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

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<td>Manuscript Type:</td>
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<tr>
<td>Date Submitted by the Author:</td>
<td>28-Aug-2012</td>
</tr>
<tr>
<td>Complete List of Authors:</td>
<td>Cowie, Dorothy; Goldsmiths, University of London, Department of Psychology Makin, Tamar; University of Oxford, FMRIB Centre Bremner, Andrew; Goldsmiths, University of London, Department of Psychology;</td>
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<tr>
<td>Keywords:</td>
<td>Cognitive Development, Human Body, Perception</td>
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Children’s responses to the Rubber Hand Illusion reveal dissociable pathways in body representation

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SUBMITTED TO: PSYCHOLOGICAL SCIENCE (MARCH, 2012)

ABSTRACT WORD COUNT: 148 (max = 150)

WORD COUNT: 3995 (max = 4000, includes footnotes & acknowledgements)

REFERENCES: 37 (max = 40)

KEYWORDS: COGNITIVE DEVELOPMENT, HUMAN BODY, PERCEPTION

ACKNOWLEDGEMENTS: We acknowledge support from the European Research Council (FP7/2007-2013; no. 241242; grant awarded to AJB), Royal Society and Marie Curie Actions (to TRM). Thanks to Herne Hill School, Dulwich Hamlet Junior School, Ivydale Primary School, Goldsmiths Casting Laboratory, and Madeleine Miller-Bottome.
ABSTRACT

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.
Children’s responses to the Rubber Hand Illusion reveal dissociable pathways in body representation

Our sense of self is constructed from multisensory information, including that from vision, touch, and proprioception (Makin, Holmes, & Ehrsson, 2008; Longo, Schüur, Kammers, Tsakiris, & Haggard, 2008; Tsakiris, 2010; Ehrsson, 2012). While it is clear that both multisensory bodily perception (Bremner, Holmes, & Spence, 2012; Rochat, 1998; Zmyj, Jank, Schütz-Bosbach, & Daum, 2011) and the sense of self (e.g. Lewis, 2011; Rochat, 2010; Slaughter & Brownell, 2011) develop in infancy and early childhood, there has been little investigation of the relationship between these processes. For example, it is clear from young infants’ visual preferences that they can perceive the visual-proprioceptive (Bahrick & Watson, 1985; Morgan & Rochat, 1997; Schmuckler, 1996) and visual-tactile (Zmyj et al., 2011) correspondences which underpin own-body perception in adults. Yet the extent to which young children actually derive a sense of bodily self or body-ownership from these multisensory correspondences is difficult to determine (see Bremner, Holmes & Spence, 2012). Using the “Rubber Hand Illusion” (Botvinick & Cohen, 1998), we tracked the development of young children’s use of multisensory information to localise their own body parts and gain a subjective sense of body ownership. In this illusion, the sight of a fake hand being stroked, combined with synchronous tactile cues on the real hidden hand, causes adult participants to feel as if the fake hand is their own, and perceive the touch they feel as arising from the seen brush, stroking the fake hand.

Although the relation between the multisensory bodily self and the subjective sense of self in childhood is poorly understood, a wide range of studies have addressed these two issues separately. The subjective sense of self in children has been studied using explicit measures of self-knowledge including mirror self-recognition, the use of personal pronouns,
and the tendency to engage in pretend play (Lewis, 2011; Rochat, 2010). Some aspects of an explicit subjective sense of the self appear to continue developing well into childhood (e.g. Povinelli, Landry, Theall, Clark, & Castille, 1999).

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

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

Method

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

Participants

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

**Experimental procedure**

In order to keep the postural configuration and motor demands of the setup the same across differently-sized participants, we scaled setups and measured behavioural responses in units of % arm length rather than absolute distance (e.g. cm). The right hand was placed on a tray under the table, at 50% of the participant’s arm length to the right of the body midline. On two training trials, the left hand was visible and rested on the table. Participants were trained to slide the right index finger along a horizontal groove so that it was underneath the left index finger. This meant that in all trials points were only made in the mediolateral axis.

