



## Children's responses to the Rubber Hand Illusion reveal dissociable pathways in body representation

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RUNNING HEAD: DEVELOPMENT OF THE BODILY SELF

**Children's responses to the Rubber Hand Illusion reveal dissociable pathways in body representation**

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## ABSTRACT

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The bodily self is constructed from multisensory information. However, little is known of the relationship between multisensory development and the emerging sense of self. We investigated this question by measuring the strength of the “Rubber Hand Illusion” in young children (4 to 9 years old) and adults. Intermanual pointing showed that children were as sensitive as adults to visual-tactile synchrony cues for hand position, indicating a visual-tactile pathway to the bodily self which matures by at least 4 years of age. However, regardless of synchrony cues, felt hand position was captured more by the fake hand for children than for adults. This indicates a second, later-maturing process based on visual-proprioceptive information. Furthermore, explicit feelings of embodiment were only related to the visual-tactile process. These findings demonstrate two dissociable processes underlying body representation in early life, and call into question current models of body representation and ownership in adulthood.

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3 **Children's responses to the Rubber Hand Illusion reveal dissociable pathways in body**  
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5 **representation**  
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10 Our sense of self is constructed from multisensory information, including that from  
11 vision, touch, and proprioception (Makin, Holmes, & Ehrsson, 2008; Longo, Schüür,  
12 Kammers, Tsakiris, & Haggard, 2008; Tsakiris, 2010; Ehrsson, 2012). While it is clear that  
13 both multisensory bodily perception (Bremner, Holmes, & Spence, 2012; Rochat, 1998;  
14 Zmyj, Jank, Schütz-Bosbach, & Daum, 2011) and the sense of self (e.g. Lewis, 2011; Rochat,  
15 2010; Slaughter & Brownell, 2011) develop in infancy and early childhood, there has been  
16 little investigation of the relationship between these processes. For example, it is clear from  
17 young infants' visual preferences that they can perceive the visual-proprioceptive (Bahrick &  
18 Watson, 1985; Morgan & Rochat, 1997; Schmuckler, 1996) and visual-tactile (Zmyj *et al.*,  
19 2011) correspondences which underpin own-body perception in adults. Yet the extent to  
20 which young children actually derive a sense of bodily self or body-ownership from these  
21 multisensory correspondences is difficult to determine (see Bremner, Holmes & Spence,  
22 2012). Using the "Rubber Hand Illusion" (Botvinick & Cohen, 1998), we tracked the  
23 development of young children's use of multisensory information to localise their own body  
24 parts and gain a subjective sense of body ownership. In this illusion, the sight of a fake hand  
25 being stroked, combined with synchronous tactile cues on the real hidden hand, causes adult  
26 participants to feel as if the fake hand is their own, and perceive the touch they feel as arising  
27 from the seen brush, stroking the fake hand.  
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49 Although the relation between the multisensory bodily self and the subjective sense of  
50 self in childhood is poorly understood, a wide range of studies have addressed these two  
51 issues separately. The subjective sense of self in children has been studied using explicit  
52 measures of self-knowledge including mirror self-recognition, the use of personal pronouns,  
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3 and the tendency to engage in pretend play (Lewis, 2011; Rochat, 2010). Some aspects of an  
4  
5 explicit subjective sense of the self appear to continue developing well into childhood (e.g.  
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7 Pavinelli, Landry, Theall, Clark, & Castille, 1999).

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10 The multisensory bodily self has been studied with a range of tasks. Research has  
11  
12 shown that young infants can achieve crossmodal transfer between visual and tactile stimuli  
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14 (e.g. Sann & Streri, 2007), perceive temporal synchrony between visual and tactile  
15  
16 stimulation to the limbs (Zmyj *et al.*, 2011), and perceive synchrony between visual and  
17  
18 proprioceptive signals during limb movement (see Rochat, 1998). Despite this early  
19  
20 competence, research investigating children's intermanual pointing and ballistic movements  
21  
22 indicates a protracted development of multisensory body representations across childhood.  
23  
24 More specifically, while adults integrate proprioceptive and visual cues for localising the  
25  
26 hand (van Beers, Sittig, & Denier van der Gon, 1996), in middle childhood visual cues to the  
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28 hand appear to dominate proprioception (Smothergill, 1973; Von Hofsten & Rösblad, 1988;  
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30 Hay, Bard, Fleury, & Teasdale, 1991; Smyth, Peacock, & Katamba, 2004; although see  
31  
32 Pagel, Heed, & Röder, 2009). This late development is also in line with recent evidence  
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34 concerning the development of multisensory processing more generally (Gori, Del Viva,  
35  
36 Sandini, & Burr, 2008; Nardini, Jones, Bedford, & Braddick, 2008).

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40 There are several key issues concerning the development of the bodily self which are,  
41  
42 as yet, unaddressed. First, it is not clear whether, in childhood, vision of the hand dominates  
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44 in establishing a subjective sense of hand ownership to the extent that it does in establishing a  
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46 sense of hand position. Second, as well as receiving information about our body from vision  
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48 and proprioception, nearby objects can play a role, through touch, in determining where we  
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50 perceive our limbs to be (Botvinick & Cohen, 1998; Makin *et al.*, 2008). No studies have  
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52 examined how, during childhood, these tactile cues interact with visual cues in establishing  
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54 hand position and ownership.  
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3 Here we report an experiment in which we used the Rubber Hand Illusion to  
4 investigate how young children (aged from 4 to 9 years) use visual and visual-tactile  
5 information to localise the body and establish a subjective sense of bodily self. Following  
6 either synchronous or asynchronous stroking on the real and fake hands, perceived hand  
7 position was measured by asking participants, with eyes closed, to point underneath the table  
8 to the index finger of the stimulated hand (Botvinick & Cohen, 1998). Finally the  
9 participants' sense of body ownership was quantified using a questionnaire. Based on what  
10 we know of the development of multisensory processing for hand localisation (Smothergill,  
11 1973; Von Hofsten & Rösblad, 1988), and more broadly (Gori *et al.*, 2008; Nardini *et al.*,  
12 2008), one might expect to find developmental progression throughout early and mid-  
13 childhood.

