The developing bodily self: Posture constrains embodiment in children as in adults

Janna M. Gottwald\textsuperscript{1,2}, Laura Bird\textsuperscript{1}, Samantha Keenaghan\textsuperscript{1}, Clare Diamond\textsuperscript{1}, Eliana Zampieri\textsuperscript{1}, Haleema Tosodduk\textsuperscript{3}, Andrew J. Bremner\textsuperscript{3,4}, and Dorothy Cowie\textsuperscript{1}

\textsuperscript{1} Department of Psychology, University of Durham, Durham, DH1 3LE, UK
\textsuperscript{2} Department of Psychology, Uppsala University, Uppsala, Sweden
\textsuperscript{3} Sensorimotor Development Unit, Department of Psychology, Goldsmiths, University of London, New Cross, London, SE14 6NW, UK
\textsuperscript{4} School of Psychology, University of Birmingham, Edgbaston, Birmingham, B15 2SB, UK

\___________________________________________________________________________

This is a preprint (CC BY 4.0 Open Access). For updates and comments, see https://doi.org/10.31234/osf.io/62aqc, for data, see https://doi.org/10.17605/osf.io/gtu6e.

___________________________________________________________________________

Authors’ note

This project received funding from the Economic and Social Research Council (ESRC ES/P008798/1 to DC), the European Research Council (ERC 241242 to AJB), and the Swedish Research Council (VR-PG 2017-01504 to JMG). The authors declare that they had no conflicts of interest with respect to their authorship or the publication of this article. We thank the children and adults participating in this study and the local primary schools for collaboration. All procedures performed were in accordance with the ethical standards of the regional ethics committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Informed consent was obtained from the parents of all individual participants included in the study.

MANUSCRIPT WORD COUNT: 6318

CORRESPONDENCE TO: Dr J M Gottwald, Department of Psychology, Durham University, South Road, Durham, DH1 3LE, UK; email: janna@jannagottwald.com
Abstract

For adults, the feeling of inhabiting a body (a sense of embodiment) is constrained by bottom-up multisensory information such as spatiotemporal correlations between visual and tactile sensations, and by top-down knowledge of the body such as its possible postures. However, to date it is unknown what kinds of body models children have. Here we asked whether common factors constrain embodiment in children and adults. In two experiments, we compared 6- to 7-year-olds’ and adults’ embodiment of a fake hand in the rubber hand illusion, measuring illusion-induced proprioceptive drift and questionnaire responses. In Experiment 1 ($N = 120$), the fake hand was either congruent with the participant’s own hand, or incongruent by $90^\circ$ and, as a result, in an impossible posture with respect to the current position of their body. In Experiment 2 ($N = 60$), the fake hand was incongruent with the participant’s own hand by $20^\circ$, but still in a possible posture. Across both experiments, and in both children and adults, visual-proprioceptive congruency of posture, and visual-tactile spatiotemporal congruency in stroking independently yielded greater proprioceptive drift towards the rubber hand. Subjective ratings of embodiment were also higher when visual-tactile information was congruent, but were not affected by posture. Top-down knowledge of body posture therefore partially constrains embodiment in middle childhood, as in adulthood. This shows that, although childhood is a period of significant change in both bodily dimensions and sensory capabilities, 6- to 7-year-olds have sensitive, robust mechanisms for maintaining a sense of bodily self.

[Word count: 246]

