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

Dorothy Cowie[1], Aisling McKenna[2], Andrew J. Bremner[2], Jane E. Aspell[3]

[1]Department of Psychology, Durham University

[2]Sensorimotor Development Research Unit, Department of Psychology, Goldsmiths, University of London

[3]Department of Psychology, Anglia Ruskin University

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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 embodiment: 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 embodiment develop significantly across childhood. This suggests a long period of development in bodily self-consciousness 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). 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). Body ownership is the feeling that one's own physical body and its parts belong to 'me' – that it is 'my' body (Blanke, 2012).

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). 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, & Blankel, 2011) and body temperature (Salomon, Lim, Pfeiffer, Gassert, & Blanke, 2013). Neuroimaging studies using this technique have demonstrated associated changes in the activity of the temporo-parietal junction (Ionta *et al*., 2011), which has been implicated in out of body experiences (Blanke, Landis, Spinelli, & Seeck, 2004; Blanke *et al*., 2005).

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) 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 (Cowie, Makin & Bremner, 2013; Cascio, Foss-Feig, Burnette, Heacock & Cosby, 2012) has shown that manipulation of visual-tactile cues can also generate bodily illusions in children. Cowie *et al*. (2013) showed that in 4- to 9-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; Cowie, Sterling & Bremner, submitted). 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 a full body illusion 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 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 the video camera zoomed in order that each participant was shown a region from the bottom of their back upwards to the top of their head and above. 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 investigate these, we used for each measure repeated measures analysis of variance (ANOVA) with the factors Synchrony (synchronous, asynchronous) and Age (6-7 years, 8-9 years, 10-11 years, adult). To further investigate effects, we used t-tests. Where we made multiple comparisons, bonferroni-corrected alpha levels are reported.

Results

Insert Figure 2 about here

Q3 (control question)

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?”). On inspection of Fig 2a it is obvious that children and adults responded somewhat differently to this question. ANOVA confirmed that while there was no significant effect of synchrony, F(1,95)=0.38, p=.54, η^2_p = 0.004, and no interaction between synchrony and age, F(3,95)=1.1, p=.36, η^2_p = 0.03, there was a significant effect of age, F(3,95)=10.0, p<.001 η^2_p = 0.24. This included significant linear (p<.001) and quadratic (p=.001) components, with children tending to agree with statements more positively than adults, peaking in the 8-9 yrs group. These age-related differences in response style would not affect the crucial synchronous *vs.* asynchronous comparisons made for other questionnaire items, but may have contributed to effects of age in these items.

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 'corrected' scores for Q1, Q2 and Q4. 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. We therefore removed participants for whom this was the case (6-7 year olds n=5; 8-9 year olds n=9; 10-11 year olds n=3).

The remaining sample was as follows: 6- to 7-year-olds (M=6.9y, SD=0.4y, n=23); 8- to 9-year-olds (M=9.0y, SD=0.2y, n=12); 10- to 11-year-olds (M=11.2y, SD=0.4y, n=16); adults (as before, M=27.4y, SD=9.0y, n=31). The corrected questionnaire values for this sample are shown in Figs 2c, e and g. As Figure 2 shows, the correction and removal of participants affected results only slightly. All ANOVA results remained the same. Eight- to nine- year-olds show an effect of Synchrony for uncorrected values only (probably because that age group had the largest number of participants removed during correction). Nevertheless, in our view correction was an effective and rigorous way to prevent age-related answering effects contaminating the data.

Q1 (Touch Referral)

An ANOVA of the full sample's uncorrected scores (Fig 2b) shows a main effect of Age, F(3,95)=4.1, p=.009, η^2_p = 0.12; a main effect of Synchrony, F(1,95)=85.6, p<.001, η^2_p = 0.47; and a significant interaction of Age x Synchrony, F(3,95)=15.1, p<.001, η^2_p = 0.32. However, we have reasoned that the data are best understood once scores have been corrected for answer style. ANOVA on Q1 corrected values (Fig 2c) likewise showed a main effect of Age, F(3,78)=5.3, p=.002, η^2_p = 0.17, a main effect of Synchrony, F(1,78)=65.8, p<.001, η^2_p = 0.46; and a significant interaction, F(3,78)=12.0, p<.001, η^2_p = 0.32. Synchronous stroking (M=4.2) produced stronger feelings of referred touch than asynchronous stroking (M=2.6). Age showed a significant quadratic contrast (p=.006): averaged across stroking conditions, 10- to 11-year-olds had a lower mean rating (M=2.7) than 6- to 7-year-olds (M=3.5), 8- to 9-year-olds (M=3.3), or adults (M=4.1).

