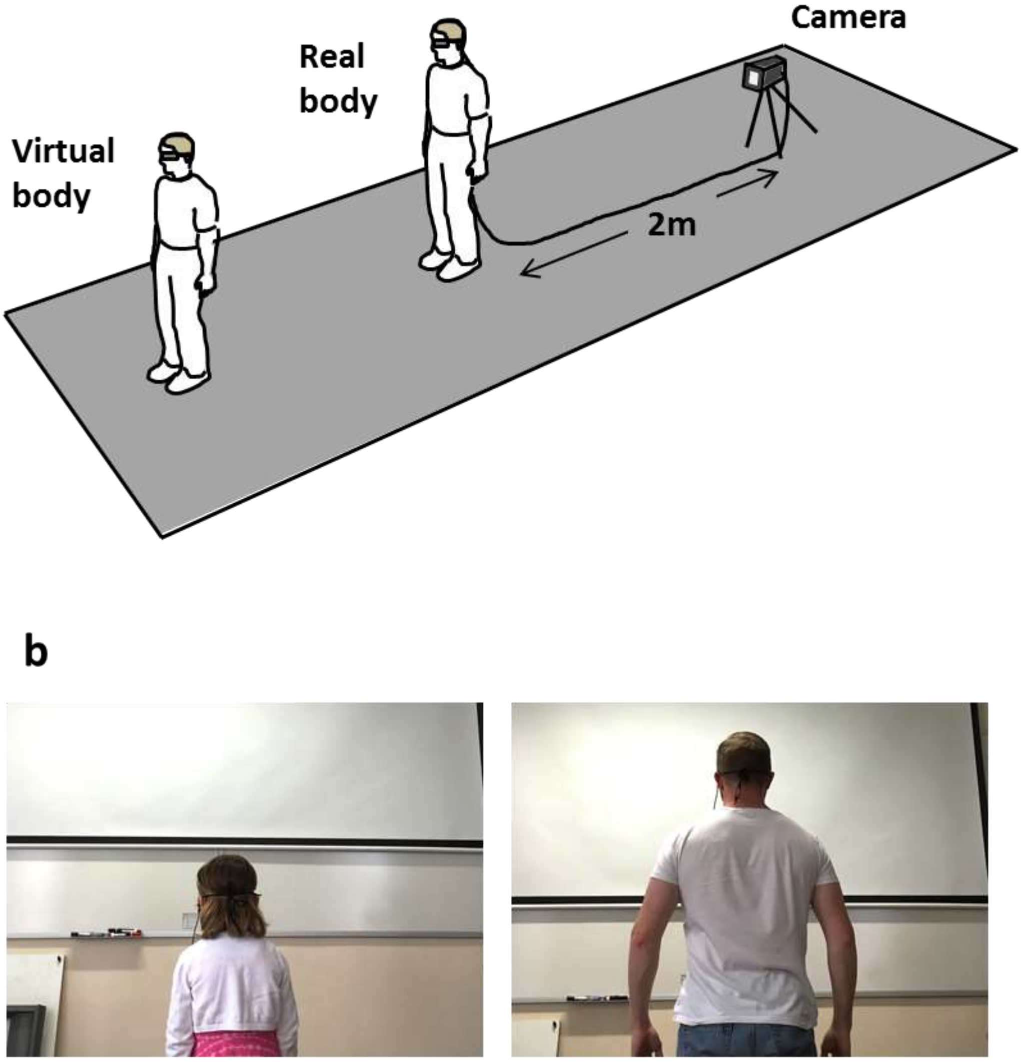
Table 2. Baseline drift responses. Constant error (average distance between baseline estimates and target: positive errors are forwards). Variable error (unsigned difference between the two baseline estimates). Means (standard errors) shown.

Age group	**Constant error (m)**	**Variable error (m)**
6-7 y	-.012 (0.06)	0.310 (0.05)
8-9 y	-.087 (0.06)	0.271 (0.05)
10-11 y	-.192 (0.05)	0.203 (0.04)
Adult	0.023 (0.03)	0.145 (0.02)

Table 3. T-tests comparing baseline-corrected drift responses to zero. Using one-sample t-tests, with p values corrected for 8 multiple comparisons.

Age group	**Condition**	**t**	**df**	**Sig**	**Effect size (Cohen's d)**
6-7 y	S	-2.1	27	1.0	-0.4
	A	-1.3	27	1.0	-0.2
8-9 y	S	1.0	20	1.0	0.2
	A	0.01	20	1.0	0.0
10-11 y	S	-0.8	18	1.0	-0.2
	A	1.7	18	1.0	0.4
Adult	S	5.4	30	<.001*	1.0
	A	0.1	30	1.0	0.0

a



b

Figure 1. a. Equipment setup. A camera 2m behind the participant films their back. This view is fed into a head mounted display he wears, to produce a virtual body positioned ahead of the participant. **b.** Typical views for a child and an adult.