After training, participants completed four baseline trials. The right hand was positioned as before, with the left hand resting on the table at 25% arm length to the left of body midline. With eyes closed, participants were asked to point with their right index finger underneath their left index finger. The position of each point was marked under the table. For each participant the mean and standard deviation of these four points were used in analysis. Participants then chose a sticker from a small box. This encouraged the children and reduced the likelihood of the baseline trials biasing subsequent test-condition pointing.

The test condition started with the participant’s eyes closed, the real left hand placed at 25% arm length to the left of the body midline, the fake left hand at the midline, and the right hand, as before, under the table at 50% arm length to the right of midline. Positioning the fake hand at body midline eliminated any disturbances of tactile localisation due to changes in head or eye position (Harrar & Harris, 2009; Ho & Spence, 2007). A cloth was
now placed over the left arm. The fake hand was a painted, plaster-cast hand, appropriately-sized for each age group (child participants’ hand lengths were all within 2cm of their age-appropriate fake hand; within 3cm for adults). After the hands were positioned, the participant watched for two minutes while the fake and real left hands were stroked by the researcher with two identical paintbrushes. In a between-subjects design, stroking on the fake hand was either synchronous (same time, same position) or asynchronous (different time, different position) with stroking on the real hand. Next the participant was asked to close their eyes and point with their right index finger under the left index finger of their own hand (as in baseline trials). The right hand was repositioned, eyes opened, stroking repeated for 20 seconds, and the participant asked to close their eyes and point again. In total the participant made four points. As in baseline trials, the position of each point was recorded by the experimenter, and the mean of these four ‘post-induction’ points used in the analyses. In a fifth ‘catch’ trial, participants were asked to point first under the fake finger, then under their own finger. These data were not included in the analyses presented below, but used to exclude children whose point ‘under the real finger’ was further towards the fake hand than their point ‘under the fake finger’.

Finally participants were asked two questions: 1. “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?” and 2. “When I was stroking with the paintbrush, did you sometimes feel like the fake hand was your hand, or belonged to you?”. The answer scale was designed to be understood easily by children: “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”).

Results
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, $F(3,116)=4.89, p=.003$, $\eta^2=.112$, 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, $F(3,116)=14.45, p<.001$, $\eta^2=.272$, with both linear and quadratic components (Linear $R^2=.25$, $F(1,118)=39.9, p<.001$; Quadratic $R^2=.25$, $F(2,117)=19.8, p=.001$).

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
fake hand were stronger with synchronous visual-tactile information than with asynchronous information. In order to determine whether visual-tactile cues influenced adults’ and children’s hand localisation differently, we compared proprioceptive drifts across both stroking modes, in children (all ages) and adults. A Mann-Whitney U test revealed that children showed significantly greater proprioceptive drifts than adults, $U(120)=925$, $Z=-2.6$, $p=.01$. Additional analyses showed that this was true for both synchronous, $U(60)=196$, $Z=-2.4$, $p=.016$, and asynchronous, $U(60)=222$, $Z=-1.97$, $p=.049$, stroking modes. This was further confirmed with ANOVA on proprioceptive drift scores, which showed main effects of stroking mode (synchronous vs. asynchronous; $F(1,119)=14.72$, $p<.001$) and age (children vs. adults; $F(1,119)=8.39$, $p=.005$), and no significant interaction between these factors ($F(1,119)=1.12$, n.s.). Therefore children responded more strongly than adults to the illusory, visually-specified hand position, whether or not tactile stroking information was congruent with visual stroking information.

We next considered the performance of children separately. For children (all ages combined), post-illusion points were significantly different from baseline points with synchronous stroking, $t(44)=6.62$, two-tailed $p<.001$, and approached significance with asynchronous stroking, $t(44)=1.95$, two-tailed $p=.058$. ANOVA with Age (4-5 years, 6-7 years, 8-9 years) and Stroking mode (synchronous, asynchronous) as factors revealed a main effect of Stroking mode, $F(1,84)=18.8$, $p<.001$, $\eta_p^2=.183$, no effect of Age, $F(2,84)=.022$, n.s., $\eta_p^2=.001$ and no interaction between Age and Stroking mode, $F(2,84)=.288$, n.s., $\eta_p^2=.007$. Trend analyses across all children revealed no linear or quadratic effects of Age in days on proprioceptive drift, in either synchronous or asynchronous conditions.¹