Keywords: rubber hand illusion, multisensory, body representation, visual-tactile congruency, body ownership, body perception
The feeling of inhabiting a body (a sense of embodiment) is fundamental for self-experience (Kilteni, Groten, & Slater, 2012; Longo, Schüür, Kammers, Tsakiris, & Haggard, 2008). For adult humans, a sense of embodiment is grounded in both current multisensory information, such as seeing and feeling of being touched, and in internal models which specify the form or structure of one’s own body, i.e., top-down knowledge (Tsakiris & Haggard, 2005). Recent findings show that bottom-up information deriving from multisensory interactions between visual, tactile and proprioceptive cues is crucial for embodiment from early childhood (Cowie, Makin, & Bremner, 2013; Cowie, McKenna, Bremner, & Aspell, 2018; Cowie, Sterling, & Bremner, 2016), but there is no direct research on the influence of top-down knowledge of the shape or layout of the body on embodiment 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 embodiment in adults (Botvinick & Cohen, 1998; Tsakiris, 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, 1998; 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 embodiment in older children from the age of four to thirteen 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 real hand out of sight and on a fake hand in sight (visuotactile correlation) leads to the illusion that the fake hand is the participant’s own, and to the drift of
perceived hand position towards the fake hand (‘proprioceptive drift’, see Tsakiris & Haggard, 2005). These illusory percepts occur in both adults and four- to thirteen-year-olds, indicating that, from the age of four years, multisensory visuotactile information, i.e. 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 (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 (Ehrsson, Spence, & Passingham, 2004), and crossmodal congruency effects (Pavani, Spence, & Driver, 2000). The size of the RHI decreases when the fake hand is rotated by 180° (Austen, Soto-Faraco, Enns, & Kingstone, 2004; 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, Holmes, & Ehrsson, 2008; Tsakiris, 2010), i.e., the sense that one’s body belongs to oneself (Gallagher, 2000). According to Tsakiris (2010), we can imagine the incoming synchronous visuotactile information to either pass the form and the postural ‘gate’ and to lead to the embodiment of a fake hand, or to not
pass and consequently not lead to the illusion that a fake hand is one’s own (see also Allen & Friston, 2016; Apps & Tsakiris, 2014; Friston, 2009).

In adults, top-down knowledge about possible body postures therefore constrains embodiment. There is some suggestion that infants already have a coarse knowledge about postural differences: three- to five-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, the contribution of such elements to a sense of bodily self is unknown. Further, even if such large postural discrepancies are detectable early in life, we thus far have little evidence that such perceptual differentiations proceed to guide infants’ sense of embodiment (see Bremner & Cowie, 2013). Furthermore, there are two main reasons to suppose that children may still have substantially more flexible body representations than adults.

First, children’s bodies, physical and functional abilities are rapidly and dynamically changing during development (Thelen, 1992; Thelen & Smith, 1994). When the body fundamentally changes in size or layout, so its representation must change to match in order to enable skilful movements. In particular, perception of body posture may be affected by changing physical constraints, 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. Thus, the growing child is confronted with ever-changing bodily parameters and might not be able to keep up with this speed of developmental change (cf. Bremner, Holmes, & Spence, 2008; Gori, Del Viva, Sandini, & Burr, 2008). At the age of 6 to 7 years, children are still developing this bodily expertise, which might result in children using less precise body models than adults.
A second argument in favour of flexible body representation in mid-childhood is that the sensory bases for perceiving one’s own body characteristics are relatively poor in childhood. Relatively coarse body perception may result from variable and biased proprioceptive estimates of limb position in childhood (Nardini, Begus, & Mareschal, 2013; von Hofsten & Rösblad, 1988). Additionally, combining proprioception with vision is rather difficult: 8-10 year olds make errors of up to 20° (6° on average) in a task of this sort (Goble, Lewis, Hurvitz, & Brown, 2005), and statistically optimal integration is not reliably present until around 10 years of age (Nardini et al., 2013). Therefore, one may expect coarser matches between vision and proprioception in children than in adults, resulting in somewhat flexible body representation. In sum therefore, flexible body representations in children may result from the daily need to adapt to a growing body, as well as from immature sensory abilities.

This study is the first direct empirical investigation of whether and how posture constrains embodiment in childhood, where multisensory processing is different and postural perception may be more difficult than in adulthood. The current paper comprises two experiments. These address in turn whether 6- to 7-year-olds use a postural model of the body as adults do (Experiment 1) and how finely-tuned these effects of posture are (Experiment 2). Additionally, the question of long-term and short-term body models of posture is addressed by using generally anatomically implausible postures (Experiment 1) and possible, but currently incongruent postures with respect to one’s own hand (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 could 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 embodiment (Cowie et al., 2013; Longo et al., 2008; Rohde, Luca, & Ernst, 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 embodiment, we used synchronous and asynchronous stroking conditions. 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 minimise testing time (an important consideration in studies with children of this age), all manipulations were made between participants.