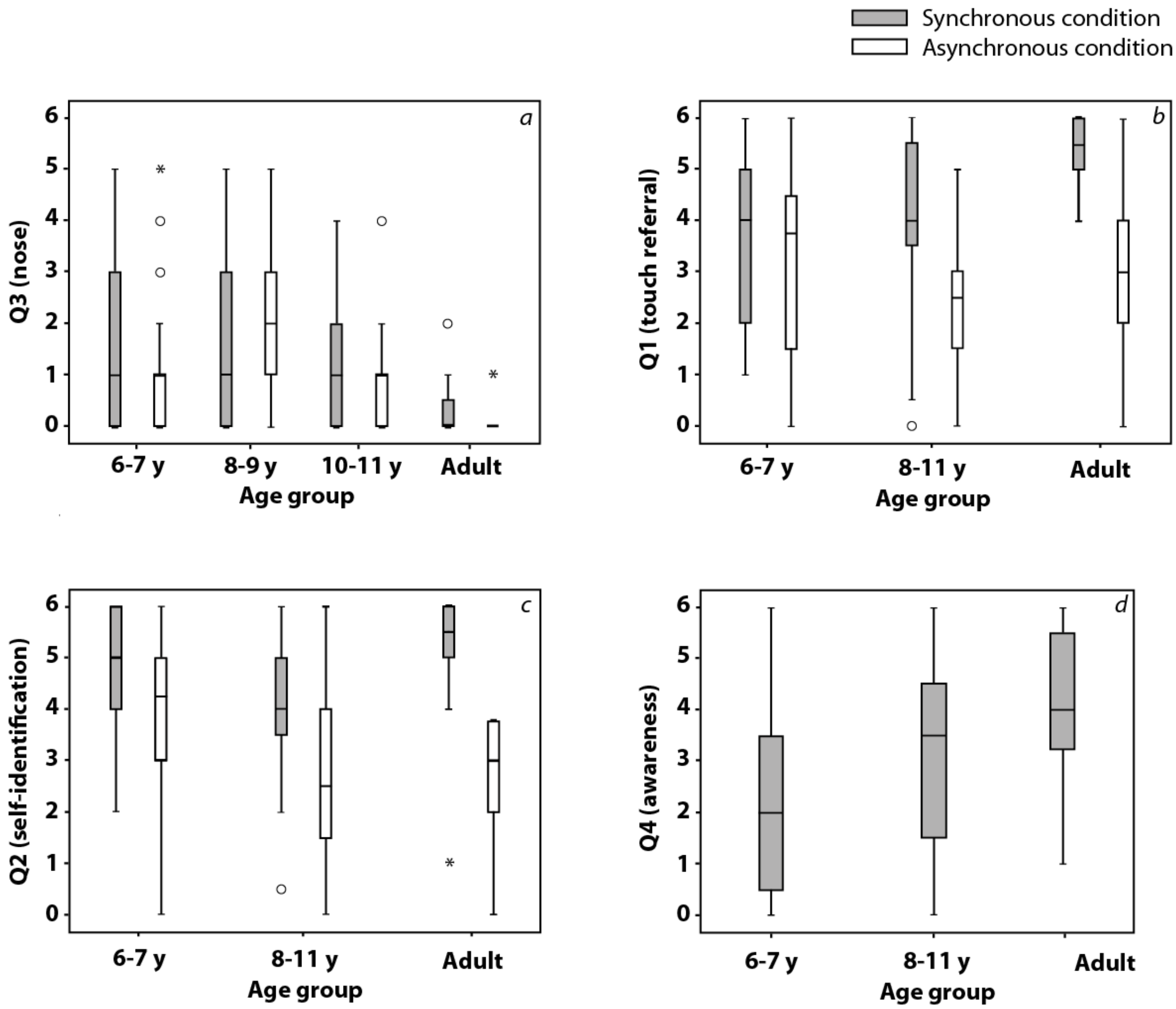


Figure 2. Group medians (black lines) and interquartile ranges. Whiskers represent 1.5 x IQR. Outliers (1.5-3 x IQR) shown by unfilled circles; extreme values (>3 x IQR) shown by asterisks. Shown for **a** Q3 (control question) raw scores. **b** Q1 (touch referral) scores. **c** Q2 (self-identification) scores. **d** Q4 (awareness) scores.

