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The Developing Bodily Self: How Posture Constrains Body Representation in Childhood

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Adults' body representation is constrained by multisensory information and knowledge of the body such as its possible postures. This study ($N = 180$) tested for similar constraints in children. Using the rubber hand illusion with adults and 6- to 7-year olds, we measured proprioceptive drift (an index of hand localization) and ratings of felt hand ownership. The fake hand was either congruent or incongruent with the participant's own. Across ages, congruency of posture and visual–tactile congruency yielded greater drift toward the fake hand. Ownership ratings were higher with congruent visual–tactile information, but unaffected by posture. Posture constrains body representation similarly in children and adults, suggesting that children have sensitive, robust mechanisms for maintaining a sense of bodily self.

The feeling of inhabiting a body is fundamental for self-experience (Kilteni, Groten, & Slater, 2012; Longo, Schüür, Kammers, Tsakiris, & Haggard, 2008). For adult humans, body representation is grounded in the interaction between current multisensory information, such as seeing and feeling of being touched, and in internal models or expectations about the form or structure of one's own body, that is, top-down knowledge (Apps & Tsakiris, 2014; Tsakiris & Haggard, 2005). Body representation is comprised of multiple components, including the localization of one's hand in space, and feelings of ownership over it (Longo et al., 2008; Rohde, Luca, & Ernst, 2011). Crucially, these are separable and will be addressed in this study through multiple measures. Recent findings also show that bottom-up information deriving from multisensory interactions between visual, tactile, and proprioceptive cues is crucial for body representation in childhood (Cowie, Makin, & Bremner, 2013; Cowie, McKenna, Bremner, & Aspell, 2018; Cowie, Sterling, & Bremner, 2016). However, there is no direct research on how knowledge of body shape or layout constrains body representation in children. This study is the first to address the role of top-down information, namely internal short- and long-term models of body posture in childhood.

Multisensory abilities underpin body representation in adults (Botvinick & Cohen, 1998; Tsakiris,

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2010). Aspects of these abilities seem to be present very early in life, but then also seem to undergo an extended period of fine tuning and development from infancy into childhood. Preferential looking studies have shown that newborns and young infants can detect multisensory visual–tactile, visual–interoceptive, auditory–tactile, and visual–-motor congruencies (Filippetti, Johnson, Lloyd-Fox, Dragovic, & Farroni, 2013; Freier, Mason, & Bremner, 2016; Maister, Tang, & Tsakiris, 2017; Rochat & Morgan, 1995; Thomas et al., 2018; Zmyj, Jank, Schütz-Bosbach, & Daum, 2011). Recent work has used the rubber hand illusion (RHI) to test the sensory bases of body representation in older children from the age of 4 to 13 years (Cowie et al., 2013, 2016; Nava, Bolognini, & Turati, 2017). In this illusion (Botvinick & Cohen, 1998; for review see Tsakiris, 2010), synchronous stroking with a paintbrush on a hidden real hand and visible fake hand (visuotactile correlation) can lead to the illusion that the fake hand is the participant's own, and to the drift of perceived hand position toward the fake hand ("proprioceptive drift," see Tsakiris & Haggard, 2005). These illusory percepts occur in both adults and 4- to 13-year olds, indicating that, from the age of 4 years, multisensory visuotactile information, that is, bottom-up information, drives a subjective sense of bodily identity and location (Cowie et al., 2013, 2016; Nava et al., 2017).

In addition to multisensory information, top-down knowledge about the body and its structure is crucial for own-body perception. For adults, a fundamental constraint on perceiving a hand to be one's own is that it must be viewed in an anatomically plausible posture (Makin, Holmes, & Ehrsson, 2008; Tsakiris & Haggard, 2005) and even small postural incongruencies prevent embodiment of a hand that is not one's own (Costantini & Haggard, 2007). This is visible across a range of measures, including proprioceptive drift (Tsakiris & Haggard, 2005), brain imaging, subjective ratings (e.g., Ehrsson, Spence, & Passingham, 2004), and skin conductance responses (Ferri, Chiarelli, Merla, Gallese, & Costantini, 2013). The size of the RHI decreases when the fake hand is rotated by 180° (Ehrsson et al., 2004) or 90° (Tsakiris & Haggard, 2005) relative to the actual hand. In these cases, the illusion may reduce not only because the posture of the fake hand is anatomically impossible, which relates to long-term body representation, but also because it does not match one's own *current* hand posture, which relates to short-term body representation (cf. de Vignemont, 2006). Indeed, adults' sensitivity to small (e.g., 10°) mismatches (Costantini & Haggard, 2007; Ehrsson et al., 2004; Tsakiris & Haggard, 2005) suggests a finely tuned postural matching mechanism comparing viewed and felt hand posture, which is central to generating a sense of body ownership (Makin et al., 2008; Tsakiris, 2010), that is, the sense that one's body belongs to oneself (Gallagher, 2000). We can imagine that the incoming synchronous visuotactile information must pass through *form* and *postural* "gates" to produce feelings of embodiment over the fake hand (Tsakiris, 2010; see also Allen & Friston, 2016; Apps & Tsakiris, 2014; Friston, 2009).

In adults, top-down knowledge about possible body postures therefore constrains body representation. It is likely that learning about the bodily self begins very early in life: some have even argued that there is evidence for self-directed, intentional arm movements in fetuses (Zoia et al., 2007) and newborns (Delafield-Butt et al., 2018; van der Meer, van der Weel, & Lee, 1995). These early movements could possibly shape the bodily self from early on by continuously providing active experience of their body schema (i.e., the postural map of the body in space) and of perception–action coupling (Chinn, Noonan, Hoffmann, & Lockman, 2019; Gallagher, 2006). There is some suggestion that infants already have a coarse knowledge about postural differences: 3- to 5-month-old infants kick more and look longer in response to a video display of their own legs moving when the legs are oriented at 180° to their own (Rochat & Morgan, 1995). However, there is also evidence of early failures to consider current body posture (Bremner, Mareschal, Fox, & Spence, 2008; Rigato, Begum Ali, Van Velzen, & Bremner, 2014) and the contribution of such elements to a sense of bodily self in early life is unknown: Even if large or small postural discrepancies are detectable early in life, we thus far know little about whether such perceptual differentiations proceed to guide infants' sense of embodiment (see Bremner & Cowie, 2013).

Indeed, there are reasons to suppose that children may still have substantially more flexible body representations than adults. First, children's bodies, physical, and functional abilities change rapidly and dynamically during development (Thelen, 1992; Thelen & Smith, 1994). For instance, the statistical visual exposure of an individual child to variations in hand posture may be affected by changing physical dimensions such as arm length; as arms grow, the same joint angle results in a different (larger) displacement in hand position. The need to decouple posture and arm length during growth may mean to introduce an element of uncertainty, and mean that some flexibility must be built in to own-body perception (cf. Bremner, Holmes, & Spence, 2008; Gori, Del Viva, Sandini, & Burr, 2008). Second, the sensory bases for perceiving one's own body characteristics are relatively poor in childhood. Proprioceptive estimates of limb position are variable (Nardini, Begus, & Mareschal, 2013; von Hofsten & Rösblad, 1988); combining proprioception with vision can still result in substantial errors at 8–10 years (Nardini et al., 2013). In sum, the daily need to adapt to a growing body, as well as changing sensory abilities could have substantial effects on the kinds of body models which children use to construct a sense of embodiment.