To explore the Age by Synchrony interaction, we first measured the effects of Synchrony at each age with one-tailed paired samples t-tests (α =.0125, corrected for four multiple comparisons). Synchronous stroking produced stronger feelings of referred touch than asynchronous stroking at 10-11 years, t(15)=5.9, p<.001, d=1.5, and adult, t(30)=8.5, p<.001, d=1.5, but not at 6-7 years, t(22)=2.0, p=.03, d=0.4, or 8-9 years, t(11)=0.6, p=.30, d=0.2. Thus, the effects of Synchrony on touch referral to the virtual body increase with age, becoming fully apparent at around 10 years of age. Indeed one-sample t-tests against the neutral value show that in the synchronous condition responses were larger than the neutral value only for 10- to 11-year-olds and adults (Table 1). This confirms that, for 10- to 11-year-olds and adults, synchronous stroking produced illusory touch referral onto the virtual body.

Insert Table 2 about here

To explore the Age by Synchrony interaction further, we measured the effects of age in each stroking condition. There were effects of age in both the synchronous and asynchronous conditions. In the synchronous condition, the significant effect of Age, F(3,81)=9.7, p<.001, $\eta^2 = 0.27$, reflected both a linear increase with age (p<.001) and a quadratic effect (p=.016) such that scores were similar in the 6- to 7-year-olds and 8- to 9-year-olds but rose in the 10- to 11-year-olds and adults. In the asynchronous condition, the main effect of Age F(3,81)=6.0, p=.001, $\eta^2 = 0.19$, reflected both a linear decrease with age (p=.044) and a quadratic effect (p=.029) such that scores dipped in the 10- to 11-year-old group. Thus, both synchronous and asynchronous stroking produced increasingly adult-like effects of touch referral with age.

Q2 (self-identification)

An ANOVA on the full sample's uncorrected scores (Fig. 2d) showed a main effect of Age, F(3,95)=5.3, p=.002, η^2_p =0.143; a main effect of Synchrony, F(1,95)=81.0, p<.001, η^2_p =0.46; and a significant interaction, F(3,95)=10.4, p<.001, η^2_p =0.25. ANOVA on Q2 corrected values of the final group (Fig. 2e) similarly showed a main effect of Age, F(3,78)=4.0, p=.011,η^2_p = 0.13; a main effect of Synchrony, F(1,78)=67.8, p<.001, η^2_p = 0.47; and a significant interaction, F(3,78)=8.5, p<.001, η^2_p = 0.25. Synchronous stroking (M=4.5) produced stronger agreement than asynchronous stroking (M=2.9). There was a significant quadratic effect of age (p=.003) such that that 6- to 7-year-olds (M=4.2) and adults (M=4.0) scored most highly, with 8- to 9-year-olds (M=3.5) and 10- to 11-year-olds (M=3.0) scoring more moderately.

To explore the Age by Synchrony interaction, we first measured the effects of synchrony at each age with one-tailed paired samples t-tests (α =.0125, corrected for multiple comparisons). These showed that synchronous stroking produced stronger agreement than asynchronous at 6-7 years, t(22)=2.6, p=.008, d=0.5; 10-11 years, t(15)=7.4, p<.001, d=1.5; and adult, t(30)=7.3, p<.001, d=1.3, but not at 8-9 years, t(11)=1.1, p=.15, d=0.3. One-sample t-tests against the neutral value show that in the synchronous condition responses were larger than the neutral value for all ages except 8- to 9-year-olds (Table 3). Thus, synchronous stroking produced illusory touch referral onto the virtual body for the youngest group of children tested.