#### Method

14 We measured the strength of the Rubber Hand Illusion in adults and children.  
15 Participants sat with their left hand on a table in front of them, hidden from view. To measure  
16 baseline hand localisation ability, participants were asked to point underneath their left hand.  
17 Following this a fake hand was placed on the table, and stroked synchronously or  
18 asynchronously with the real hand. Participants again pointed underneath their left finger. We  
19 measured whether these "post-induction" points shifted with respect to the baseline points.  
20 Finally we asked questions concerning the sense of ownership felt over the fake hand, and the  
21 perceived location of the paintbrush touches.

#### Participants

22 We tested adults ( $M=23.9y$ ,  $SD=4.2y$ ,  $n=30$ ), and 3 age groups of children (4- to 5-  
23 year-olds:  $M=5.1y$ ,  $SD=0.3y$ ,  $n=30$ ; 6- to 7-year-olds:  $M=7.1y$ ,  $SD=0.5y$ ,  $n=30$ ; 8- to 9-year-  
24 olds:  $M=9.2y$ ,  $SD=0.4y$ ,  $n=30$ ). Two 4-year-olds from our initial sample were excluded due  
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3 to their performance on the “catch trial” (see below), and replaced with two further 4-year-  
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5 olds so that the final sample for this age-group comprised 30 participants. For half of each  
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7 age-group, the fake and real hands were stroked synchronously; for the other half they were  
8  
9 stroked asynchronously. This between-subjects design (see Botvinick & Cohen, 1998)  
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11 minimised testing time for the young participants.  
12

### 13 Experimental procedure

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16 In order to keep the postural configuration and motor demands of the setup the same  
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18 across differently-sized participants, we scaled setups and measured behavioural responses in  
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20 units of % arm length rather than absolute distance (e.g. cm). The right hand was placed on a  
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22 tray under the table, at 50% of the participant’s arm length to the right of the body midline.  
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24 On two training trials, the left hand was visible and rested on the table. Participants were  
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26 trained to slide the right index finger along a horizontal groove so that it was underneath the  
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28 left index finger. This meant that in all trials points were only made in the mediolateral axis.  
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32 After training, participants completed four baseline trials. The right hand was  
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34 positioned as before, with the left hand resting on the table at 25% arm length to the left of  
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36 body midline. With eyes closed, participants were asked to point with their right index finger  
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38 underneath their left index finger. The position of each point was marked under the table. For  
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40 each participant the mean and standard deviation of these four points were used in analysis.  
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42 Participants then chose a sticker from a small box. This encouraged the children and reduced  
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44 the likelihood of the baseline trials biasing subsequent test-condition pointing.  
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48 The test condition started with the participant’s eyes closed, the real left hand placed  
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50 at 25% arm length to the left of the body midline, the fake left hand at the midline, and the  
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52 right hand, as before, under the table at 50% arm length to the right of midline. Positioning  
53  
54 the fake hand at body midline eliminated any disturbances of tactile localisation due to  
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56 changes in head or eye position (Harrar & Harris, 2009; Ho & Spence, 2007). A cloth was  
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3 now placed over the left arm. The fake hand was a painted, plaster-cast hand, appropriately-  
4 sized for each age group (child participants' hand lengths were all within 2cm of their age-  
5 appropriate fake hand; within 3cm for adults). After the hands were positioned, the  
6 participant watched for two minutes while the fake and real left hands were stroked by the  
7 researcher with two identical paintbrushes. In a between-subjects design, stroking on the fake  
8 hand was either synchronous (same time, same position) or asynchronous (different time,  
9 different position) with stroking on the real hand. Next the participant was asked to close  
10 their eyes and point with their right index finger under the left index finger of their own hand  
11 (as in baseline trials). The right hand was repositioned, eyes opened, stroking repeated for 20  
12 seconds, and the participant asked to close their eyes and point again. In total the participant  
13 made four points. As in baseline trials, the position of each point was recorded by the  
14 experimenter, and the mean of these four 'post-induction' points used in the analyses. In a  
15 fifth 'catch' trial, participants were asked to point first under the fake finger, then under their  
16 own finger. These data were not included in the analyses presented below, but used to  
17 exclude children whose point 'under the real finger' was further towards the fake hand than  
18 their point 'under the fake finger'.  
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39 Finally participants were asked two questions: 1. "When I was stroking with the  
40 paintbrush, did it sometimes seem as if you could feel the touch of the brush where the fake  
41 hand was?" and 2. "When I was stroking with the paintbrush, did you sometimes feel like the  
42 fake hand was your hand, or belonged to you?". The answer scale was designed to be  
43 understood easily by children: "No, definitely not"/ "No"/ "No, not really"/ "In between"/  
44 "Yes, a little"/ "Yes, a lot"/ "Yes, lots and lots". For analysis, these responses were given  
45 equivalent scores from 0 ("No, definitely not") to 6 ("Yes, lots and lots").  
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## 57 Results