This study is the first direct empirical investigation of whether and how posture constrains body representation in childhood. As we have laid out, early childhood is a particularly important stage to examine this question, as it is a period when multisensory processing is still not adult-like (Cowie et al., 2013; Gori et al., 2008; Nardini et al., 2013), and postural perception may pose problems. The current paper comprises two experiments, which address in turn whether 6- to 7-year olds use a postural model of the body for body representation as adults do (Experiment 1) and how finely tuned such a model is (Experiment 2).

Experiment 1

Using the RHI, we measured how children's perceptions of their own body were influenced by the match between viewed and felt limb posture; and whether children were able to embody a fake hand in an anatomically impossible posture. We tested adults and 6- to 7-year olds (who are highly susceptible to the illusion; Cowie et al., 2013). We assessed dissociable dimensions of body representation (Cowie et al., 2013; Longo et al., 2008; Rohde et al., 2011; Tamè, Linkenauger, & Longo, 2018), using questionnaire items on the sense of ownership over the fake hand and the sense of felt touch on the fake hand; and a pointing measure of perceived hand position ("proprioceptive drift"). To assess the contribution of multisensory visuotactile information to body representation, we used synchronous and asynchronous stroking conditions. We stroked 12 locations on the participant's and on the fake hand. These locations were on the back of the hand and on the finger phalanxes, sparing the knuckles and the thumb. We stroked each of these locations in two consecutive short distinct strokes with a duration of around 300 ms each. We did not follow a particular order of locations. The intervals between each triple of strokes, when we moved to a different location, were around 500 ms approximately. To address the role of body posture, we manipulated the postural orientation of the hand across conditions. In one condition, the fake hand was placed in the same orientation as the real hand. In another, it was rotated 90° anticlockwise, as viewed from above. In the rotated condition, therefore, the fake hand was both misaligned with the real hand, and positioned in an anatomically impossible posture with respect to the participant's body. To prevent carry-over effects and minimize testing time (an important consideration in studies with children of this age), all conditions were compared between groups of participants of the same age.

Based on the evidence presented above, we expect that across children and adults, posture will modulate the effects of visuotactile synchrony, indicated by a significant synchrony-by-posture interaction. Thus, visuotactile stimulation would have an effect only when the hand is posturally congruent with one's own. In line with previous studies, this would indicate that viewing a hand in peripersonal space triggers multisensory integration of visual and tactile stimuli near it, but only when the hand is placed in an anatomically possible posture (Makin et al., 2008; Tsakiris, 2010). Alternatively, posture might constrain body representation differently in children and adults, with children for example being more willing to accept non-aligned hands as their own because they have more flexible body models.

Method

Participants

The sample of participants comprised sixty 6- to 7-year olds ($M = 7.1$ years, $SD = 0.5$ years, 32 girls and 28 boys) and 60 adults ($M = 21.4$ years, $SD = 3.0$ years, 31 women and 29 men) living in inner London. Participants were recruited from November 2012 to September 2016 and tested from January 2013 to October 2016. The data gathered from three children were excluded due to extreme drift scores (see Results section). All participants had normal or corrected-to-normal vision with no known sensory, neurological, or neurodevelopmental problems. The sample size of 15 participants for each of the four Synchrony × Posture conditions (total $N_{\text{children}} = 60$ and $N_{\text{adults}} = 60$) was chosen to make this study comparable to previous developmental work which has yielded medium-to-large estimated effect sizes when comparing proprioceptive drift and subjective rating scores across synchrony conditions with this same number of participants per condition (Cowie et al., 2013, 2016). This sample was in fact slightly larger than that recommended by *a priori* power calculation with GPower 3.1 (Faul, Erdfelder, Buchner, & Lang, 2017). This used the estimated effect size of Synchrony on proprioceptive drift from children in Cowie et al. (2016; $\eta_p^2 = .17$), with α error probability of .05, and power of 0.8, to gave a sample of $N_{\text{children}} = 42$, with $N = 21$ in each synchrony condition. As this study is the first one investigating the effect of postural constraints on proprioceptive drift in children, there were no estimated sizes of the posture effect available for power calculations. This investigation was approved by the local research ethics committees at the two universities where the data were collected.

Experimental Procedure

The same procedure as that used by Cowie et al. (2013, 2016) in previous RHI studies with children was used here, which we now redescribe. To keep the postural and motor demands of the task the same across age groups and sizes of participants, we used each participant's arm length to scale setups and measure responses (Figure 1). To start each trial, the right hand was placed under the table, to the right of the body midline. The distance between the midline and the hand was scaled for each participant to be 50% of their arm length.

On training trials, the participant then placed their left hand on a table-top. They were taught to slide the right index finger along a horizontal groove under the table so that it was underneath their left index finger. Following training, a screen was positioned to the left of body midline to block the participant's view of their left hand. Four baseline trials were conducted. These followed the procedure for training trials except that the participant had their eyes closed, and the left hand rested on the table at 25% arm length to the left of body midline. The participant was then asked to choose a sticker reward from a box. This was done to encourage the children and to reduce the possible effects of the baseline on the subsequent test trials by introducing some fine motor activity in between. Note that the adults were asked to pick a sticker too, even though they sometimes chose to not keep them.

In the test trials which followed the baseline trials, the participant closed their eyes and placed their hands in the same places as in the baseline trials. A fake left hand (painted, plaster-cast, and appropriately sized for the age group being tested) was placed on the table at body midline, and a cloth was placed over the left arm. The participant then watched for 2 min while the experimenter stroked the fake and real left hands with paintbrushes. Stroking on the fake hand was either synchronous or asynchronous with stroking on the real hand. Synchrony of stroking was compared according to a between-participants design, as was fake hand posture. The fake hand was positioned in either a congruent or an incongruent posture (90° anticlockwise with respect to the congruent posture when viewed from above; see Figure 1).

Following exposure to the stroking, the participants were asked to close their eyes and estimate the perceived position of their real hand by pointing under the table (as in the baseline trials). After a further 20 s of stroking, another pointing estimate was made, and so on for two more points, so that each participant made a total of four points in the test trials. A final "catch trial" tested whether the

