Journal of Experimental Child Psychology 223 (2022) 105477

Contents lists available at ScienceDirect

Journal of Experimental Child Psychology

journal homepage: www.elsevier.com/locate/jecp

Exploring the development of high-level contributions to body representation using the rubber hand illusion and the monkey hand illusion

Catherine Preston[a,*], Elizabeth Kirk[b]

[a] Department of Psychology, University of York, Heslington, York YO10 5DD, UK
[b] School of Psychology and Sport Science, Anglia Ruskin University, Cambridge CB1 1PT, UK

A R T I C L E I N F O

Article history:
Received 22 October 2021
Revised 19 May 2022

Keywords:
Rubber hand illusion
Fantasy proneness
Development
Body ownership
Multisensory integration
Embodiment

A B S T R A C T

During development our body undergoes significant changes, yet we are able to maintain a coherent experience of our body and sense of self. Bodily experience is thought to comprise integration of multisensory signals (vision, touch, and proprioception) constrained by top-down knowledge of body appearance. Evidence from developmental studies suggests that low-level multisensory integration develops throughout childhood, reaching adult levels by 10 years of age. However, how high-level cognitive knowledge changes during childhood to constrain our multisensory body experience is unknown. This study describes four experiments examining high-level contributions to the bodily experience in children compared with adults using the rubber hand illusion and a monkey hand illusion. We found that children (5–17 years of age) exhibited more flexible body representations, showing stronger illusions for small and fantastical (monkey) fake hands compared with adults. Conversely, using a task indirectly capturing changes in hand size, we found that children and adults demonstrated statistically equivalent increases and decreases in hand size following illusions over large and small hands, respectively. Interestingly, at baseline children showed a bias in reporting larger hand size judgments that decreased with age. Finally, we did not find a relationship between individual differences in fantasy proneness and illusion strength for a fantastical (monkey) hand for children or adults, suggesting that developmental changes of top-down constraints are not purely driven by more diffuse

* Corresponding author.
E-mail address: catherine.preston@york.ac.uk (C. Preston).

https://doi.org/10.1016/j.jecp.2022.105477

boundaries between imagination and reality. These data suggest that high-level constraints acting on our multisensory body experience change during development, allowing children a more flexible bodily experience compared with adults.

Introduction

As humans, our body affords us the capacity to explore and engage with our environment, but also it is firmly integrated in our sense of self (Tsakiris, 2017). Throughout a normal lifespan, our body changes dramatically, and yet despite these changes healthy individuals maintain a stable sense of self and their own body. The experience of body ownership has been studied extensively in adults using body illusions such as the rubber hand illusion (RHI), which uses multisensory integration to produce an illusion that a fake body part (hand) is actually part of one's own body (Botvinick & Cohen, 1998). Touching the real and fake hands asynchronously inhibits the illusion. Critical to the strength of body illusions, and thus to the fundamental experience of body ownership, is the integration of visual, tactile, and proprioceptive sensory inputs. In the RHI, synchronously touching a viewed fake (rubber) hand and the hidden real hand means that what is seen (a hand being touched) matches what is felt (*your* hand being touched) and consequently produces a recalibration of the felt position of the hand (proprioception) and the experience that the fake hand is the real hand (Botvinick & Cohen, 1998). This proprioceptive recalibration can be captured using methods such as proprioceptive drift, which measures the shift in perceived hand location toward the fake hand following the illusion (Tsakiris & Haggard, 2005).

In terms of development, integration of some multisensory information in relation to the body appears to be present from birth. Newborn babies are found to attend more to a baby's face that is stroked synchronously with touches applied to their own face compared with asynchronous touch (Filippetti, Johnson, Lloyd-Fox, Dragovic, & Farroni, 2013). However, visual–proprioceptive integration seems to develop more slowly throughout childhood (Cowie, Makin, & Bremner, 2013). Optimal weighting of visual and haptic information is thought to not reach maturity until 8–10 years of age, after which children perform like adults (statistically optimal) (Gori, Del Viva, Sandini, & Burr, 2008). This maturation of sensory weighting coincides with observations of children experiencing the RHI. Young children are found to recalibrate proprioception more readily than adults irrespective of synchrony of touch. In other words, they demonstrate proprioceptive drift in both synchronous and asynchronous conditions. After 10 years of age, children are found to perform like adults, demonstrating greater proprioceptive drift in synchronous conditions compared with asynchronous conditions (Cowie, Sterling, & Bremner, 2016). However, children's bodies are still changing considerably through puberty along with substantial changes in synaptic density (Chechik, Meilijson, & Ruppin, 1998). Therefore, it is feasible that some aspects of neural body representations may also be still developing.