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--Insert Figure 1 about here--

Baseline (no fake hand present): In baseline trials, the participants were asked to point to their own hand with eyes closed and no additional tactile information. We measured the constant error of these points (the difference between mean pointing position and actual hand position, mediolaterally, scaled as a percentage of arm length). A positive constant error indicated that points were made away from the hand in the direction of the body midline. Constant error varied non-linearly with respect to age group,  $F(3,116)=4.89$ ,  $p=.003$ ,  $\eta_p^2=.112$ , becoming increasingly positive with age between the 4- to 5-year-old group and the 8- to 9-year-old group, but declining again in the adult group. Both linear and quadratic components were observed, Linear  $R^2=.05$ ,  $F(1,118)=5.88$ ,  $p=.017$ ; Quadratic  $R^2=.11$ ,  $F(2,117)=6.99$ ,  $p=.001$  (see Fig 1A). However it is important to note that despite these trends, there were no differences in baseline constant error between children (all ages) and adults (Mann-Whitney  $U(120)=1349$ ,  $Z=-.006$ , n.s.). Variable error (Fig 1B; within-participant standard deviation of baseline points) declined steadily with age,  $F(3,116)=14.45$ ,  $p<.001$ ,  $\eta_p^2=.272$ , with both linear and quadratic components (Linear  $R^2=.25$ ,  $F(1,118)=39.9$ ,  $p<.001$ ; Quadratic  $R^2=.25$ ,  $F(2,117)=19.8$ ,  $p=.001$ ).

--Insert Figure 2 about here--

Post-induction: To measure the extent to which intermanual pointing was influenced by multisensory cues in the induction phase, we used the difference between mean post-induction pointing position and mean baseline pointing position in the mediolateral axis scaled to a percentage of arm length (“proprioceptive drift”, as in Tsakiris & Haggard, 2005). In other words, we subtracted the baseline responses from the post-induction responses to yield drift towards the fake hand relative to baseline. This drift was greatest with synchronous stroking, and larger in children than in adults. Across all participants, drift was significantly affected by stroking mode, Mann-Whitney  $U(120)=923$ ,  $Z=-4.60$ ,  $p<.001$ . Drifts towards the

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3 fake hand were stronger with synchronous visual-tactile information than with asynchronous  
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5 information. In order to determine whether visual-tactile cues influenced adults' and  
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7 children's hand localisation differently, we compared proprioceptive drifts across both  
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9 stroking modes, in children (all ages) and adults. A Mann-Whitney U test revealed that  
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11 children showed significantly greater proprioceptive drifts than adults,  $U(120)=925$ ,  $Z=-2.6$ ,  
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13  $p=.01$ . Additional analyses showed that this was true for both synchronous,  $U(60)=196$ ,  $Z=-$   
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15  $2.4$ ,  $p=.016$ , and asynchronous,  $U(60)=222$ ,  $Z=-1.97$ ,  $p=.049$ , stroking modes. This was  
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17 further confirmed with ANOVA on proprioceptive drift scores, which showed main effects of  
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19 stroking mode (synchronous vs. asynchronous;  $F(1,119)=14.72$ ,  $p<.001$ ) and age (children vs.  
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21 adults;  $F(1,119)=8.39$ ,  $p=.005$ ), and no significant interaction between these factors  
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23 ( $F(1,119)=1.12$ , n.s.). Therefore children responded more strongly than adults to the illusory,  
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25 visually-specified hand position, whether or not tactile stroking information was congruent  
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27 with visual stroking information.  
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32 We next considered the performance of children separately. For children (all ages  
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34 combined), post-illusion points were significantly different from baseline points with  
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36 synchronous stroking,  $t(44)=6.62$ , two-tailed  $p<.001$ , and approached significance with  
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38 asynchronous stroking,  $t(44)=1.95$ , two-tailed  $p=.058$ . ANOVA with Age (4-5 years, 6-7  
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40 years, 8-9 years) and Stroking mode (synchronous, asynchronous) as factors revealed a main  
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42 effect of Stroking mode,  $F(1,84)=18.8$ ,  $p<.001$ ,  $\eta_p^2=.183$ , no effect of Age,  $F(2,84)=.022$ ,  
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44 n.s.,  $\eta_p^2=.001$  and no interaction between Age and Stroking mode,  $F(2,84)=0.288$ , n.s.,  
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46  $\eta_p^2=.007$ . Trend analyses across all children revealed no linear or quadratic effects of Age in  
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48 days on proprioceptive drift, in either synchronous or asynchronous conditions.<sup>1</sup>  
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52 --Insert Table 1 about here--  
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55 Questionnaire items were coded on a 7-point scale (0: 'No, definitely not' to 6: 'Yes,  
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57 lots and lots') in response to questions about feeling touch on the fake hand (Item 1), or  
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3 feeling a sense of ownership over the fake hand (Item 2). Participants tended to positively  
4 agree (i.e., score above 3) with the questionnaire items following synchronous stroking, and  
5 disagree (i.e., score below 3) following asynchronous stroking. Mann-Whitney U tests  
6 revealed no significant differences between children and adults on either questionnaire Item 1  
7 ( $U(120)=1170$ ,  $Z=-1.1$ , n.s.) or Item 2 ( $U(120)=1231$ ,  $Z=-.18$ , n.s.). For children, ANOVAs  
8 with Age and Stroking mode as factors showed that there were main effects of Stroking mode  
9 for both items (Item 1:  $F(1,84)=7.36$ ,  $p=.008$ ,  $\eta_p^2=.081$ ; Item 2:  $F(1,84)=4.597$ ,  $p=.035$ ,  
10  $\eta_p^2=.052$ ). There were no effects of Age (Item 1:  $F(1,84)=.139$ , n.s.,  $\eta_p^2=.003$ ; Item 2:  
11  $F(1,84)=.152$ , n.s.,  $\eta_p^2=.004$ ), and no interaction between Age and Stroking mode (Item 1:  
12  $F(2,84)=.893$ , n.s.,  $\eta_p^2=.021$ ; Item 2:  $F(2,84)=1.21$ , n.s.,  $\eta_p^2=.028$ ).