---Insert Table 1 about here---

Questionnaire items were coded on a 7-point scale (0: ‘No, definitely not’ to 6: ‘Yes, lots and lots’) in response to questions about feeling touch on the fake hand (Item 1), or
feeling a sense of ownership over the fake hand (Item 2). Participants tended to positively agree (i.e., score above 3) with the questionnaire items following synchronous stroking, and disagree (i.e., score below 3) following asynchronous stroking. Mann-Whitney U tests revealed no significant differences between children and adults on either questionnaire Item 1 (U(120)=1170, Z=-1.1, n.s.) or Item 2 (U(120)=1231, Z=-1.18, n.s.). For children, ANOVAs with Age and Stroking mode as factors showed that there were main effects of Stroking mode for both items (Item 1: F(1,84)=7.36, p=.008, \(\eta^2_p=.081\); Item 2: F(1,84)=4.597, p=.035, \(\eta^2_p=.052\)). There were no effects of Age (Item 1: F(1,84)=.139, n.s., \(\eta^2_p=.003\); Item 2: F(1,84)=.152, n.s., \(\eta^2_p=.004\)), and no interaction between Age and Stroking mode (Item 1: F(2,84)=.893, n.s., \(\eta^2_p=.021\); Item 2: F(2,84)=1.21, n.s., \(\eta^2_p=.028\)).

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

Discussion

For children, as for adults, viewing a fake hand stroked in synchrony with a real hand induces the “Rubber Hand Illusion”. The perceived position of the participant’s own hand was shifted towards the fake hand, while participants experienced a referral of touch to the fake hand and sense of ownership over it. These effects were apparent from pointing measures, questionnaire data, and spontaneous reactions (comments such as: “That feels like
my hand!”). As well as the induction of the illusion in children, two specific developmental results emerged from our data. First, the magnitude of the difference between synchronous and asynchronous stroking conditions was unaffected by age. This was true for both the proprioceptive drift measure and the subjective experience of ownership as assessed by questionnaire. This indicates that the role of multisensory visual-tactile cues in determining hand position and embodiment changes little across childhood. Indeed, existing data indicate that infants are clearly able to distinguish between synchronous and asynchronous tactile cues (Zmyj et al., 2011). Second, irrespective of visual-tactile cues, felt hand position was further towards the fake hand than for children than for adults. In both synchronous and asynchronous stroking conditions, children’s post-illusion pointing responses drifted significantly further towards the fake hand than adults’ responses. We suggest that, for children aged 4 – 9 years, vision of an appropriately-oriented hand is a particularly powerful cue to own-hand position; and that the strength of this cue declines between childhood and adulthood. On the basis of these findings we argue for two dissociable processes underlying body ownership, and suggest differential developmental trajectories for these processes.

The first process underlying body ownership which is implied by the data is an early-maturing ‘visual-tactile process’. The integration of visual and tactile cues in peri-hand space is a key component of several current models of body ownership and the Rubber Hand Illusion (Botvinick & Cohen, 1998; Makin et al., 2008; Tsakiris, 2010). The present data show that this visual-tactile process is present in children as young as 4 years, since, across all ages, visual capture of felt hand position toward the fake hand was significantly modulated by the stroking condition. Spatiotemporally congruent visual-tactile information significantly increased proprioceptive drift, explicit feelings of tactile displacement, and feelings of ownership over the fake hand. Early sensitivity to visual-tactile synchrony is
consistent with previous work (Zmyj et al., 2011). We therefore suggest that a visual-tactile process for own-body localisation and ownership which matures early in development.

The second process implied by the results is a late-maturing ‘visual-proprioceptive process’, subserving self-localisation. Through this process, the sight of an appropriately oriented hand is used to determine own-hand position. This type of visual-proprioceptive process has been considered both as a pre-requisite for, and a potential outcome of, successful visual-tactile integration in adults (Makin et al., 2008; Tsakiris, 2010; Rohde, Di Luca, & Ernst, 2011; Ehrsson, 2012). The present data suggest that this process is functional by 4 years, but has a protracted developmental trajectory: children aged 4 – 9 years show significantly larger proprioceptive drifts than adults across both stroking modes. Therefore, irrespective of visual-tactile information (indeed, despite it in the asynchronous condition), the visual-proprioceptive process powerfully influences the sense of hand position for children.