For adults, we expected a difference in drift and self-report measured between the synchronous and asynchronous stroking condition for the congruent (0° condition), but not for the incongruent hand posture (90° condition). In line with previous studies, this would indicate that viewing a hand in peripersonal space triggers multisensory integration, but only when the hand is placed in an anatomically possible posture (Makin et al., 2008; Tsakiris, 2010). For children, there are two likely scenarios: first, children may show this difference in drift and self-report measures only when the hand is in a congruent posture (0° condition), indicating that children show the same postural constraints as adults. Second, there may be a difference in embodiment between the stroking conditions for both the congruent (0° condition) and for the incongruent hand posture (90° condition), indicating embodiment of a hand irrespective of the posture and therefore indicating that children are more willing to accept non-aligned hands as their own, because they have more flexible body models.
Method

Participants. The participants comprised sixty 6- to 7-year-olds ($M = 7.1$ years, $SD = 0.5$ years, 32 girls and 28 boys) and sixty adults ($M = 21.4$ years, $SD = 3.0$ years, 31 women and 29 men). The data of three children were excluded due to extreme drift scores (see Results section). All had normal or corrected-to-normal vision with no known sensory, neurological or neurodevelopmental problems. The sample size of $N = 120$ (i.e., 15 participants in 8 groups) was chosen to make this study comparable to previous work which had detected medium-to-large effect sizes for the key factor Synchrony with 15 participants per group (Cowie et al., 2013, 2016). A priori power calculation using G*Power 3.1 (Faul, Erdfelder, Lang, & Buchner, 2017) suggested a smaller sample size of $N = 80$ given an $\alpha$ error probability of .05, a power of .8, and an effect size of $\eta^2_p = 0.17$ (i.e., the estimated size of the effect of Synchrony on proprioceptive drift reported by Cowie et al., 2016). This investigation was approved by the local research ethics committees at the two universities where the data was collected.

Experimental procedure. The same procedure was adopted as in previous RHI studies with children (Cowie et al., 2013; 2016), and is redescribed here. 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 (Fig. 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.

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 two minutes 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 Fig. 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 seconds 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 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 not presented below.

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: “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 towards the fake hand by subtracting, for each participant, their mean baseline pointing position from their mean test pointing position, and scaling this as a percentage of arm length.

Inspection of the data identified the data of three children (all in the synchronous, 0° condition) as 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 Age on proprioceptive drift, we used standard parametric statistics [analysis of
variance (ANOVA) and t-tests]. Data were plotted in RStudio 1.1.383 (RStudio Team, 2015) using a modified ‘raincloud’ script (Allen, Poggiali, Whitaker, Marshall, & Kievit, 2018).

**Proprioceptive drift.** The ANOVA on proprioceptive drift scores (Fig. 2) showed significant main effects of Synchrony, $F(1,109) = 8.14, p = .005$, $\eta^2_p = 0.069$, Age, $F(1,109) = 19.64, p < .001$, $\eta^2_p = 0.153$, and Posture, $F(1,109) = 5.21, p = .024$, $\eta^2_p = 0.046$. 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, $F(1,109) = 6.48, p = .013$, $\eta^2_p = 0.056$. No other interactions reached significance (all $Fs < 0.1$, $ps \geq .70$, $\eta^2_{ps} \leq .001$). To explore the Synchrony by Posture interaction, we conducted t-tests for both posture conditions. A multiple-comparison correction proposed by (Benjamini & Hochberg, 1995) was applied. 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 $\alpha = .05$).
Figure 2. Mean baseline-corrected proprioceptive drift (percentage of arm length) across all postural (0°, 20°, 90°) and multisensory conditions (synchronous, asynchronous) for (A) 6- to 7-year-olds and (B) adults. Positive values indicate drift towards the fake hand from baseline estimates (at 0, dotted line). Dots indicate individual means across four trials. Box plots display group medians (black lines) and interquartile ranges. Whiskers represent maximal 1.5 × IQR. Above each boxplot, frequency distributions are displayed. Hands illustrate the fake hands’ postures for all postural conditions (0°, 20°, 90°).
**Questionnaire.** Items 1-2 assessed 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. We therefore present medians and interquartile ranges for these (Fig. 3) rather than means and standard deviations. Further, prior to submitting the data to parametric testing, we first applied an Aligned Rank Transformation (Wobbrock, Findlater, Gergle, & Higgins, 2011). This produces ranks of nonparametric data (Conover & Iman, 1981), while also including an alignment step which also allows for the correct assessment of interaction effects. This procedure therefore acts as a bridge between non-parametric and parametric testing (Conover & Iman, 1981). After the Aligned Rank Transformation, the data were submitted to standard ANOVA.