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26 We found no correlations between proprioceptive drift and body ownership as  
27 assessed by Item 1. This was true for both children and adults in both synchronous and  
28 asynchronous conditions (Adults, synchronous:  $\rho(13)=.02$ ,  $p=.94$ ; Adults, asynchronous:  
29  $\rho(13)=.42$ ,  $p=.12$ ; Children, synchronous:  $\rho(43)=.01$ ,  $p=.94$ ; Children, asynchronous:  $\rho(43)=-$   
30  $.20$ ,  $p=.18$ ). Neither was drift correlated with visual capture of the felt hand position towards  
31 the fake hand as assessed by Item 2 (Adults, synchronous:  $\rho(13)=.28$ ,  $p=.31$ ; Adults,  
32 asynchronous:  $\rho(13)=.23$ ,  $p=.39$ ; Children, synchronous:  $\rho(43)=.11$ ,  $p=.46$ ; Children,  
33 asynchronous:  $\rho(43)=.05$ ,  $p=.77$ ).<sup>2</sup>  
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## 46 Discussion

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48 For children, as for adults, viewing a fake hand stroked in synchrony with a real hand  
49 induces the “Rubber Hand Illusion”. The perceived position of the participant’s own hand  
50 was shifted towards the fake hand, while participants experienced a referral of touch to the  
51 fake hand and sense of ownership over it. These effects were apparent from pointing  
52 measures, questionnaire data, and spontaneous reactions (comments such as: “That feels like  
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3 my hand!”). As well as the induction of the illusion in children, two specific developmental  
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5 results emerged from our data. First, the magnitude of the difference between synchronous  
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7 and asynchronous stroking conditions was unaffected by age. This was true for both the  
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9 proprioceptive drift measure and the subjective experience of ownership as assessed by  
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11 questionnaire. This indicates that the role of multisensory visual-tactile cues in determining  
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13 hand position and embodiment changes little across childhood. Indeed, existing data indicate  
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15 that infants are clearly able to distinguish between synchronous and asynchronous tactile cues  
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17 (Zmyj *et al.*, 2011). Second, irrespective of visual-tactile cues, felt hand position was further  
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19 towards the fake hand than for children than for adults. In both synchronous and  
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21 asynchronous stroking conditions, children’s post-illusion pointing responses drifted  
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23 significantly further towards the fake hand than adults’ responses. We suggest that, for  
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25 children aged 4 – 9 years, vision of an appropriately-oriented hand is a particularly powerful  
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27 cue to own-hand position; and that the strength of this cue declines between childhood and  
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29 adulthood. On the basis of these findings we argue for two dissociable processes underlying  
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31 body ownership, and suggest differential developmental trajectories for these processes.  
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37 The first process underlying body ownership which is implied by the data is an early-  
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39 maturing ‘*visual-tactile process*’. The integration of visual and tactile cues in peri-hand space  
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41 is a key component of several current models of body ownership and the Rubber Hand  
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43 Illusion (Botvinick & Cohen, 1998; Makin *et al.*, 2008; Tsakiris, 2010). The present data  
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45 show that this *visual-tactile process* is present in children as young as 4 years, since, across  
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47 all ages, visual capture of felt hand position toward the fake hand was significantly  
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49 modulated by the stroking condition. Spatiotemporally congruent visual-tactile information  
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51 significantly increased proprioceptive drift, explicit feelings of tactile displacement, and  
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53 feelings of ownership over the fake hand. Early sensitivity to visual-tactile synchrony is  
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3 consistent with previous work (Zmyj *et al.*, 2011). We therefore suggest that a *visual-tactile*  
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5 process for own-body localisation and ownership which matures early in development.  
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8 The second process implied by the results is a late-maturing '*visual-proprioceptive*  
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10 process', subserving self-localisation. Through this process, the sight of an appropriately  
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12 oriented hand is used to determine own-hand position. This type of *visual-proprioceptive*  
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14 process has been considered both as a pre-requisite for, and a potential outcome of, successful  
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16 visual-tactile integration in adults (Makin *et al.*, 2008; Tsakiris, 2010; Rohde, Di Luca, &  
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18 Ernst, 2011; Ehrsson 2012). The present data suggest that this process is functional by 4  
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20 years, but has a protracted developmental trajectory: children aged 4 – 9 years show  
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22 significantly larger proprioceptive drifts than adults across both stroking modes. Therefore,  
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24 irrespective of *visual-tactile* information (indeed, despite it in the asynchronous condition),  
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26 the *visual-proprioceptive* process powerfully influences the sense of hand position for  
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28 children.  
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33 What underlies the developments we find in visual-proprioceptive processing during  
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35 childhood? One possibility is that our data index age-related differences in baseline hand  
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37 localisation. When reaching to a hand specified by proprioception only, the reduction in  
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39 variable error which we observed (consistently with previous studies: Von Hofsten &  
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41 Rösblad, 1988; Nardini, Begus, & Mareschal, in press), could lead to decreasing reliance on  
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43 the visible fake hand. Crucially for the current study however, these baseline differences have  
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45 been discounted in order to obtain measures of drift due solely to the visible fake hand.  
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50 A second possibility is that, in determining own-hand position, reliance on the sight of  
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52 the hand changes in childhood. What aspects of the hand determine this visual reliance?  
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54 Adults rely on both orientation and corporeality. To more fully characterise this *visual-*  
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56 *proprioceptive* process in children, further investigations could assess the impacts of rotating  
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58 the fake hand or presenting children with a non-corporeal object. However, we assume that  
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3 some degree of corporeality and a broadly correct orientation of the hand are key for children,  
4  
5 as they are for adults (see Ehrsson, Spence & Passingham, 2004; Tsakiris & Haggard, 2005;  
6  
7 Tsakiris, Carpenter, James & Fotopoulou, 2010). Therefore, we suggest that reliance on the  
8  
9 sight of an appropriately-oriented hand changes during childhood.  
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11  
12 The conclusion of these analyses, namely an influential *visual-proprioceptive* process  
13  
14 early in development, is consistent with preferential looking studies of infants' responses to  
15  
16 their own limbs. These studies suggest that vision of an appropriately-oriented limb signals  
17  
18 own-body position even in infants under 1 year old: when the basic prerequisite of a body-  
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20 like object is removed by changing the visual form of the legs, looking preferences also  
21  
22 disappear (Morgan & Rochat, 1997; Zmyj *et al.*, 2011; although see Bremner & Cowie, in  
23  
24 press). This reliance on visual information concerning the limbs is a pervasive feature of  
25  
26 children's bodily control (see Introduction). A frequently invoked explanation for such visual  
27  
28 dominance is that children's proprioception provides more variable estimates of body layout  
29  
30 than vision, leading to a sensory weighting in favour of vision (King, Pangelinan, Kagerer, &  
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32 Clark, 2010). However, such an account does not provide a good explanation of our data.  
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34 While baseline variable error (proprioceptive variance) declines steadily with age (Fig. 1),  
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36 visual reliance on the sight of the hand (proprioceptive drift across both stroking modes; Fig.  
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38 2) is very similar across children of all ages.  
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45 Whatever the reason for this heavy reliance on the sight of the hand during childhood,  
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47 what is striking from the present data is that even at 9 years of age this *visual-proprioceptive*  
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49 process is not adult-like, but is in fact significantly stronger for children than for adults. We  
50  
51 propose an early-appearing *visual-proprioceptive* process, which does not become adult-like  
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53 until late childhood. We thus explain children's responses to the Rubber Hand Illusion in  
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55 terms of: i) an early developing *visual-tactile* process underlying perceived hand position and  
56  
57 a sense of hand ownership, and ii) a late developing *visual-proprioceptive* process underlying  
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3 perceived hand position only. Differential development in these *visual-tactile* and *visual-*  
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5 *proprioceptive* processes bears important implications for both our understanding of  
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7 development and models of body ownership in the mature adult. We address the implications  
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9 for each of these literatures in turn.