Insert Table 3 about here

To explore the Age by Synchrony interaction further, we tested the effects of age in each stroking condition. There was an effect of Age in the synchronous condition, F(3,81)=5.5, p=.002, η^2 = 0.17, which had significant linear (p=.027) and quadratic (p=.001) components. Scores broadly increased with age but were also highest in the youngest and older groups compared to the middle. There was a significant effect of Age in the asynchronous condition, F(3,81)=5.5, p=.002, η^2 = 0.18. This had a significant linear component (p=.002) and a marginal quadratic component (p=.054). Scores broadly decreased with age but were notably lowest at 10-11 years.

Q4 (awareness)

To ask whether participants were aware of a difference between the synchronous and asynchronous conditions, we tested the effect of Age on responses to question 4. Analysis of the full sample's uncorrected scores (Fig 2f) showed a main effect of Age F(3,95)=7.1, p<.001,η^2 = 0.18. Analysis on Q4 corrected values (Fig 2g) also showed a main effect of Age, F(3,78)=7.4, p<.001,η^2 = 0.22. With increasing age, there was a linear increase in the extent to which participants noticed the difference between stroking conditions (p<.001). T-tests (Table 4) showed that only adults were significantly aware of the difference.

Insert Table 4 about here

Drift measures

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 Figure 3 about here

We first took two baseline measures of the walking estimate, with no visuo-tactile stimulation. Baseline constant error (Fig. 3a) showed a main effect of Age, F(3,95)=3.4, p=.021, η^2 = 0.10. Neither linear nor quadratic components were significant. Baseline variable error (Fig 3b) showed a main effect of Age, F(3,95)=3.9, p=.011, η^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 effects.

Insert Figure 4 about here

This baseline-corrected drift (Fig. 4) 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, with α corrected to 0.0125 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=0.58, d = -0.2, 8- to 9-year-olds, t(20)=1.0, p=0.32, d = 0.2, or 10- to 11-year-olds, t(18)=-2.3, p=0.96, d = -0.5. One-sample t-tests comparing drift with zero showed a difference only for adults in the synchronous condition (Table 5).

Insert Table 5 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 embodiment develops, moving beyond what is known both of multisensory perception (Filippetti *et al.*, 2013, 2014; Bahrick & Watson, 1985; Rochat, 1998; Zmyj *et al.*, 2011) and a sense of ownership relating to body parts (Cowie *et al.*, 2013). It shows significant development across childhood in the sensory bases of whole body representations, which are arguably more fundamentally tied to the sense of self (Blanke & Metzinger, 2009).

Self-identification

At 6-7 years, 10-11 years and adult, 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. Baseline-corrected scores in the synchronous condition were also larger than neutral value on the rating scale. Our correction for response bias meant that the 8- to 9-year-old group had the lowest sample size, so an underlying effect of synchrony at that age is difficult to rule out. 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; Aspell *et al.*, 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. Lenggenhager, 2007; Aspell *et al.*, 2009) 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. Rather, the result is in line with the view that an "explicit, reflective" conception of the self develops in early childhood (Rochat, 2003). By 18 months or so, children are not only able to notice a contingency between felt and seen movements, but to identify a view of the body as the self - for example, removing a sticker from their own body which they see on the body in the mirror (Povinelli, 1995). Here we show that this kind of self-identification is apparent and modulated by visuo-tactile synchrony at the youngest age we tested in the current paradigm.

Strikingly, we also found that as age increased, synchrony increasingly strengthened self-identification with the virtual body, while asynchrony increasingly weakened it. This suggests that middle childhood sees a strengthening of the link between visuo-tactile synchrony and self-identification with the body, and 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 populations differ in their neural substrates (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 peripersonal space. 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 test 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 touch to the 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 supported by 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 6-9 years, there were no significant differences between responses to synchronous and asynchronous stroking. In contrast, for 10- 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.

This result 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; Bremner, Mareschal, Lloyd-Fox & Spence, 2008b).