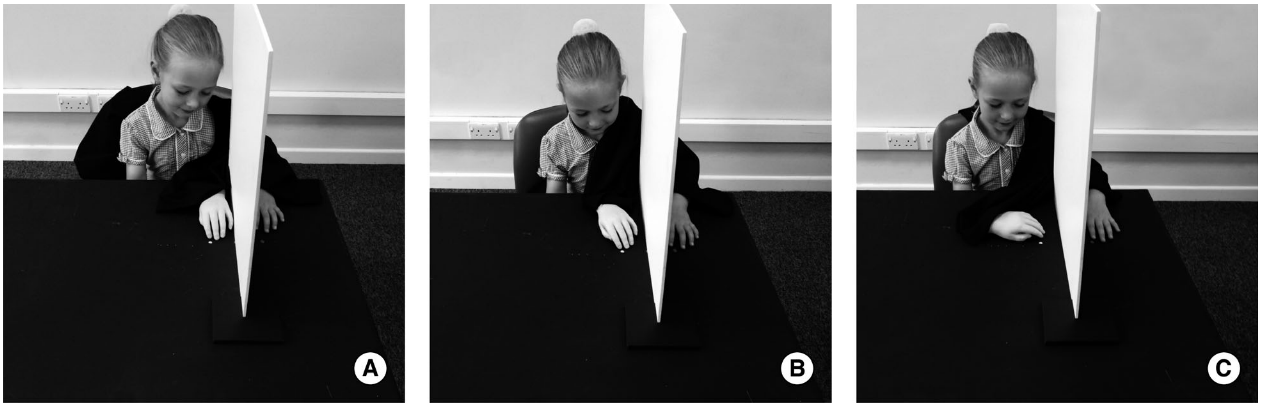

Figure 1. The participant's own left hand is hidden behind the screen, while their right hand rests under the table ready to carry out pointing estimates of own-hand position. They view a fake hand on the table at body midline. **A:** In the congruent condition (0°, Experiment 1), the fake hand is oriented congruently to their own hand. **B:** In the incongruent-possible condition, the fake hand is rotated by 20° anticlockwise (Experiment 2). **C:** In the incongruent-impossible condition, the fake hand is rotated by 90° anticlockwise (Experiment 1).

participants had correctly understood the task. In the catch trial, the participant was asked to point first under the fake finger, and then under their own real finger. All participants could do this (both points were within a few cm of the correct finger, and points to the real finger were left of points to the fake finger). Therefore, results from these trials are as follows.

Following the pointing task, the participant was asked, in randomized order, the following 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 as follows: "No, definitely not"/"No"/"No, not really"/"In between"/"Yes, a little"/"Yes, a lot"/"Yes, lots and lots." These responses were coded from 0 ("no, definitely not") to 6 ("yes, lots and lots").

Results

To correct for differences in body size and experimental setups, we express distance measures as a percentage of each participant's arm length. Thus, we calculated *proprioceptive drift* toward the fake hand by subtracting, for each participant, their mean baseline pointing position from their mean test pointing position, and scaled this as a percentage of their arm length. Inspection of the data indicated that the data gathered from three children (all in the synchronous, 0° condition) were extreme outliers (i.e., the children's observed individual averages of proprioceptive drift were outside of three times the group's interquartile range). All of the data gathered from these children were excluded from all subsequent analyses. To assess between-participants effects of Synchrony and Posture on proprioceptive drift, we used standard parametric statistics (analysis of variance [ANOVA] and *t* tests]. To assess these effects on Touch referral and Sense of ownership, we transformed the ordinal-scaled data, to apply an Aligned Rank Transformation Feys, 2016; Wobbrock, Findlater, Gergle, & Higgins, 2011), and then applied ANOVA. The data were plotted in RStudio 1.1.383 (RStudio Team, 2015) using a modified "raincloud" script (Allen, Poggiali, Whitaker, Marshall, & Kievit, 2019).

Proprioceptive Drift

The ANOVA on proprioceptive drift scores (Figure 2), with factors Synchrony (synchronous and asynchronous), Posture (0° and 90°), and Age (children, adults), showed significant main effects of Synchrony, $F(1,109) = 8.14$, $p = .005$, $\eta_p^2 = .069$, Age, $F(1,109) = 19.64$, $p < .001$, $\eta_p^2 = .153$, and Posture, $F(1,109) = 5.21$, $p = .024$, $\eta_p^2 = .046$. Drift was higher for synchronous ($M = 4.68$, $SD = 4.12$) than for asynchronous ($M = 2.69$, $SD = 4.84$) stroking; for children ($M = 5.46$, $SD = 5.05$) than for adults ($M = 2.09$, $SD = 3.49$); and when observing a fake hand in a congruent ($M = 4.45$, $SD = 5.31$) rather than in an incongruent ($M = 2.91$, $SD = 3.69$) posture. There was also an interaction of Synchrony and Posture, $F(1,109) = 6.48$, $p = .013$, $\eta_p^2 = .056$. No other interactions reached significance: Synchrony and Age, $F(1,109) < 0.001$, $p = .984$, $\eta_p^2 < .001$; Posture and Age, $F(1,109) = 0.83$, $p = .774$, $\eta_p^2 = .001$; Synchrony and Age and Posture, $F(1,109) = 0.28$, $p = .868$, $\eta_p^2 < .001$. To explore the Synchrony by Posture interaction, we conducted t tests for both posture conditions and applied a multiple-comparison correction proposed by Benjamini and Hochberg (1995). For the Congruent posture, responses were higher in the Synchronous condition ($M = 6.51$, $SD = 3.97$) than in the Asynchronous condition ($M = 2.59$, $SD = 5.72$), $t(55) = 2.97$, $p = .004$, $r = .372$ (significant at $\alpha_{\text{corrected}} = .025$). There were no significant drift differences between stroking conditions for the Incongruent posture, $t(58) = 0.25$, $p = .803$, $r = .447$ (not significant at $\alpha = .05$).

Questionnaire

Items 1–2 assessed the participants' subjective sense of ownership of, and touch referral to, the fake hand. These data, rated on a Likert scale from 0 (*no, definitively not*) to 6 (*yes, lots and lots*), were ordinal rather than interval and are consequently not suitable for parametric tests without prior transformation. We therefore present medians and interquartile ranges for these (Table 1) rather than means and standard deviations. Further, prior to submitting the data to parametric testing, we first applied an Aligned Rank Transformation (Wobbrock et al., 2011). This produces transforms nonparametric data into ranks (Conover & Iman, 1981), and then undertakes an alignment step, permitting statistically sound examinations of interaction effects. Data are then subjected to ANOVA. We then further examined interaction effects with nonparametrical tests (Mann–Whitney *U* tests). The Aligned Rank Transformation therefore acts as a bridge between nonparametric data and parametric testing (Conover & Iman, 1981). We chose this