Current models of body ownership do not rely solely on bottom-up multisensory integration but also incorporate top-down body knowledge (body structural description) (Tsakiris, 2010). This high-level representation of what a body, and specifically what one's own body, looks like is thought to play an important role either as one aspect of information with which probabilities of the object/body part belonging to the self are weighted (Kilteni, Maselli, Kording, & Slater, 2015) or as an initial gateway comparison, violations of which prevent the experience of body ownership (Tsakiris, 2010). With adults, contradictions to high-level representations of the body in terms of anatomical posture or location (Lloyd, 2007; Preston, 2013; Tsakiris & Haggard, 2005), size (Pavani & Zampini, 2007), and appearance (Tsakiris, Carpenter, James, & Fotopoulou, 2010) are found to reduce or abolish the RHI. However, illusory body distortions contradicting our high-level representations are still possible when they incorporate the entire body (van der Hoort, Guterstam, & Ehrsson, 2011), they are physically plausible (Piryankova et al., 2014; Preston & Ehrsson, 2014), and/or the distortion is part of the illusion (e.g., the illusion of a stretching arm opposed to simply taking ownership over a long arm (Byrne & Preston, 2019; Kilteni, Normand, Sanchez-Vives, & Slater, 2012).

However, little is understood about how high-level body representations develop during childhood and how this affects body ownership. Intuitively, children may have more flexible body representations because their body is undergoing more rapid change compared with adults. In addition, their knowledge about the body is also developing. Thus, because a child's body is rapidly changing, any high-level structural description of their body is likely to be less rigid compared with adults who have a more stable body size and shape. It has been suggested that by 30 months of age children possess a rudimentary knowledge of the structural configuration of the human body. This has been demonstrated using tasks relating to a human body in general (discrimination between scrambled and non-scrambled body exemplars) (Heron & Slaughter 2008) and also referring to children's own body (naming own body parts, meaningless gestures, and dressing the self and a doll) (Brownell, Nichols, Svetlova, Zerwas, & Ramani, 2010). Furthermore, using the RHI, it has been found that children aged 6 to 8 years experienced ownership over both a regular and large-sized fake hand (Filippetti & Crucianelli, 2019), suggesting that children are more flexible in terms of perceived changes in body size, although this was not directly tested in comparison with adults.

Traditionally, children are thought to have more flexible boundaries between reality and imagination compared with adults. Therefore, constraints on body representations due to high-level cognitive knowledge may be less pronounced during childhood because children are less grounded in reality. Young children engage more in pretend play and are more likely to report imaginary companions (ICs) compared with adults (Woolley, 1997), with an average age of ceasing pretense reported as 11 years (Smith & Lillard, 2012). Moreover, the act of pretense and engagement in fantasy has been suggested to play an important role for cognitive development, for example, to help with understanding false beliefs (Sobel & Lillard, 2001). Therefore, a greater tendency toward fantasy in young children may also affect other aspects of development, including forming a mental representation of the body, such that a greater role of fantasy may relate to a more liberal high-level image of their own body appearance, thereby allowing children to quickly adapt to developmental changes. However, in many studies adults are also found to engage in fantasy (Woolley, 1997). Many individuals report continuing to engage in pretense (Smith & Lillard, 2012) and retain an IC (Seiffge-Krenke, 1997) well into young adulthood. Thus, it could be that differences between adults' and children's fantasy are less distinct (Subbotsky, 2004) and therefore would have less of an impact on beliefs about, and so experience of, their own body.