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12 Firstly, our findings reveal two distinct developmental pathways to the bodily self in  
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14 young children. The *visual-tactile* process is early-developing, explicit and context-  
15  
16 dependent: it links to the explicit perception of ownership over one's body (as assessed by  
17  
18 questionnaire items) and relates this explicit bodily self to external stimuli (in this case  
19  
20 touches from the brush). In contrast the *visual-proprioceptive* process is later-developing,  
21  
22 more implicit and internal: it affects pointing responses but not explicit questionnaire  
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24 responses. The early-developing *visual-tactile* process is consistent with perspectives which  
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26 argue for an early (or innate) appreciation of the physical self (e.g., Butterworth, 1995;  
27  
28 Gergely & Watson, 1999; Rochat, 2010). However, the differential development of processes  
29  
30 underlying body localisation and body ownership presents more of a challenge to current  
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32 accounts of the developing self-concept, most of which do not draw a clear distinction  
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34 between these aspects of the bodily self. Because the *visual-tactile* and *visual-proprioceptive*  
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36 processes develop independently and utilise different sensory information, it will be crucial in  
37  
38 future research to distinguish between children's use of these different kinds of information  
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40 in their acquisition of self-perception and self-knowledge.

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45 The differential development of the processes described above also calls into question  
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47 current models of body localisation and ownership in adulthood. Most adult models have  
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49 assumed that perceived hand position and an explicit sense of body ownership are intimately  
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51 bound together: the original model proposed by Botvinick and Cohen (1998) assumes that the  
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53 feeling of ownership is a direct consequence of increased visual weighting towards the fake  
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55 hand position, as induced by the illusion. In these models, the sense of embodiment leads to  
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3 increased weighting of visual information to determine limb position (Makin *et al.*, 2008;  
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5 Tsakiris, 2010). However, the developments revealed in the present study suggest a  
6  
7 dissociation between visual weighting for hand position and a sense of embodiment in  
8  
9 children. While an explicit sense of embodiment (measured by questionnaire) seems to derive  
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11 only from a *visual-tactile* process, perceived hand position (measured by pointing) seems to  
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13 be influenced by both *visual-tactile* and *visual-proprioceptive* processes. Thus questionnaire  
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15 items were only affected by stroking mode (reflecting a *visual-tactile* process), and not by  
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17 age; while drift responses were affected by both stroking mode (reflecting a *visual-tactile*  
18  
19 process) and age (reflecting a *visual-proprioceptive* process). This pattern of results supports  
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21 recent suggestions (Rohde *et al.*, 2011; Holle, McLatchie, Maurer, & Ward, 2011, Holmes *et*  
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23 *al.*, 2012) that perceived hand position and an explicit sense of embodiment are not so  
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25 intimately bound together as was previously thought.  
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## REFERENCES