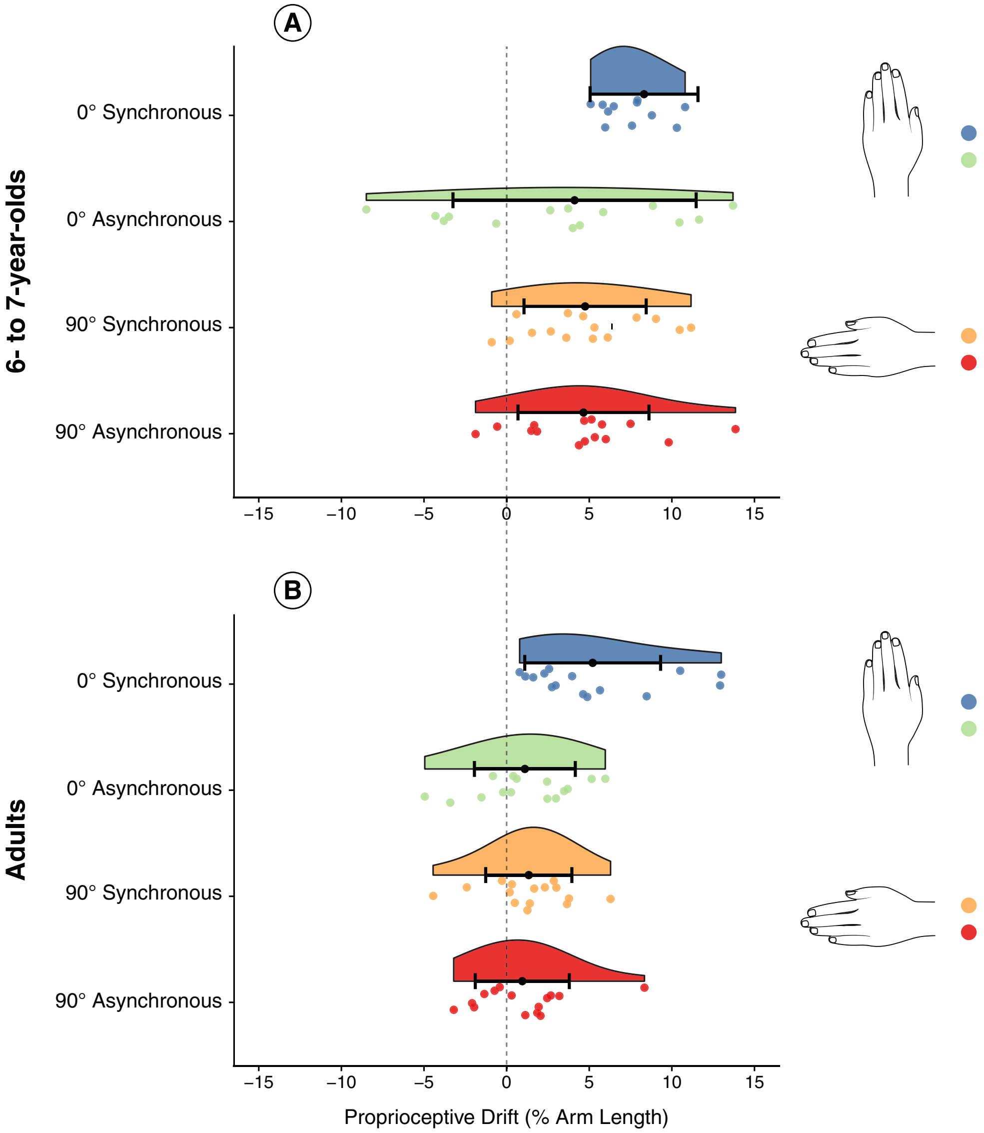

Figure 2. Mean baseline-corrected proprioceptive drift (percentage of arm length) across the postural (0°, 90°) and multisensory conditions (synchronous, asynchronous) for (A) 6- to 7-year-olds and (B) adults in Experiment 1. Positive values indicate drift towards the fake hand from baseline estimates (at 0, dotted line). Dots indicate individual means across four trials. Black dots indicate group means. Error bars indicate standard deviations. Hands illustrate the fake hands' postures (rotated by 0°, 90° anticlockwise).

transformation over using nonparametric tests to be able to also examine possible interaction effects, which would not have been possible with nonparametric tests. Such transformations are robust in comparison with other nonparametric alternatives (Feys, 2016) and have been used in similar studies (e.g., by Cowie et al., 2018).

For Question 1 (touch referral), we found significant main effects of Synchrony, $F(1,115) = 30.64$, $p < .001$, $\eta_p^2 = .210$, with higher values for the synchronous ($Mdn_{\text{raw}} = 3.0$, "In between") than for the asynchronous condition ($Mdn_{\text{raw}} = 1.0$, "No"), and Age, $F(1,115) = 11.41$, $p = .001$, $\eta_p^2 = .090$, with children ($Mdn_{\text{raw}} = 2.0$, "No, not really") rating higher than adults ($Mdn_{\text{raw}} = 1.0$, "No"). There was a significant interaction of Age and Synchrony, $F(1,113) = 4.03$, $p = .037$, $\eta_p^2 = .034$. There was no significant effect of Posture, $F(1,115) = 3.10$, $p = .081$, $\eta_p^2 = .026$. The interaction effects of Posture and Synchrony ($F(1,113) = 0.67$, $p = .414$, $\eta_p^2 = .006$), Posture and Age ($F(1,113) = 0.81$, $p = .370$, $\eta_p^2 = .007$), and Posture and Synchrony and Age $F(4,109) = 0.17$, $p = .952$, $\eta_p^2 = .006$) were not significant. Mann–Whitney U tests showed that there

Table 1

Questionnaire responses shown for each Age, Posture (0°, 90°), and Synchrony condition (S: Synchronous, A: Asynchronous). Rows show Median, Interquartile Range, and the Percentage of Responses in each category (0: "No, Definitely Not" to 6 "Yes, Lots and Lots")

	Q1 touch referral								Q2 ownership							
	6–7 years				Adults				6–7 years				Adults			
	0°		90°		0°		90°		0°		90°		0°		90°	
	S	*A*	*S*	*A*	*S*	*A*	*S*	*A*	*S*	*A*	*S*	*A*	*S*	*A*	*S*	*A*
Mdn	3	2	3	2	4	1	2	0	3	2	3	2	4	1	1	1
IQR(L)	1.97	0.63	1.30	0.56	1.63	–0.12	0.31	–0.53	2.13	0.58	1.89	0.10	1.01	–0.22	0.11	–0.03
IQR(U)	4.36	3.64	4.17	3.98	4.77	1.86	4.36	1.59	4.20	3.55	4.38	3.63	5.19	2.62	4.42	1.23
0	0	13.3	6.7	6.7	6.7	33.3	20.0	66.7	0	20.0	0	26.7	26.7	40.0	26.7	46.7
1	8.3	26.7	13.3	33.3	6.7	60.0	26.7	26.7	0	20.0	6.7	20.0	0	33.3	26.7	46.7
2	16.7	20.0	26.7	33.3	20.0	0	13.3	0	33.3	13.3	33.3	26.7	0	6.7	6.7	6.7
3	41.7	20.0	13.3	0	13.3	0	6.7	0	25.0	26.7	13.3	6.7	20.0	6.7	0	0
4	16.7	13.3	33.3	13.3	40.0	6.7	13.3	6.7	33.3	20.0	33.3	13.3	20.0	13.3	20.0	0
5	16.7	6.7	6.7	6.7	6.7	0	13.3	0	8.3	0	13.3	0	33.3	0	13.3	0
6	0	0	0	6.7	6.7	0	6.7	0	0	0	0	6.7	0	0	6.7	0

were significant effects of synchrony for both ages, but that there were no significant effects of age in each synchrony group: for the 6- to 7-year olds, responses were higher in the Synchronous condition ($Mdn = 3$, $SD = 1.33$) than in the Asynchronous condition ($Mdn = 2$, $SD = 1.58$), $U = 280.50$, $z = -2.03$, $p = .043$, $r = -.188$; for the adults, responses were likewise higher in the Synchronous condition ($Mdn = 3$, $SD = 1.83$) than in the Asynchronous condition ($Mdn = 0.5$, $SD = 1.02$), $U = 156.50$, $z = -4.49$, $p < .001$, $r = .410$. Whereas for the Asynchronous condition children's responses ($Mdn = 2$, $SD = 1.58$) were higher than adults' ($Mdn = 0.5$, $SD = 1.02$), $U = 170.00$, $z = -4.32$, $p < .001$ there were no statistically significant age-related differences for the Synchronous mode, $U = 384.50$, $z = -0.33$, $p = .74$, $r = .031$.