The current study aimed to examine high-level constraints on body ownership in children compared with adults using the RHI across a series of four experiments. Specifically, we compared the experience of ownership over a small child-sized hand and a large adult-sized hand in children and adults using subjective reports, judgments of hand size, and illusion onset time. Because our body undergoes more rapid changes during childhood compared with adulthood, we predicted that children would demonstrate greater flexibility of body representations by reporting stronger illusion experiences over fake hands that are incongruent with their own hand size and experiencing the illusion faster than adults. Furthermore, if fantasy is crucial for dictating the flexibility of body representations during development, then children may also be more susceptible to fantastical body changes. Thus, we employed an adaptation to the RHI using a "fantastical" monkey hand, for which children were predicted to experience greater RHI compared with adults. We also examined the experience of ownership in relation to fantasy proneness in children by comparing children who did and did not report having an IC and in adults by examining the relationship between illusion strength and self-reported fantasy proneness. We anticipated that children reporting an IC would experience stronger illusions compared with children without an IC. We also predicted that higher engagement in fantasy in adults would be associated with stronger illusions over fantastical (monkey) hands.

Finally, to fully examine the development of high-level constraints of body ownership, we also wanted to probe potential differences between children and adults on a task that was more closely associated with low-level processes. It has been suggested that subjective reports of body ownership in young children are strongly related to visual–tactile integration but are dissociated from visual–proprioceptive integration, which develops later (Cowie et al., 2013). Such studies investigating separate developmental pathways have compared proprioceptive drift and subjective reports. Here, however, we wanted to use a task suitable for young children that was also directly associated with changes in hand size. Therefore, this study aimed to devise the Holes Task to capture changes in hand size following the illusion of different sized fake hands, in which participants were asked to make judgments as to what size holes they could fit their hand through. Due to this task being more strongly related to low-level processes such as reaching, as opposed to explicitly asking participants whether their hand felt larger or smaller, it may be less affected by high-level constraints in both children and adults.

For Experiments 1, 2, and 4, participants were recruited from public venues, events, and summer activity clubs in the North East of the United Kingdom. Written parental consent was obtained for children, followed by verbal consent from the children. Written consent for adults (18 + years of age) was gained directly. For Experiment 3, participants were recruited via their primary school and parental consent was sought by sending information home to their parents. Individual verbal consent from the children was also obtained. Ethical approval was obtained from the university department ethics committee.

Experiment 1

Method

Participants

Participants were 100 children (50 male and 50 female; M_{age} = 9 years [111 months], *SD* = 2.8 years [32.3 months], range = 5–16 years [63–200 months]) and 99 adults (29 male and 70 female; M_{age} = 35 years, *SD* = 16.1, range = 19–72).

Materials

Rubber hand illusion. Participants sat at a table resting their right hand on the tabletop in front of them underneath a wooden platform (35 × 30 × 13 cm). On top of the platform was a wooden artist's right hand, resting with the palm faced down, wearing a blue latex-free nitrile rubber glove (Fig. 1). The large fake hand measured 30 cm from the base of the wrist to the tip of the middle finger (22 cm of hand and 8 cm of wrist). The small fake hand measured 12 cm in length (9 cm of hand and 3 cm of wrist). Participants wore an identical latex-free glove on their own right hand and placed their left hand by their side. Participants wore a black cape around their neck, which occluded their right forearm and the open wrist of the fake hand, such that the fake hand appeared in an anatomically congruent position relative to the body. Touches were delivered using a soft makeup brush.

Holes Task. This task was adapted from a previous study (Ishak, Franchak, & Adolph, 2014), consisting of two 55 × 35-cm Perspex test boards. Each test board contained 11 nonadjustable circular holes that varied in size (50–100 mm in diameter, increasing in 5-mm increments) in a random configuration (Fig. 1). Hole sizes were based on pilot data from hand size measurements (metacarpophalangeal joint of the index finger to the equivalent joint of the little/pinky finger) of children aged 22 months to 13 years (*n* = 7). Hole sizes were selected to ensure that children and adults were presented with holes that were smaller and larger than they could physically fit their hand through.