What underlies the developments we find in visual-proprioceptive processing during childhood? One possibility is that our data index age-related differences in baseline hand localisation. When reaching to a hand specified by proprioception only, the reduction in variable error which we observed (consistently with previous studies: Von Hofsten & Rösblad, 1988; Nardini, Begus, & Mareschal, in press), could lead to decreasing reliance on the visible fake hand. Crucially for the current study however, these baseline differences have been discounted in order to obtain measures of drift due solely to the visible fake hand.

A second possibility is that, in determining own-hand position, reliance on the sight of the hand changes in childhood. What aspects of the hand determine this visual reliance? Adults rely on both orientation and corporeality. To more fully characterise this visual-proprioceptive process in children, further investigations could assess the impacts of rotating the fake hand or presenting children with a non-corporeal object. However, we assume that
some degree of corporeality and a broadly correct orientation of the hand are key for children, as they are for adults (see Ehrsson, Spence & Passingham, 2004; Tsakiris & Haggard, 2005; Tsakiris, Carpenter, James & Fotopoulou, 2010). Therefore, we suggest that reliance on the sight of an appropriately-oriented hand changes during childhood.

The conclusion of these analyses, namely an influential visual-proprioceptive process early in development, is consistent with preferential looking studies of infants’ responses to their own limbs. These studies suggest that vision of an appropriately-oriented limb signals own-body position even in infants under 1 year old: when the basic prerequisite of a body-like object is removed by changing the visual form of the legs, looking preferences also disappear (Morgan & Rochat, 1997; Zmyj et al., 2011; although see Bremner & Cowie, in press). This reliance on visual information concerning the limbs is a pervasive feature of children’s bodily control (see Introduction). A frequently invoked explanation for such visual dominance is that children’s proprioception provides more variable estimates of body layout than vision, leading to a sensory weighting in favour of vision (King, Pangelinan, Kagerer, & Clark, 2010). However, such an account does not provide a good explanation of our data. While baseline variable error (proprioceptive variance) declines steadily with age (Fig. 1), visual reliance on the sight of the hand (proprioceptive drift across both stroking modes; Fig. 2) is very similar across children of all ages.

Whatever the reason for this heavy reliance on the sight of the hand during childhood, what is striking from the present data is that even at 9 years of age this visual-proprioceptive process is not adult-like, but is in fact significantly stronger for children than for adults. We propose an early-appearing visual-proprioceptive process, which does not become adult-like until late childhood. We thus explain children’s responses to the Rubber Hand Illusion in terms of: i) an early developing visual-tactile process underlying perceived hand position and a sense of hand ownership, and ii) a late developing visual-proprioceptive process underlying
perceived hand position only. Differential development in these visual-tactile and visual-propioreceptive processes bears important implications for both our understanding of development and models of body ownership in the mature adult. We address the implications for each of these literatures in turn.

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

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


Ecological Psychology, 9, 1-23.


FOOTNOTES

1. Pointing errors were measured as a percentage of arm length. In absolute terms, adults’
driffs (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

Figure 1: Baseline trials. (A) shows constant error of points towards the midline, and (B) shows variable error. Means and standard errors across participants are shown.

Figure 2: Proprioceptive drift toward the midline as a result of the visual-tactile stimulation induction. Drift is calculated by subtracting pointing position towards the midline (as a percentage of arm length) at baseline from pointing position towards the midline after visual-tactile stimulation. Means for synchronous stroking and asynchronous stroking are displayed separately. Means and standard errors across participants are shown. Asterisks indicate significant effects of stroking mode within age groups, compared using t-tests (*=p<.05; **=p<.01).
Table 1

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Baseline-corrected proprioceptive drift (%arm length towards midline after visuotactile stimulation - %arm length towards midline at baseline)

Synchronous
Asynchronous

Stroking mode

4-5 6-7 8-9 Adult

Age (yrs)