For Question 2 (ownership), we found a significant effect of Synchrony, $F(1{,}115) = 27.44$, $p < .001$, $\eta_p^2 = .193$, with higher values for the synchronous ($Mdn_{\text{raw}} = 3.0$, "In between") than for the asynchronous condition ($Mdn_{\text{raw}} = 1.0$, "No"), and a significant effect of Age, $F(1{,}115) = 6.52$, $p = .012$, $\eta_p^2 = .054$ with children ($Mdn_{\text{raw}} = 2.0$, "No, not really") rating higher than adults ($Mdn_{\text{raw}} = 1.0$, "No"). There was no significant effect of Posture, $F(1{,}115) = 2.21$, $p = .140$, $\eta_p^2 = .019$. The interaction effects of Synchrony and Age ($F(1{,}113) = 0.58$, $p = .448$, $\eta_p^2 = .005$), Posture and Synchrony ($F(1{,}113) = 0.088$, $p = .768$, $\eta_p^2 = .001$), Posture and Age ($F(1{,}113) = 0.97$, $p = .326$, $\eta_p^2 = .009$), and Posture and Synchrony and Age ($F(4{,}109) = 0.418$, $p = .796$, $\eta_p^2 = .015$) were not significant.

Discussion

In line with our hypotheses and previous research (Cowie et al., 2013, 2016), Experiment 1 showed that 6- to 7-year-old children use multisensory visual–tactile information for body representation, as indicated by both higher proprioceptive drift and higher self-ratings of touch referral and ownership in the synchronous (vs. asynchronous) stroking condition. As with previous investigations, and independently of multisensory correlations, we also find that 6- to 7-year-old children show substantially greater embodiment of a fake hand than adults, as indicated by overall higher questionnaire scores. Additionally, and again in line with previous work, 6- to 7-year-olds show overall larger drift toward the fake hand than adults (Cowie et al., 2013, 2016).

Regarding postural constraints on the use of visual–tactile information, we found that both children and adults use posture as a cue to embodiment, as measured by proprioceptive drift, and we did not find any evidence suggesting that children might be more flexible using posture as a cue to embodiment than adults. Thus in line with our hypothesis, in localizing a hand children and adults only process body-relevant multisensory information if the viewed hand matches the felt posture of their own hand. In case of an incongruent posture, it does not seem to matter whether or not multisensory information matches—the difference in posture prevents an initial recalibration of hand position (Makin et al., 2008) as well as subsequent integration of visual and tactile information (Tsakiris, 2010).

Interestingly, the self-report measures indicate no impact of posture on the subjective experience of embodiment at either age. In the 6- to 7-year olds, both self-reported experiences of touch referral and ownership were higher in the case of matching visuotactile information irrespective of the fake hand's posture. In adults, this was the case for the experience of touch on the fake hand. For ownership, adult's responses did not differ between stroking conditions and were relatively low (*Mdns* = 1, "No"), indicating that irrespective of its posture, adults did not strongly experience the fake hand as their own. Note in this context that estimated effect sizes of posture were rather small.

Experiment 2

Experiment 1 suggests that posture is a strong constraint on hand localization as measured by proprioceptive drift at 6–7 years of age, as it is in adults. It is unclear however, whether participants were sensitive to the fact that the rubber hand was incongruent with their own *current* posture or merely that the posture was anatomically impossible (Makin et al., 2008; Rohde et al., 2011). Being sensitive to differences related to the own current posture taps into short-term body representation; a representation that has sometimes been referred to as the *postural schema*, *first-order body schema* or *short-term body representation*. (cf. de Vignemont, 2006; Gallagher, 2000). Being sensitive to what is anatomically (im)possible for the own body in turn taps into long-term body representation; a representation which relates to the *higher-order body schema*. Furthermore, if they were sensitive to the postural incongruence between hands, it is unclear what the resolution of this postural matching system might be, and so how close a match is needed for children to embody a hand, especially given the limits of proprioception (cf. Cowie et al., 2013; King, Pangelinan, Kagerer, & Clark, 2010; Nardini et al., 2013; von Hofsten & Rösblad, 1988) and the rapid physical changes in childhood (cf. Thelen, 1992; Thelen & Smith, 1994). In Experiment 2, we therefore aimed to disentangle these factors by addressing the resolution of children's postural matching. In Experiment 1, we compared an incongruent anatomically impossible posture (90°) with a congruent posture (0°). Here in Experiment 2, we presented children with an intermediate condition only, where the fake hand was rotated 20° anticlockwise into an incongruent, but anatomically *possible* posture. This means that this experiment is addressing the first-order body schema. As in Experiment 1, synchronous and asynchronous stroking conditions were varied between participants. We chose 20° based on children's errors in postural matching in this age group, as reported by Goble, Lewis, Hurvitz, and Brown (2005), and on adults' sensitivity to smaller mismatches (Costantini & Haggard, 2007). Alongside the rubber hand paradigm, we used a perceptual judgment task to determine that participants could visually distinguish between the congruent (0°) and incongruent (20°) hand postures.

For adults in this experiment, we expected to replicate previous work suggesting finely tuned postural matching (Costantini & Haggard, 2007; Ehrsson et al., 2004; Tsakiris & Haggard, 2005): A specific prediction is that there should be no difference in drift and self-report measured between the synchronous and asynchronous stroking condition for the incongruent-possible posture (20° condition). Previous studies have shown that when the posture of real and fake hand is incongruent, then viewed and felt strokes are not bound together into a multisensory percept, and so there is no effect of visuotactile synchrony (for model, see Tsakiris, 2010). Furthermore, proprioceptive drift and questionnaire scores should be low (drift near zero and ratings below median). In line with previous studies and Experiment 1, this would indicate no embodiment of an incongruent hand. For children, there are two likely results scenarios: In one which we will call an *early-development scenario*, we may find that children demonstrate the same pattern of findings as adults, showing no difference and low scores in measures of body representation across conditions when shown a hand in 20° incongruent posture. This would indicate that children have the same postural constraints on their hand representations as adults. Alternatively, in a *late-development scenario*, we may find differences in measures of body representation between the two stroking conditions for 20° incongruent posture with higher values for the synchronous stroking condition, indicating embodiment of a hand irrespective of the posture and therefore suggesting more flexibility in body representations in children than in adults. This would indicate that children and adults differ in their short-term, but not in their long-term body representation (cf. de Vignemont, 2006; Gallagher, 2000). Because of the strong arguments in favor of both scenarios, we made neither prediction.

Method

Participants

The participants comprised thirty 6- to 7-year olds (*M* = 6.9 years, *SD* = 0.3 years, 18 boys and 12 girls) and 30 adults (*M* = 22.5 years, *SD* = 0.4 years, 24 women and 6 men) living in the North-East of England. The sample size was chosen as in Experiment 1. Participants were recruited from January to March 2018 and tested from January to April 2018. The data of one child were excluded due to an extreme drift score (synchronous, 20° condition). All participants had normal or corrected-to-normal vision with no known sensory, neurological, or neurodevelopmental problems. This investigation was approved by the local research ethics committees.