For Question 1 (touch referral), we found significant main effects of Synchrony, $F(1,115) = 30.64, p < .001, \eta^2_p = 0.210$, with higher values for the synchronous ($Mdn_{raw} = 3.0$, “In between”) than for the asynchronous condition ($Mdn_{raw} = 1.0$, “No”), and Age, $F(1,115) = 11.41, p = .001, \eta^2_p = 0.090$, with children ($Mdn_{raw} = 2.0$, “No, not really”) rating higher than adults ($Mdn_{raw} = 1.0$, “No”). There was a significant interaction of Age and Synchrony, $F(1,113) = 4.03, p = .037, \eta^2_p = 0.034$. There was no significant effect of Posture, $F(1,115) = 3.10, p = .081, \eta^2_p = 0.026$, and no other effects were significant, $Fs < 0.2, ps > .7, \eta^2_ps < .007$.

Mann-Whitney U-tests showed that the Age by Synchrony interaction was not driven by differential effects of synchrony across ages: 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 ($Mdn = 1, SD = 1.52$), $U = 156.50, z = -4.49, p < .001, r = .410$. Rather, the interaction was driven by differential effects of age in the two conditions: whereas for the Asynchronous condition, children’s responses ($Mdn = 2, SD = 1.58$) were higher than adults’ ($Mdn = 0.5, SD$
226 = 1.02), \( U = 170.00, z = -4.32, p < .001 \), there were no age-related differences for the
227 Synchronous mode, \( U = 384.50, z = -0.33, p = .74, r = .031 \).
228
229 For Question 2 (ownership), we found a significant effect of Synchrony, \( F(1,115) = 229.44, p < .001, \eta^2_p = 0.193 \), with higher values for the synchronous (\( Mdn_{raw} = 3.0 \), “In
230 between”) than for the asynchronous condition (\( Mdn_{raw} = 1.0 \), “No”), and a significant effect
231 of Age, \( F(1,115) = 6.52, p = .012, \eta^2_p = 0.054 \) with children (\( Mdn_{raw} = 2.0 \), “No, not really”) rating higher than adults (\( Mdn_{raw} = 1.0 \), “No”). There was no significant effect of Posture,
233 \( F(1,115) = 2.21, p = .140, \eta^2_p = 0.019 \), and no other effects were significant, \( Fs < 0.6, ps > .4, \eta^2_ps \leq .015 \).

---

**Figure 3** – Group medians (black lines) and interquartile ranges. Whiskers represent maximal \( 1.5 \times \) IQR. Dots represent individual scores. Shown for (A, B) Q1 (touch referral) scores, (C, D) Q2 (ownership) scores, for (A, C) 6- to 7-year-olds, and for (B, D) adults. Scale: 0 - “No, definitely not”, 1 - “No”, 2 - “No, not really”, 3 - “In between”, 4 - “Yes, a little”, 5 - “Yes, a lot”, 6 - “Yes, lots and lots”. Note that dots are jittered to improve visibility of each single value (in the rating, only integers were possible).
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 embodiment, 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 as well in line with previous work, 6-to 7-year-olds show overall larger drift towards 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. The self-report measures however indicate no impact of posture on experience of embodiment in both age groups. In line with our hypotheses, and our first results scenario, at both ages proprioceptive drift was only higher in the synchronous condition when the fake hand was in a congruent posture (0° condition), but not in the congruent and clearly anatomically impossible posture (90° condition). Thus, in the sense that embodiment is indicated by the processing of multisensory information near the body, children and adults embody a congruent, but not an incongruent hand. 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.
To conclude from the drift measure, children and adults only process body-relevant multisensory information and accept a hand as their own if it 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 is matching – the difference in posture prevent an initial recalibration of hand position (Makin et al., 2008) as well as subsequent integration of visual and tactile information (Tsakiris, 2010). However, and interestingly, self-reported experiences of embodiment are mostly not constrained by postural matches.