Procedure

Participants were asked to keep their hidden right hand still underneath the platform and to watch the fake hand in front of them. The experimenter brushed the real hand, and the corresponding location of the fake hand, either at exactly the same time (synchronously) or with the fake hand brushed after a delay of ~500 ms (asynchronously). Each trial lasted for 1 min, timed by a second experimenter using a stopwatch. For each hand size, there were four trials: two trials (one synchronous and one asynchronous) after which participants completed the Holes Task and two trials after which they gave responses concerning the subjective experience of the illusion (see Table 1 and online supplementary material). A baseline measure of the Holes Task was always completed first to measure participants' hand size judgments before experiencing the illusion. Participants then completed the RHI with both

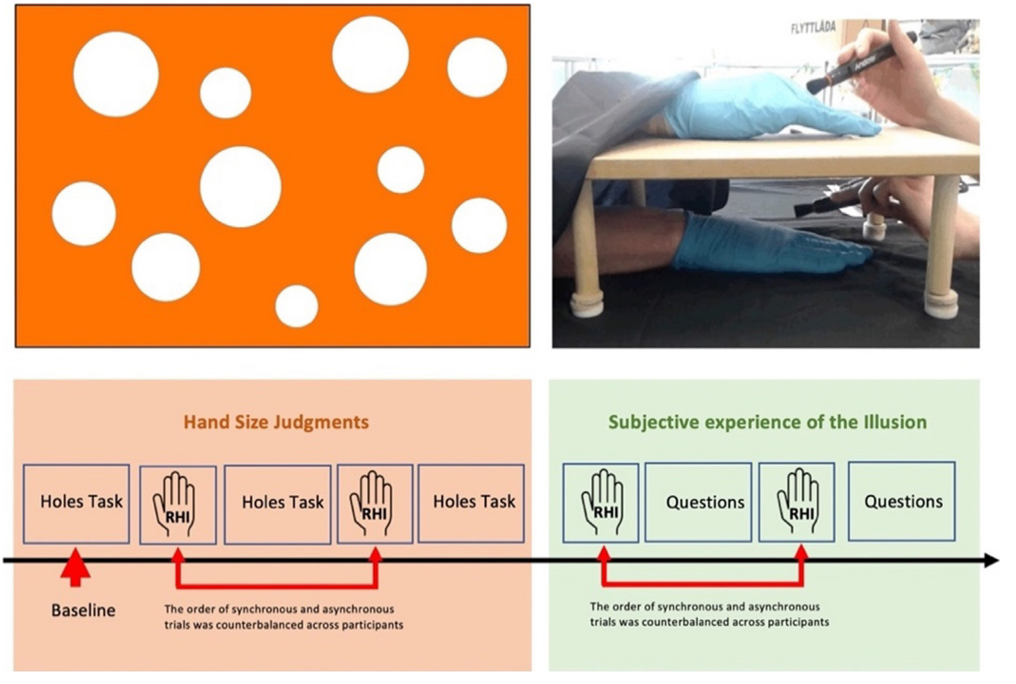

Fig. 1. Experimental setup and procedure. (Top left) Diagram of one of the boards used for the Holes Task. (Top right) The rubber hand illusion setup. (Bottom) Schematic of trials for Experiment 1.

Table 1
Questions used to capture the experience of the illusion in each experiment.

Question	Purpose	Experiment(s)
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?	Referral of touch (illusion)	1
When I was stroking with the brush, did you sometimes feel like the fake hand was your hand or belonged to you?	Ownership (illusion)	1,2,3,4
When I was stroking with the brush, did you sometimes feel like your real hand had disappeared?	Loss of own hand (control)	3,4

Note. This table includes the questions used for each of the experiments (Experiments 1–4).

the small and large hands (the order of synchronous and asynchronous trials and large and small hands was counterbalanced), and then they completed the holes task again to ascertain whether experiencing the illusion with the small/large hand influenced their hand size judgments (Fig. 1). At the end of the experiment, measurements of participants' actual hand size from the metacarpophalangeal joint of the index finger to the equivalent joint of the little finger (pinky) were taken. These measurements were compared with the equivalent measurements on the large (75 mm) and small (45 mm) hands as well as the smallest hole selected.

Holes Task. Participants were presented with a test board at a distance such that they could not touch it. The experimenter pointed to each hole in turn and asked participants whether they thought that they could fit their right hand through the hole, and they provided a verbal forced-choice yes or no response. They were instructed not to physically try to fit their hand through but rather to imagine whether their hand could reach through the hole. They were given no instruction as to the posture of their hand when fitting through the hole, unlike previous similar tasks that required grasping and retrieving an object (Ishak et al., 2014). To prevent participants from remembering their previous responses, the orientation of the test boards, and thus the order and configuration of the holes, was changed between pre- and post-tasks (turned upside down) and different boards were used for synchronous and asynchronous trials.