Experimental Procedure

The procedure was exactly as in Experiment 1 apart from two amendments: First, the fake hand was rotated by 20° anticlockwise so that it appeared in an incongruent but possible posture in comparison to the participant's own hand. Second, an additional visual judgment task was introduced at the end of the testing session. Again, the stroking mode was either synchronous or asynchronous, manipulated between subjects. After the RHI induction and the questionnaire, a visual judgment task was performed. On each of 10 trials, the participant's own left hand was placed on the table left to the screen and out of sight for the participant, as in the RHI task. The participants were asked to close their eyes, while the fake hand was placed in front of them, which was done for 10 randomized trials. In half of the trials, the fake hand was placed in a congruent position, and in the other half it was placed at 20° anticlockwise to their own hand. On each trial, the participant was asked to say whether their own hand and the fake hand were oriented in the same or different directions.

Results

We conducted analyses on proprioceptive drift (Figure 3) and on the aligned rank transformed questionnaire data (Table 2) as we have reported in Experiment 1.

Proprioceptive Drift

There were no effects of Synchrony ($F(1,55) = 1.26$, $p = .267$, $\eta_p^2 = .022$) or Age, ($F(1,55) = 0.33$, $p = .566$, $\eta_p^2 = .006$), and no interaction between these factors ($F(1,55) = 0.499$, $p = .483$, $\eta_p^2 = .009$), indicating no drift differences between stroking conditions and or age groups. To quantify the support for the null hypotheses, we did a Bayesian fixed-effect ANOVA using the BayesFactor package (version 0.9.2+) in RStudio Version 1.1.463 (RStudio Team, 2015). Comparing all models against intercept revealed all Bayes factors below 1 (Synchrony $BF_{10} = 0.692 \pm 0.01\%$, Synchrony by Age $BF_{10} = 0.475 \pm 0.01\%$, Age $BF_{10} = 0.266 \pm 0\%$), suggesting to favor the null over the alternative hypotheses (Dienes, 2014).

Questionnaire

For Question 1 (touch referral), there was a significant main effect of Synchrony, $F(1,57) = 7.687$, $p = .008$, $\eta_p^2 = .119$, with higher values for the synchronous ($Mdn_{\text{raw}} = 4.0$, "Yes, a little") than for the asynchronous condition ($Mdn_{\text{raw}} = 2.0$, "No, not really"). There was a significant effect of Age, $F(1,57) = 4.238$, $p = .044$, $\eta_p^2 = .069$, with children ($Mdn_{\text{raw}} = 4.0$, "Yes, a little") rating higher than adults ($Mdn_{\text{raw}} = 2.0$, "No, not really"). The interaction of Age and Synchrony was not significant, $F(1,55) = 0.007$, $p = .935$, $\eta_p^2 < .001$. For Question 2 (ownership), there was a significant main effect of Synchrony, with higher values for the synchronous ($Mdn_{\text{raw}} = 3.0$, "In between") than for the asynchronous condition ($Mdn_{\text{raw}} = 1.0$, "No"), $F(1,57) = 11.910$, $p = .001$, $\eta_p^2 = .173$. The effect of Age, $F(1,58) = 1.42$, $p = .239$, $\eta_p^2 = .024$, and the interaction effect, $F(1,56) = 0.01$, $p = .920$, $\eta_p^2 < .001$, were not significant.

Visual Judgment Task

We totaled hits (correct identifications of postural differences between real and rubber hands) and false alarms (incorrect identifications). Subtracting the false alarm rate from the hit rate gave us an overall correct judgment rate of 79% (70% for children, 88% for adults), indicating that on average, participants could correctly identify the fake hand's posture as being congruent or incongruent with their own hand's posture. We calculated *d* prime (d') by subtracting the z-transformed false alarm rate from the *z*-transformed hit rate standardized by the likelihood of .5 (cf. Godfrey, Syrdal-Lasky, Millay, & Knox, 1981) and applied a correction as suggested by Hautus (1995). An ANOVA on the corrected d' revealed no significant effect of Synchrony ($F(1,55) = 0.14$, $p = .712$, $\eta_p^2 = .002$) or Age ($F(1,55) = 2.72$, $p = .105$, $\eta_p^2 = .047$), and no interaction between these factors ($F(1,55) = 0.01$, $p = .994$, $\eta_p^2 < .001$). This means we found no statistical support (a) for possible effects on stroking mode on