**Experiment 2**

Experiment 1 suggests that posture is a strong constraint on embodiment as measured by proprioceptive drift at 6 to 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 (this representational ability has sometimes been referred to as the “postural schema”, “(first-order) body schema” or short-term representation (cf. de Vignemont, 2006; Gallagher, 2000), or merely that it was anatomically impossible (Makin et al., 2008; Rohde et al., 2011), which relates to long-term body representation (this representational ability has sometimes been called the “higher-order body schema”; cf. de Vignemont, 2006; Gallagher, 2000). Further, 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 et al., 2010; Nardini et al., 2013; von Hofsten & Rööblad, 1988) and the rapid physical changes in childhood (cf. Thelen, 1992; Thelen & Smith, 1994). In Experiment 2 we therefore aimed to disentangle the effect of incongruent and impossible hand posture on embodiment, and to measure the resolution of children’s postural matching. Therefore, we presented children with an intermediate condition, where the fake hand was rotated 20° anticlockwise into an incongruent, but anatomically *possible* posture. We chose 20° based on
children’s errors in postural matching in this age group, as reported by Goble et al. (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): 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). 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: Firstly, we may find that children demonstrate the same pattern of findings as adults, showing no difference in measures of embodiment 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, we may find differences in measures of embodiment between the two stroking conditions with the hand in the 20° incongruent posture, 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 representation, but not in their long-term representation of their body (cf. de Vignemont, 2006; Gallagher, 2000). Because of the strong arguments in favour of both scenarios, we make no predictions in favour of one or the other scenario.

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 thirty adults ($M = 22.5$ years, $SD = 0.4$ years, 24 women and 6 men). The sample size was chosen as in Experiment 1. A priori power calculations using
G*Power 3.1 (Faul et al., 2017) suggested a total sample size of $N = 60$ given the same parameters as for Experiment 1, but for four groups. The data of one child were excluded due to an extreme drift score (synchronous, $20^\circ$ 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 $20^\circ$ 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 $20^\circ$ 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 (Fig. 2) and on the aligned transformed questionnaire data (Fig. 3) as we have reported in Experiment 1.

**Proprioceptive drift.** There were no effects of Synchrony or Age, and no interaction between these factors, $F < 1.3$, $p > .20$, $\eta^2_p < .03$, indicating no drift differences between stroking conditions and or age groups.
Questionnaire. For Question 1 (touch referral), there was a significant main effect of Synchrony, $F(1,57) = 7.687$, $p = .008$, $\eta^2_p = 0.119$, with higher values for the synchronous ($Mdn_{raw} = 4.0$, “Yes, a little”) than for the asynchronous condition ($Mdn_{raw} = 2.0$, “No, not really”). There was a significant effect of Age, $F(1,57) = 4.238$, $p = .044$, $\eta^2_p = 0.069$, with children ($Mdn_{raw} = 4.0$, “Yes, a little”) rating higher than adults ($Mdn_{raw} = 2.0$, “No, not really”). The interaction of Age and Synchrony was not significant, $F(1,57) = 0.007$, $p = .935$, $\eta^2_p < .001$.

For Question 2 (ownership), there was a significant main effect of Synchrony, with higher values for the synchronous ($Mdn_{raw} = 3.0$, “In between”) than for the asynchronous condition ($Mdn_{raw} = 1.0$, “No”), $F(1,57) = 11.910$, $p = .001$, $\eta^2_p = 0.173$. The main effect of Age and the interaction effect were not significant, $Fs \leq 1.4$, $ps \geq .20$, $\eta^2_p < .03$.

Visual judgment task. We totalled 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 from their own hand’s posture. Based on signal detection theory, we calculated $d'$ (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 or Age, and no interaction between these factors, $Fs < 2.8$, $ps > .10$, $\eta^2_p < .05$, revealing that the visual posture judgments were not affected by the stroking mode in the previous RHI task and did not differ between children and adults.
Discussion

We found no evidence for more flexibility in children’s body representations. The proprioceptive drift results suggest that children and adults do not embody a fake hand in a slightly different posture than their own hand, as there was no difference in drift between the synchronous and the asynchronous visual-tactile conditions for the 20° posture. The questionnaire results also present a similar picture across children and adults. However, both groups subjectively experience 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. Both results are in line our first result scenario in which children have similar postural constraints to adults. However, drift and questionnaire data suggest different uses of postural information for both children and adults. Posture constrains embodiment as measured by proprioceptive drift, but not subjective experiences of embodiment.