- 1  
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8  
9  
10 Bahrick, L. & Watson, J. (1985). Detection of intermodal proprioceptive-visual  
11 contingency as a potential basis of self-perception in infancy. *Developmental*  
12 *Psychology*, **21**, 963-973.  
13  
14  
15  
16 Botvinick, M. & Cohen, J. (1998). Rubber hands 'feel' touch that eyes see. *Nature*, **391**,  
17 756.  
18  
19  
20  
21 Bremner, A.J., & Cowie, D. (in press). Developmental origins of the hand in the mind,  
22 and the role of the hands in the development of the mind. In Z. Radman (Ed.),  
23 *The hand: An organ of the mind*. MIT Press: Cambridge, MA.  
24  
25  
26  
27 Bremner, A. J., Holmes, N. P., & Spence, C. (2012). The development of multisensory  
28 representations of the body and the space around the body. In A. J. Bremner, D. J.  
29 Lewkowicz, & C. Spence (Eds.), *Multisensory development* (pp. 113-136).  
30 Oxford University Press: Oxford, UK.  
31  
32  
33  
34  
35  
36 Butterworth, G. (1995). An ecological perspective on the origins of self. In J. L.  
37 Bermudez, A. J. Marcel, & N. Eilan, N. (Eds.), *The body and the self* (pp. 87-  
38 106). MIT Press: Cambridge, MA.  
39  
40  
41  
42  
43 Ehrsson, H. H., Spence, C. & Passingham, R.E. (2004). That's my hand! Activity in  
44 premotor cortex reflects feeling of ownership of a limb. *Science*, **305**, 875-877.  
45  
46  
47 Ehrsson, H. H. (2012). The concept of body ownership and its relation to multisensory  
48 integration. In B. E. Stein (Ed.), *The new handbook of multisensory processes*  
49 (pp. 775-792). MIT Press: Cambridge, MA.  
50  
51  
52  
53  
54 Gergely, G., & Watson, J. S. (1999). Early social-emotional development: Contingency  
55 perception and the social-biofeedback model. In P. Rochat (Ed.), *Early*  
56  
57  
58  
59  
60

- 1  
2  
3           *Socialization*. Mahwah, NJ: Lawrence Erlbaum Associates Inc.  
4  
5 Gori, M., del Viva, M., Sandini, G., & Burr, D. C. (2008). Young children do not  
6  
7           integrate visual and haptic form information. *Current Biology*, **18**, 694-698.  
8  
9  
10 Harrar, V., & Harris, L.R. (2009). Eye position affects the perceived location of  
11  
12           touches. *Experimental Brain Research*, 198 (2-3), 403-410 .  
13  
14 Hay, L., Bard, C., Fleury, M., & Teasdale, N. (1991). Kinematics of aiming in direction  
15  
16           and amplitude: A developmental study. *Acta Psychologica*, **77**, 203-215.  
17  
18 Ho, C., & Spence, C. (2007). Head orientation biases tactile localization. *Brain Research*,  
19  
20           1144C, 136-141.  
21  
22  
23 Holle, H., McLatchie, N., Maurer, S., & Ward, J. (2011). Proprioceptive drift without  
24  
25           illusions of ownership for rotated hands in the “rubber hand illusion” paradigm.  
26  
27           *Cognitive Neuroscience*, **2**, 171-178.  
28  
29  
30 Holmes, N. P., Makin, T. R., Cadieux, M., Williams, C., Naish, K. R., Spence, C., &  
31  
32           Shore, D. I. (2012). Hand ownership and hand position in the rubber hand illusion  
33  
34           are uncorrelated. *Seeing & Perceiving*, **25** (Suppl.), 52.  
35  
36  
37 King, B., Pangelinan, M.M., Kagerer, F.A., & Clark, J.E. (2010). Improvements in  
38  
39           proprioceptive functioning influence multisensory-motor integration in 7- to 13-  
40  
41           year-old children. *Neuroscience Letters*, **483**, 36-40.  
42  
43  
44 Lewis, M. (2011). The origins and uses of self-awareness or the mental representation of  
45  
46           me. *Consciousness & Cognition*, **20**, 120-129.  
47  
48 Longo, M., Schüür, F., Kammers, M.P.M., Tsakiris, M., & Haggard, P. (2008) What is  
49  
50           embodiment? A psychometric approach. *Cognition*, **107**, 978–998.  
51  
52  
53 Makin, T. R., Holmes, N. P., & Ehrsson, H. H. (2008). On the other hand: dummy hands  
54  
55           and peripersonal space. *Behavioural & Brain Research*, **191**, 1-10.  
56  
57 Morgan, R. & Rochat, P. (1997). Intermodal calibration of the body in early infancy.  
58  
59  
60

1  
2  
3 *Ecological Psychology*, **9**, 1-23.

4  
5 Nardini, M., Begus, K., & Mareschal, D. (in press). Multisensory uncertainty reduction  
6  
7 for hand localization in children and adults. *Journal of Experimental Psychology:*  
8  
9 *Human Perception and Performance*.