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 peripersonal space is body-scaled (as for manual peripersonal space (Gabbard, Cordova & Ammar, 2007)), then in absolute terms children’s whole-body PPS will not extend as far as adults’. In walking adults, PPS extends to 165 cm from the body (approaching sounds at that distance reduced reaction times to a touch on the chest; Noel *et al*., 2014)). In our task participants walk 150 cm backwards and typically <25 cm forwards of their start position (e.g., Lenggenhager *et al*., 2007; Aspell *et al*., 2009). While this would be inside the 'walking PPS boundary' for adults, it may fall outside it for children. This could make touch localization difficult and raises the question of how whole-body peripersonal space develops in childhood, which should be tested 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 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 assessed, 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 bodily 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 temporo-parietal 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 design-related issues 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.

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 embodiment from visuo-tactile correlations. It raises the interesting question of how peripersonal space 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 like 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 a child's body (Banakou, Groten & Slater, 2013), we still need to understand the limits of generating virtual bodies for children to use. 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.

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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. T-tests comparing baseline-corrected touch referral questionnaire responses to the neutral value (3). α is corrected to 0.0125 for 8 multiple comparisons.

Age group	**Condition**	**t**	**df**	**Sig**	**Effect size (Cohen's d)**
6-7 y	Sync	2.2	22	.035	0.5
	Async	0.4	22	.672	0.1
8-9 y	Sync	.75	11	.467	0.2
	Async	.40	11	.698	0.1
10-11 y	Sync	3.9	15	.001*	1.0
	Async	-5.0	15	<.001*	-1.3
Adult	Sync	19.8	30	<.001*	3.6
	Async	-0.6	30	.567	-0.1

Table 3. T-tests comparing baseline-corrected self-identification questionnaire responses to the neutral value (3). α is corrected to 0.0125 for 8 multiple comparisons.

Age group	**Condition**	**t**	**df**	**Sig**	**Effect size (Cohen's d)**
6-7 y	Sync	7.3	22	<.001*	1.5
	Async	2.1	22	.049	0.4
8-9 y	Sync	1.7	11	.118	0.5
	Async	0.7	11	.486	0.2
10-11 y	Sync	4.6	15	<.001*	1.2
	Async	-3.1	15	.007*	-0.8
Adult	Sync	12.4	30	<.001*	2.2
	Async	-1.0	30	.344	-0.2

Table 4. T-tests comparing baseline-corrected awareness questionnaire responses to the neutral value (3). α is corrected to 0.025 for 4 multiple comparisons.

Age group	**t**	**df**	**Sig**	**Effect size (Cohen's d)**
6-7 y	-2.2	22	.042	-0.5
8-9 y	-1.1	11	.284	0.3
10-11 y	2.0	15	.067	0.5
Adult	4.0	30	<.001*	0.7

Table 5. T-tests comparing baseline-corrected drift responses to zero. α is corrected to 0.0125 for 8 multiple comparisons.

Age group	**Condition**	**t**	**df**	**Sig**	**Effect size (Cohen's d)**
6-7 y	S	-2.1	27	0.048	-0.4
	A	-1.3	27	.200	-0.2
8-9 y	S	1.0	20	.352	0.2
	A	0.01	20	.993	0.0
10-11 y	S	-0.8	18	.420	-0.2
	A	1.7	18	.105	0.4
Adult	S	5.4	30	<.001*	1.0
	A	0.1	30	.931	0.0

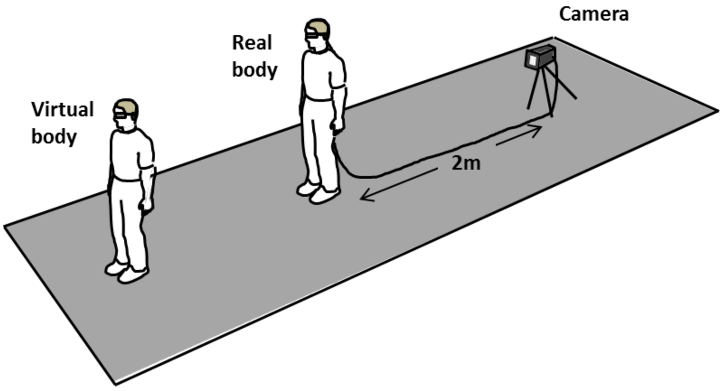

Figure 1. Equipment setup. A camera 2m behind the participant films their back. This view is fed into a head mounted display he wears, to produce a virtual body positioned ahead of the participant.