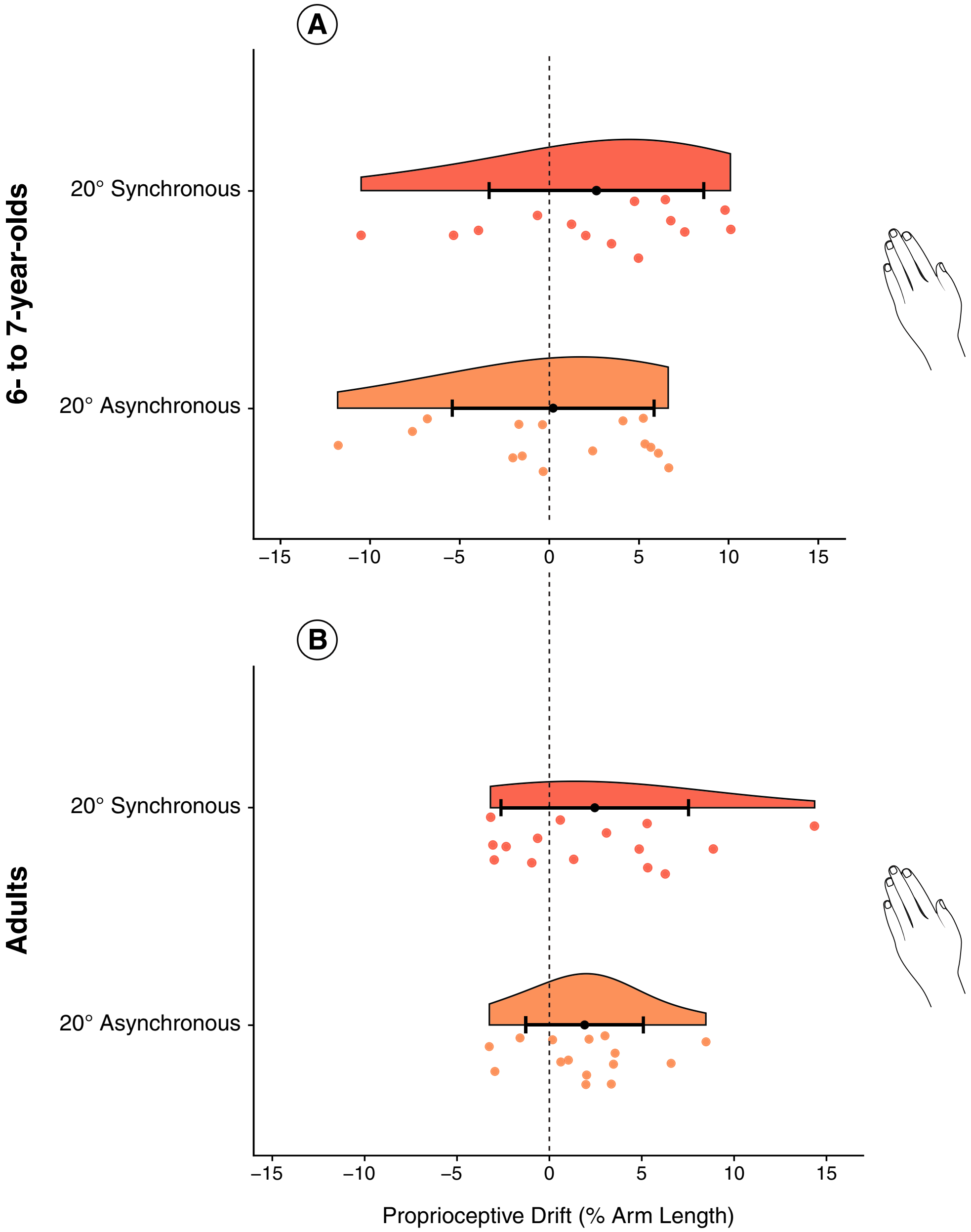

Figure 3. Mean baseline-corrected proprioceptive drift (percentage of arm length) for the postural (20°) and multisensory conditions (synchronous, asynchronous) for (A) 6- to 7-year-olds and (B) adults in Experiment 2. Positive values indicate drift towards the fake hand from baseline estimates (at 0, dotted line). Dots indicate individual means across four trials. Black dots indicate group means. Error bars indicate standard deviations. Hands illustrate the fake hands' postures (rotated by 20° anticlockwise)

visual posture judgment and (b) for different visual posture judgments in children and adults.

Discussion

Again, we found evidence for adult-like body representations in children of this age. The proprioceptive drift results suggest in localizing their own hand, children and adults do not use a fake hand which is in a slightly different posture to their own hand: in the 20° posture, drift was low and there was no difference in drift between the synchronous and the asynchronous visual–tactile conditions for the 20° posture. The questionnaire results present a similar picture across children and adults. Adults and children also respond similarly on

Table 2

Questionnaire responses shown for each Age and Synchrony condition (S: Synchronous, A: Asynchronous), in the 20° Posture Condition. Rows show Median, Interquartile Range, and the Percentage of Responses in each category (0: "No, Definitely Not" to 6 "Lots and Lots")

	Q1 touch referral				Q2 ownership			
	6–7 years		Adults		6–7 years		Adults	
	S	*A*	*S*	*A*	*S*	*A*	*S*	*A*
Mdn	4	3	2	2	2.5	1	3	2
IQR(L)	1.71	0.94	1.69	4.31	0.54	−0.16	1.62	0.17
IQR(U)	6.00	4.66	0.59	3.01	4.60	2.29	4.11	3.16
0	14.3	6.7	0	13.3	14.3	46.7	0	26.7
1	7.1	26.7	6.7	33.3	28.6	20.0	20.0	20.0
2	0	13.3	46.7	20.0	7.1	13.3	20.0	33.3
3	7.1	13.3	0	26.7	14.3	20.0	13.3	6.7
4	28.6	26.7	33.3	6.7	21.4	0	46.7	6.7
5	14.3	0	13.3	0	0	0	0	6.7
6	28.6	13.3	0	0	14.3	0	0	0

questionnaire items, in that they report some subjective embodiment of the incongruent fake hand, as indicated by higher ratings of touch and ownership for the synchronous than for the asynchronous condition. Children's ratings were overall higher than adults. However, we do note that median ratings are overall low. Both results are in line our *early-development scenario* in which children have similar postural constraints to adults by 6- to 7-year olds. However, drift and questionnaire data suggest different uses of postural information for both children and adults. Posture constrains body representation as measured by proprioceptive drift, but not subjective experiences of embodiment.

General Discussion

Both the proprioceptive drift measure and subjective ratings demonstrate that bottom-up multisensory information from vision, touch, and proprioception drives body representation for both children and adults. This is consistent with previous findings (Cowie et al., 2013, 2016; Greenfield, Ropar, Smith, Carey, & Newport, 2015; Nava et al., 2017): Visual–tactile spatiotemporal correlations are used to establish a sense of ownership over the viewed hand (questionnaire), a sense of touch on it (questionnaire), and a sense of hand position near it (proprioceptive drift). Our novel finding is that children (as do adults) apply top-down knowledge of the possible posture of their body to constrain body representation. The current study is the first one to investigate the effects of different postures on the sense of embodiment in children. Here, we show that orientation of the hand appears to be an important aspect of the visual model of the body in childhood. Interestingly, we find that across children and adults, posture specifically constrains the sense of hand position, as measured by proprioceptive drift, but not the subjective experiences of hand ownership or touch location.

We find that children use similar constraints to body representation as adults do, anchoring their sense of bodily self to its known layout and posture. We find no indication of more flexible, less posturally specific, body representations in 6- to 7-year olds (although nuanced age-modulation of the posture-by synchrony interaction might be detectable in an even larger sample size, the age-independent postural constraint found here is clearly larger in magnitude). Furthermore, we demonstrate that these effects of posture are finely tuned: On average, in terms of hand localization, children's hand localization is influenced neither by a fake hand in an incongruent-impossible (90°) nor in an incongruent-possible posture (20°). Although not directly tested, we assume that both long-term knowledge of anatomically impossible hand postures (cf. de Vignemont, 2006; Makin et al., 2008; Rohde et al., 2011;) and short-term knowledge of the *current* hand posture constrain body representation in childhood, as previously demonstrated in adulthood (Costantini & Haggard, 2007; Tsakiris & Haggard, 2005). This is the first demonstration that children can not only detect postural differences between their own limbs and misoriented limbs (as already indicated in some infant studies; Rochat & Morgan, 1995) but also use this information to form a sense of their bodily self.

As well as demonstrating this relative maturity in the use of postural information at 6–7 years of age, we replicate previous investigations (Cowie et al., 2013, 2016) which find a significant difference between children and adults. Specifically, irrespective of hand posture or visuotactile synchrony 6- to 7-year-old children show larger drifts of perceived hand position toward the fake hand than adults, as well as higher-rated experiences of touch and ownership. This age difference is not easily explained by the generally poorer resolution of proprioception and more variable pointing at 6–7 years of age (Goble et al., 2005; King et al., 2010; von Hofsten & Rösblad, 1988): we controlled for potential pointing biases by baseline correction of our drift measure. Rather, the hand is localized by combining two estimates: one given by vision of the fake hand, and one given by proprioception of the real hand. In children, the weighting is further toward the visual position (at the fake hand) than in adults (cf. Cowie et al., 2013) so that there is a tendency to localize a hand where you see it rather than where you feel it to be. This tendency to embody a hand-shaped object viewed in front of you is a simple, appealing mechanism that appears to be present early in life and replaced by more subtle balances of sensory input later in adulthood.

In terms of classic models of body ownership (Makin et al., 2008; Tsakiris, 2010), we argue that multisensory information from vision and touch leading to body representation is processed by perihand mechanisms: slight changes in posture, such as rotations by 20°, prevent an initial recalibration of hand position (Makin et al., 2008) as well as subsequent integration of visual and tactile information (Tsakiris, 2010). As the proprioceptive signals weaken over time however (Rohde et al., 2011), they are less strongly informative about the hand's posture, and visuotactile congruence alone might allow a subjective experience of ownership of the fake hand.