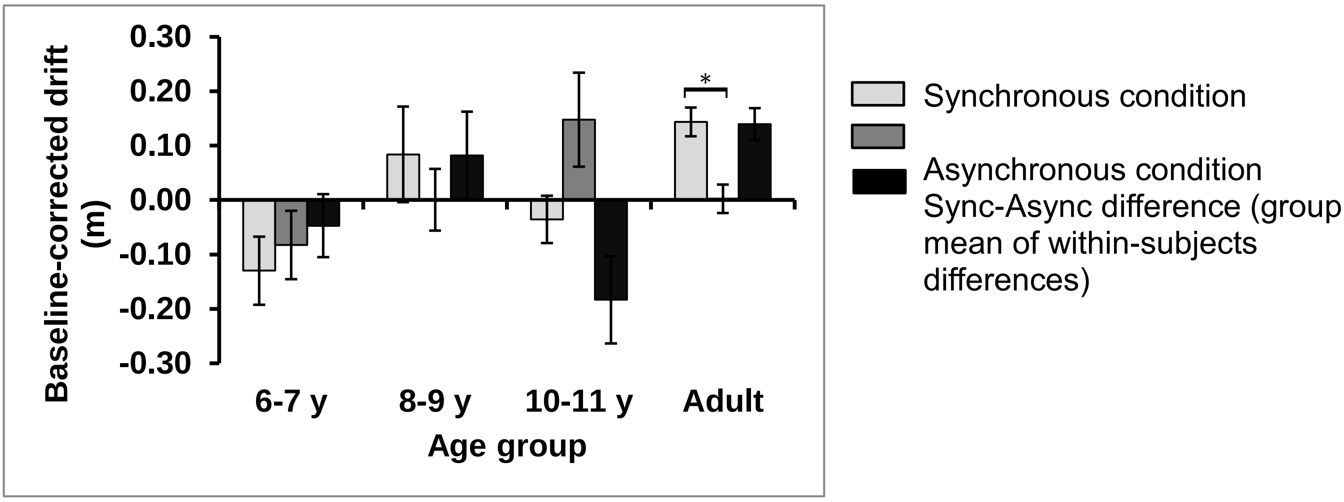
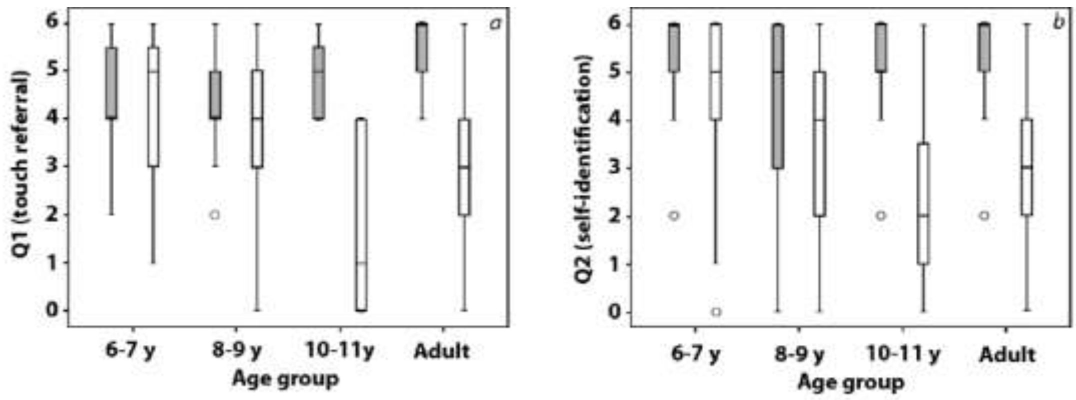


Fig 3. Group means ±SEM of baseline-corrected drift following synchronous and asynchronous stroking, and within-subjects differences between drift in these conditions.



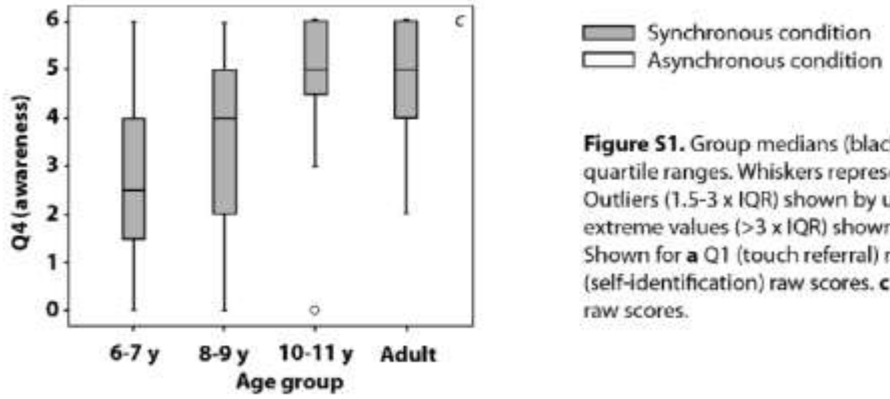


Figure S1. Group medians (black lines) and interquartile ranges. Whiskers represent 1.5 x IQR. Outliers (1.5-3 x IQR) shown by unfilled circles; extreme values (>3 x IQR) shown by asterisks. Shown for **a** Q1 (touch referral) raw scores. **b** Q2 (self-identification) raw scores. **c** Q4 (awareness) raw scores.