10  
11 Nardini, M., Jones, P., Bedford, R., & Braddick, O. (2008). Development of cue  
12  
13 integration in human navigation. *Current Biology*, **18**, 689-693.

14  
15 Pagel, B., Heed, T., & Röder, B. (2009). Change of reference frame for tactile  
16  
17 localization during child development. *Developmental Science*, **12**, 929-937.

18  
19 Povinelli, D. J., Landry, A. M., Theall, L. A., Clark, B. R., & Castille, C. M. (1999).  
20  
21 Development of young children's understanding that the recent past is causally  
22  
23 bound to the present. *Developmental Psychology*, **35**, 1426-1439.

24  
25 Rochat, P. (1998). Self-perception and action in infancy. *Experimental Brain Research*,  
26  
27 **123**, 102-109.

28  
29 Rochat, P. (2010). The innate sense of the body develops to become a public affair by 2–3  
30  
31 years. *Neuropsychologia*, **48**, 738-745.

32  
33 Rohde, M., Di Luca, M., & Ernst, M.O. (2011). The Rubber Hand Illusion: Feeling of  
34  
35 ownership and proprioceptive drift do not go hand in hand. *PloS ONE*, **6**(6),  
36  
37 e21659.

38  
39 Sann, C., & Streri, A. (2007). Perception of object shape and texture in human newborns:  
40  
41 Evidence from cross-modal transfer tasks. *Developmental Science*, **10**, 399-410.

42  
43 Schmuckler, M. A. (1996). Visual-proprioceptive intermodal perception in infancy. *Infant*  
44  
45 *Behavior and Development*, **19**, 232.

46  
47 Slaughter, V., & Brownell, C.A. (2011). *Early development of body representations:*  
48  
49 *Cambridge studies in cognitive and perceptual development*. Cambridge  
50  
51 University Press: Cambridge, UK.  
52  
53  
54  
55  
56  
57  
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59  
60

- 1  
2  
3 Smothergill, D. W. (1973). Accuracy and variability in the localization of spatial targets  
4  
5 at three age levels. *Developmental Psychology*, **8**, 62-66.  
6  
7  
8 Smyth, M. M., Peacock, K. A., & Katamba, J. (2004). The role of sight of the hand in the  
9  
10 development of prehension in childhood. *Quarterly Journal of Experimental*  
11  
12 *Psychology*, **57**, 269-296.  
13  
14 Tsakiris, M. (2010). My body in the brain: a neurocognitive model of body-ownership.  
15  
16 *Neuropsychologia*, **48**, 703-712.  
17  
18 Tsakiris, M. & Haggard, P. (2005). The rubber hand illusion revisited: visuotactile  
19  
20 integration and self-attribution. *Journal of Experimental Psychology: Human*  
21  
22 *Perception & Performance*, **31**, 80-91.  
23  
24 Tsakiris, M., Carpenter, L., James, D. & Fotopoulou, A. (2010). Hands only illusion:  
25  
26 multisensory integration elicits sense of ownership for body parts but not for non-  
27  
28 corporeal objects. *Experimental Brain Research*, **204**, 343-352.  
29  
30  
31 van Beers, R. J., Sittig, A. C., & Denier van der Gon, J. J. (1996). How humans combine  
32  
33 simultaneous proprioceptive and visual position information. *Experimental Brain*  
34  
35 *Research*, **111**, 253-261.  
36  
37  
38 von Hofsten, C. & Rösblad, B. (1988). The integration of sensory information in the  
39  
40 development of precise manual pointing. *Neuropsychologia*, **26**, 805-821.  
41  
42  
43 Zmyj, N., Jank, J., Schütz-Bosbach, S., & Daum, M. M. (2011). Detection of visual-  
44  
45 tactile contingency in the first year after birth. *Cognition*, **120**, 82-89.  
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## FOOTNOTES

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1. Pointing errors were measured as a percentage of arm length. In absolute terms, adults' drifts (Synchronous stroking: ~3% arm length) equated to ~2cm, whereas children's drifts (Synchronous stroking: ~8% arm length) equated to ~4cm. Statistical analyses on the participants raw (absolute) pointing errors yield the same findings as those conducted on scaled pointing errors, and very similar coefficients of variation within the age-groups tested.

2. When measuring drift in an absolute metric (cms), drift does not correlate with the questionnaire responses for either item across both children and adults and both stroking conditions.

## TABLE CAPTIONS

Table 1: Responses to the two questionnaire items concerning the Rubber Hand Illusion across conditions and ages. Item 1 asked, “When I was stroking with the paintbrush, did it sometimes seem as if you could feel the touch of the brush where the fake hand was?” Item 2 asked, “When I was stroking with the paintbrush, did you sometimes feel like the fake hand was your hand, or belonged to you?” Possible scores ranged from 0 (“No, definitely not”) to 6 (“Yes, lots and lots”). Means and Standard Errors (in parentheses) are shown.