Why do our drift and self-report results in children and adults differ with regard to the effect of fake hand posture? To recapitulate our findings, while visual–tactile stroking drives the subjective experience of touch on the fake hand (questionnaire), ownership over the fake hand (questionnaire), and the sense of hand position near it (proprioceptive drift), top-down knowledge of posture seems only to constrain the sense of hand position (proprioceptive drift), but not the subjective experience of embodiment.

This accords with previous work reporting a dissociation between drift and questionnaire measures of body representation (Cowie et al., 2013; Pavani & Zampini, 2007; Rohde et al., 2011), suggesting two different underlying mechanisms instead of only one, as originally assumed (Botvinick & Cohen, 1998; for further discussion see Rohde et al., 2011). Indeed, these measures operate on different time scales, are accompanied by different levels of awareness, reflect processes in different neural areas, and furthermore afford different behavioral qualities of reply (pointing vs. speaking). Furthermore, the difference between drift and questionnaire results is probably related to the fact that we measure different aspects of body representation. Proprioceptive drift is related to the sense of self location; the questionnaire is related to the sense of body ownership (cf. Kilteni et al., 2012). Both measures combined can provide a more holistic picture of own-body representation in development than one measure alone. However, we note that in this context the children's median responses did not indicate a strong subjective sense of the illusion in either the synchronous condition (where median responses rested between "In between" and "Yes, a little") or the asynchronous condition (where median responses rested between "No, not really", and "No").

Regarding age-group-related differences between drift scores, it is noteworthy that children demonstrated lower drift responses to the incongruent-possible fake hand than adults as compared to the incongruent-impossible and the congruent fake hand. In Experiment 1, children demonstrated overall larger drift than adults. These differences in the experiments could tie to children's higher inter-individual variability in the intermediate, less clear-cut 20° condition. There were, for example, more and larger overcompensations in children's drift responses (i.e., negative values) in Experiment 2 as compared to Experiment 1. This may reflect a considered rejection of the fake hand and metacognitive processes in children (Deroy, Spence, & Noppeney, 2016). However, as this experiment was not designed to answer this question systematically, we can only speculate about possible explanations for these observed differences. Future research should investigate these questions.

We note that some of the most widely cited studies of postural incongruency in the RHI (Costantini & Haggard, 2007; Tsakiris & Haggard, 2005) measured drift only, and we have clearly replicated their findings that hand localization is significantly affected by postural incongruency. A few others have measured ownership via questionnaire. While Ehrsson et al. (2004) found reduced ownership for a fake hand at 180°, and Pavani, Spence, and Driver (2000) found reduced ownership for a hand at 90°, Ide (2013) found only minor ownership reductions at 90°, with far greater effects at angles beyond this. Our result therefore contributes to the available empirical literature and suggests that perhaps the postural congruency effect on ownership specifically, as opposed to drift, deserves reconsideration.

A further interesting aspect of our data is the inter-individual variability we observe. Overall, there is a higher variability in drift in children than in adults, in the asynchronous than in the synchronous stroking condition, and in the 20° as an intermediate postural condition than in the more clearly defined postural conditions of 0° or 90°. The first two mentioned differences are in line with previous work (Cowie et al., 2013, 2016), as indicated by differences in standard errors. Higher variability in children in the asynchronous condition might for instance indicate that *some children* disregard whether multisensory information is synchronous and instead predominantly use visual information for body representation (as indicated by high drift toward the fake hand), as it has been shown for the full body illusion (Cowie et al., 2018). In contrast, *other children* might take multisensory information into account and consequently do not embody the fake hand (as indicated by drift values close or smaller than zero). The comparatively high variability in our intermediate condition (20°), especially combined with the synchronous stroking, raises the question of whether there are further individual differences in multisensory and posture processing: It might be that some individuals disregard the slight postural incongruency of 20° and nevertheless use multisensory correlation for body representation, whereas others require a precise postural match. The more clear-cut 0° and 90° conditions in comparison evoke less variability in drift. However, we did not investigate interindividual variability in the current study. The aim of the current work was to establish whether children show similar postural constraints in embodiment of a fake hand as adults. Future research should systematically address individual differences in body representation and clarify the mechanisms underlying them. It could, for instance, be that some children are more sensitive to postural differences and in turn less likely to sense embodiment toward limbs in deviating postures as compared to less posture-sensitive children. Recent work, for instance, demonstrated effects of hand size on children's body representation: Children systematically underestimate their own hand's size relative to a fake hand (Cardinali, Gori, & Serino, 2019) and report a sense of ownership over both a child-sized and an adult-sized fake hand in the RHI paradigm (Filippetti & Crucianelli, 2019).

Limitations

Six caveats should be mentioned. First, our sample comprises individuals from a WEIRD population (cf. Rad, Martingano, & Ginges, 2018). The population in the areas where data were collected is mainly white-British (55% and 88% according to the British Office for National Statistics, 2009). Our adult sample comprised undergraduate students around the age of 21 years. We therefore have to be cautious with generalizing the results to people from different backgrounds and other age groups. Second, and related to this, the child samples in the present study consist of 6- to 7-year olds. It would of course be fascinating to study how posture constrains younger children's body representation, however, we selected 6- to 7-year-old children for a number of reasons. Four years is the youngest age at which data exist for children on the RHI task (Cowie et al., 2013, 2016; Nava et al., 2017). Because previous studies (Cowie et al., 2013, 2016; Nava et al., 2017) have demonstrated that 4- to 5-year olds demonstrate substantial variability in their pointing responses and show only very noisy (and statistically unreliable) differences in proprioceptive drift between the synchronous and the asynchronous conditions, we decided to test older children. In sum, given that proprioceptive drift is not as reliably measured in 4- to 5-year olds, we felt that 6- to 7-year olds were a group which, as well as being likely to yield reliable measurements, well represented the broadly homogenous 4- to 9-year-old age band which is known to differ from adults in their responses to the illusion. Fourth, of course our ordinal questionnaire data are somewhat limited. Subjective feelings of embodiment are difficult to quantify: nevertheless, we note that the direction and magnitude of differences we find are in line with previous work (Longo et al., 2008). Finally, the rubber hand paradigm is artificial in that it requires participants to keep their body still to make the illusion work. Moving the affected hand during the experiment usually breaks the illusion. However, posture is especially relevant for the moving body and movement in turn informs us about our bodily posture. Future work needs to address effects of posture on the sense of embodiment during movement. Virtual Reality, where avatar movement can track one's own, and visually perceived posture can systematically deviate from proprioceptively perceived posture, would offer such possibilities.

Conclusion

Children of 6–7 years already use a relatively refined postural model of the body to inform a sense of bodily self, as adults do. Even though children rely more heavily on vision than on proprioception for locating the body (cf. King et al., 2010; Nardini et al., 2013; von Hofsten & Rösblad, 1988), the sight of a hand in an incongruent posture relative to their own hand, accompanied by synchronous touch on the two hands, does not elicit body representation as measured by proprioceptive drift. Rather, a viewed hand must match a postural model of the body to be embodied. This shows that, although childhood is a period of significant change in both bodily dimensions and sensorimotor capabilities, 6-to 7-year olds have sensitive, robust mechanisms for maintaining a sense of bodily self.

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