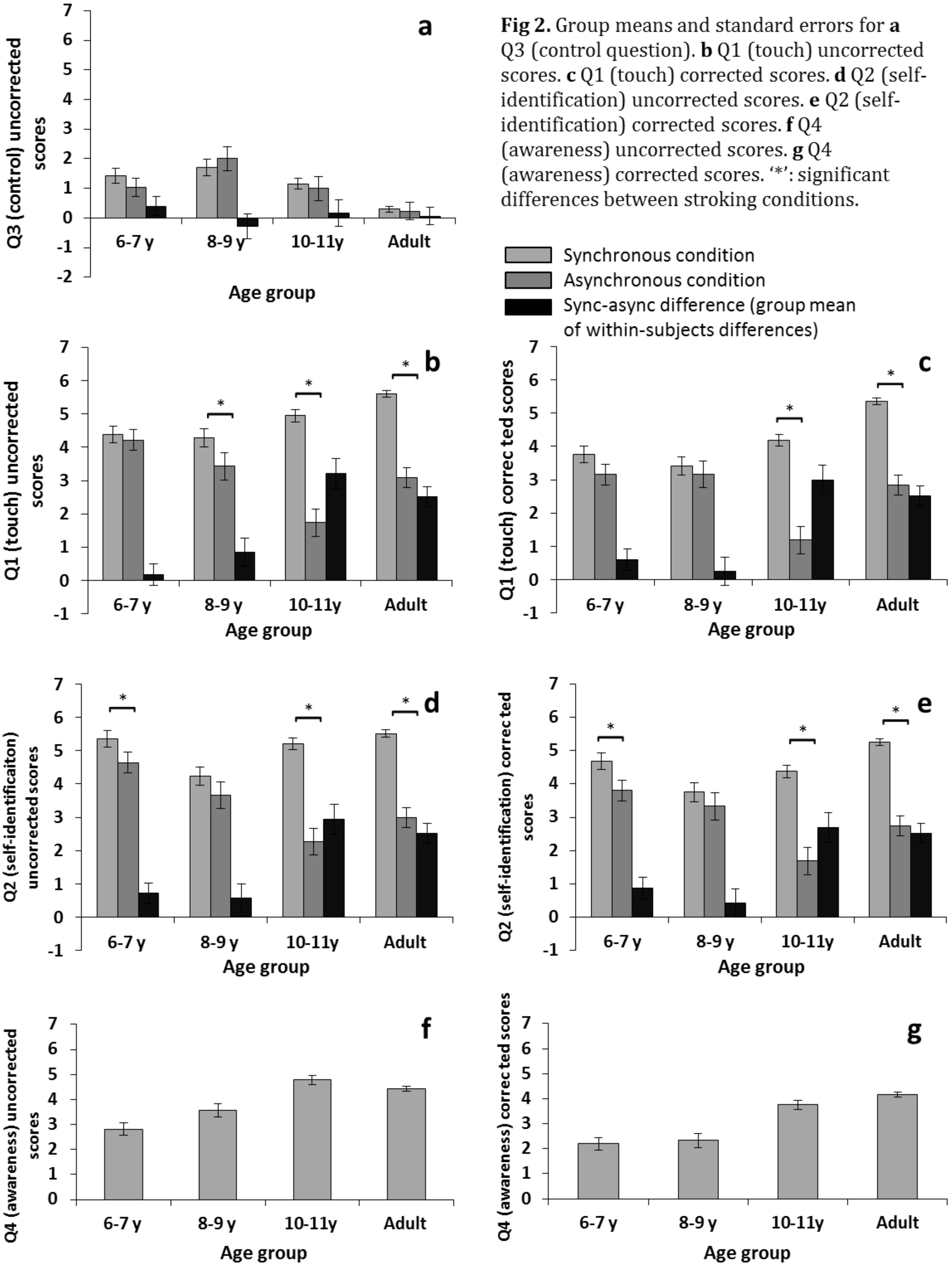

Fig 2. Group means and standard errors for **a** Q3 (control question). **b** Q1 (touch) uncorrected scores. **c** Q1 (touch) corrected scores. **d** Q2 (self-identification) uncorrected scores. **e** Q2 (self-identification) corrected scores. **f** Q4 (awareness) uncorrected scores. **g** Q4 (awareness) corrected scores. '*': significant differences between stroking conditions.