## FIGURE CAPTIONS

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10 Figure 1: Baseline trials. (A) shows constant error of points towards the midline, and (B)  
11 shows variable error. Means and standard errors across participants are shown.  
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16 Figure 2: Proprioceptive drift toward the midline as a result of the visual-tactile stimulation  
17 induction. Drift is calculated by subtracting pointing position towards the midline (as a  
18 percentage of arm length) at baseline from pointing position towards the midline after visual-  
19 tactile stimulation. Means for synchronous stroking and asynchronous stroking are displayed  
20 separately. Means and standard errors across participants are shown. Asterisks indicate  
21 significant effects of stroking mode within age groups, compared using t-tests (\*= $p < .05$ ;  
22 \*\*= $p < .01$ ).  
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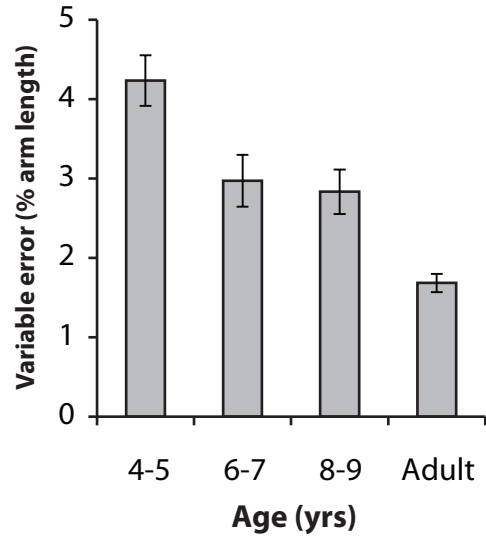
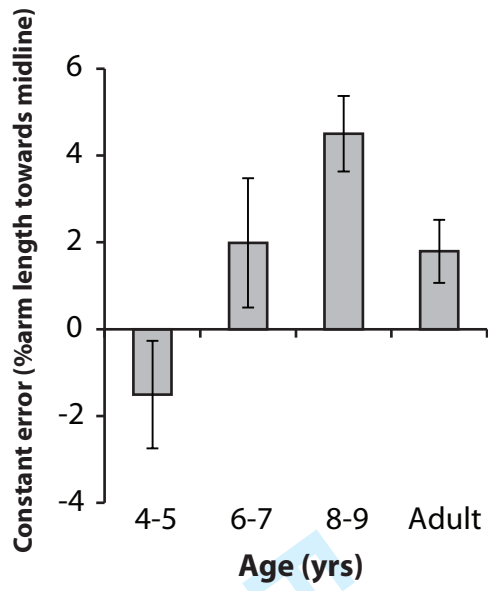
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Table 1

	Q1 touch 0 least->6most		Q2 ownership 0 least->6most	
	Sync	Async	Sync	Async
Age				
4-5 yrs	3.33 (.64)	2.80 (.62)	3.46 (.68)	2.53 (.62)
6-7 yrs	3.67 (.48)	2.53 (.60)	3.93 (.51)	2.07 (.55)
8-9 yrs	4.33 (.37)	2.33 (.54)	3.33 (.40)	3.20 (.56)
Adult	3.20 (.42)	2.27 (.52)	3.27(.44)	2.87 (.52)

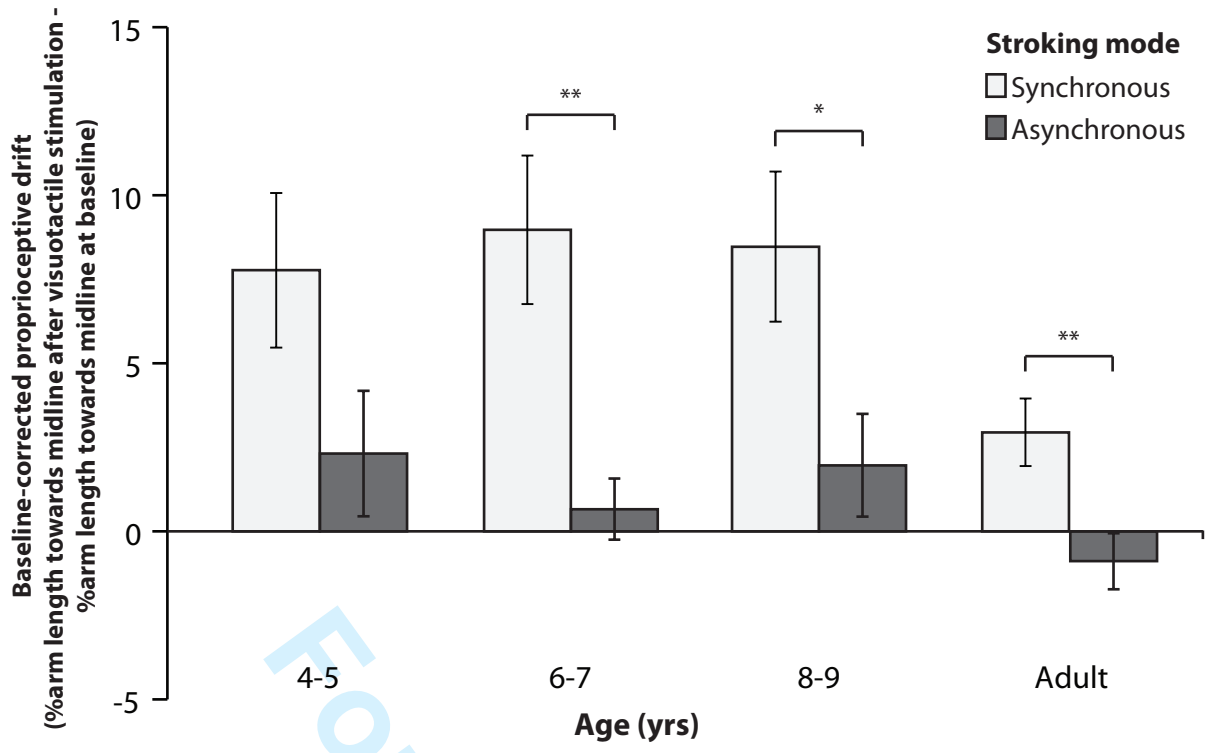
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