General discussion

Results of proprioceptive drift and subjective rating suggest that bottom-up multisensory information from vision, touch and proprioception drives embodiment for both children and adults, which 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). Furthermore, for both children and adults, top-down knowledge of posture influences embodiment as measured by proprioceptive drift, but not for subjective experiences of embodiment (ownership and touch) as measured by questionnaire.
Thus, the answer to our main question, whether and how posture constrains embodiment in childhood, is that children show similar postural constraints as adults. In line with our second alternative result scenario, we did not find indications for more flexible (i.e., less posturally specific) body representations in 6- to 7-year-olds. Crucially, this study is the first one to demonstrate that children use posture as a cue for embodiment in a similar fashion as adults do: Both age groups show larger proprioceptive drift in the synchronous than in the asynchronous stroking condition for the congruent hand posture only (0° condition), but not for incongruent hand postures (20°, 90° conditions). Furthermore, we demonstrate that these effects of posture are finely-tuned: Children embody neither a fake hand in an incongruent-impossible (90°) nor in an incongruent-possible posture (20°). Hence, not only long-term knowledge of anatomically impossible hand postures (cf. de Vignemont, 2006; Makin et al., 2008; Rohde et al., 2011), but also short-term knowledge of the current hand posture constrains embodiment in childhood, as previously demonstrated in adulthood (Costantini & Haggard, 2007; Tsakiris & Haggard, 2005).

At the same time and in line with previous investigations (Cowie et al., 2013, 2016), we find that 6- to 7-year-old children show overall substantially larger drift in both conditions and rate experiences of touch and ownership substantially higher than adults. This age difference might be explained by the generally poorer resolution of proprioception at 6 to 7 years of age (Goble et al., 2005; King et al., 2010; von Hofsten & Rösbldad, 1988), which could lead to less precise pointing to the resting hand (cf. von Hofsten & Rösbldad, 1988). However, we controlled for potential pointing biases by baseline correction of our drift measure. Rather, the hand is localised 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 towards the visual position (at the fake hand) than in adults (cf. Cowie et al., 2013), so that there is a tendency to localise a hand where you see it rather than where you feel it to be.
Why do our drift and self-report results differ with regard to the effect of fake hand posture? To recapitulate our results, 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 embodiment (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 subjective awareness, reflect processes in different neural areas, and furthermore afford different behavioural qualities of reply (pointing vs. speaking). In the current study, proprioceptive signals from the stationary own hand weaken over time (Rohde et al., 2011). Proprioceptive signals for hand position but also for hand posture are stronger during rubber hand induction and drift measurement than during the subsequent questionnaire assessment. Hence, posture might be more intimately linked to embodiment as assessed by drift than when assessed by questionnaire measures. Both measures combined can provide a more holistic picture of own-body representation in development than one measure alone.

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 embodiment is processed by peri-hand 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 (Rohde et al., 2011), they less strongly inform about the own hand’s posture the more time has
Multisensory information from vision and touch therefore might pass in the congruent and incongruent hand conditions leading to subjective experience of embodiment. However, there is a caveat to the interpretation of subjective experiences of embodiment regardless of posture. Spelled-out median responses were rather weak for both the synchronous condition (Q1: “Yes, a little”, Q2: “In between”) and especially the asynchronous condition (Q1: “No, not really”, Q2: “No”). These median responses might not reflect strong feelings of touch on the fake hand or ownership over it.

A further interesting aspect of our data is the inter-individual variability. 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 a medium 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 synced and instead predominantly use visual information for embodiment (as indicated by high drift towards 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 medium condition (20°), especially combined with the synchronous stroking, raises the question 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 embodiment, whereas others require a precise postural match. The more clear-cut 0° and 90° conditions in comparison evoke less variability in drift. Future research should address individual differences in embodiment and clarify the mechanisms underlying them.
In conclusion, children of 6 to 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 with concurrent synchronous touch does not elicit embodiment 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.

[Word count: 6318]
References


https://doi.org/10.1016/j.cognition.2007.12.004


[47 references]