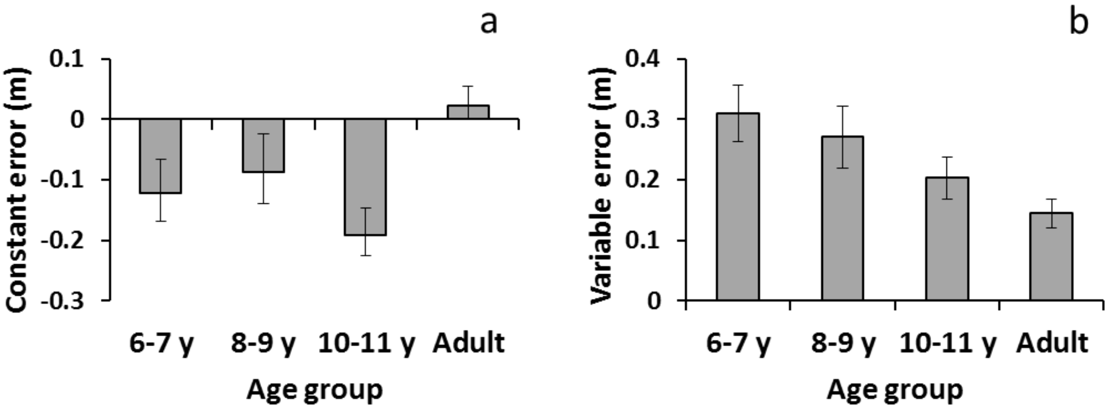

Fig 3. Group mean ±SEM baseline walking measures. (A) 'Constant error': baseline estimate distance from target position. (B) 'Variable error': difference between baseline trials 1 and 2.

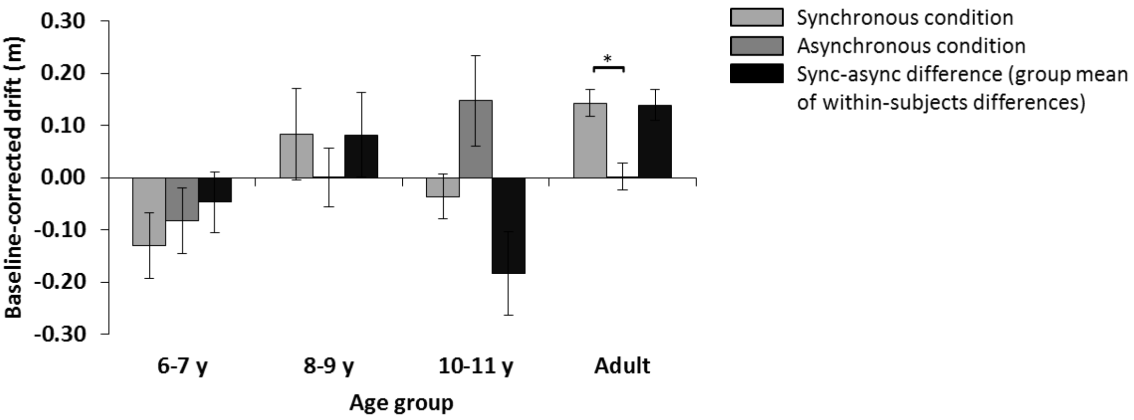

Fig 4. Group means ±SEM of baseline-corrected drift following synchronous and asynchronous stroking, and within-subjects differences between drift in these conditions.