Analysis

Preliminary analyses were conducted to test whether the fake hands used in the RHI were congruous or incongruous with the adults' and children's own hand sizes (see supplementary material). Because both small and large hand sizes were incongruent for children, we analyzed the data with small and large levels of hand size rather than congruent and incongruent.

Ordinal data (Illusion questions) were analyzed using nonparametric statistics (Mann–Whitney U for between comparisons, Wilcoxon signed ranks for within comparisons, and Spearman's rho for correlations). Bayes factors (BFs) for parametric and nonparametric data (van Doorn, Ly, Marsman, & Wagenmakers, 2020) were calculated where possible to supplement frequentist analysis. BFs present likelihood ratios of the alternative hypothesis relative to the null hypothesis (Dienes, 2014). A BF > 3 indicates evidence for the alternative hypothesis. A BF < 0.33 indicates evidence for the null hypothesis. A BF between 0.33 and 3 is inconclusive (Dienes, 2014); however, a BF between 1 and 3 provides anecdotal evidence for the alternative hypothesis, and a BF between 0.33 and 1 provides anecdotal evidence for the null hypothesis (Assaf & Tsionas, 2018). Analyses were conducted using IBM SPSS Statistics for MacOS Version 26.0 (IBM Corp., Armonk, NY, USA) and JASP Team (2020) Version 0.13.

Results

An illusion score was created by taking the mean of the two illusion questions. Bonferroni correction was used (critical p =.006). First, we wanted to determine whether both of our samples experienced the illusion in line with synchrony of vision and touch; therefore, we examined illusion scores for synchronous versus asynchronous touch for each hand size with children and adults independently using Wilcoxon signed ranks tests. For both children and adults, synchronous touch elicited significantly greater illusion ratings compared with asynchronous touch for the small hand (adults: z = 7.81, p <.001, r =.79, BF = 3.83e+18, synchronous *Mdn* = 4, asynchronous *Mdn* = 1.5; children: z = 8.09, p <.001, r =.81, BF = 3.47e+18, synchronous *Mdn* = 5, asynchronous *Mdn* = 2.5) and the large hand (adults: z = 7.98, p <.001, r =.81, BF = 2.05e+21, synchronous *Mdn* = 5, asynchronous *Mdn* = 1.5; children: z = 7.96, p <.001, r =.81, BF = 1.91e+19, synchronous *Mdn* = 5, asynchronous *Mdn* = 2.5). Thus, as expected, synchronous touch was most effective in creating the illusion.

Next, we wanted to see whether the size of the hand affected illusion strength for either group. With this aim, we examined differences in illusion scores between the large and small hand sizes for synchronous touch (illusion) conditions with children and adults using Wilcoxon signed ranks tests. For adults, illusion scores were significantly lower for the small hand (*Mdn* = 4) compared with the large hand (*Mdn* = 5) (z = 4.71, p <.001, r =.48, BF = 4652). For children, there was no significant difference between the hand sizes (z = 0.562, p =.574, r =.06, BF = 0.11). This finding supports the idea that children's body representations are more flexible than those of adults.

Next, we explored potential differences of illusion strength between children and adults by examining differences in illusion strength during the synchronous conditions between the groups for each hand size using Mann–Whitney U tests. There was no significant difference for the illusion over the large hand (z = 0.764, p =.445, r =.05, BF = 0.22). With the small hand, children reported significantly stronger illusions (*Mdn* = 5) compared with adults (*Mdn* = 4) (z = 4.32, p <.001, r =.31, BF = 160.6) (Fig. 2), indicating greater illusion susceptibility in children.

To examine whether the relationship between the illusion and children's age was driven by the relative similarity in size between children's real hand and the fake hand, a series of partial correlations was conducted.

The width of the fake small hand was subtracted from the equivalent measurement of the real hand (metacarpophalangeal joint of the index finger to the metacarpophalangeal joint of the little finger) to create a difference score. Age and difference score met assumptions for parametric analysis.

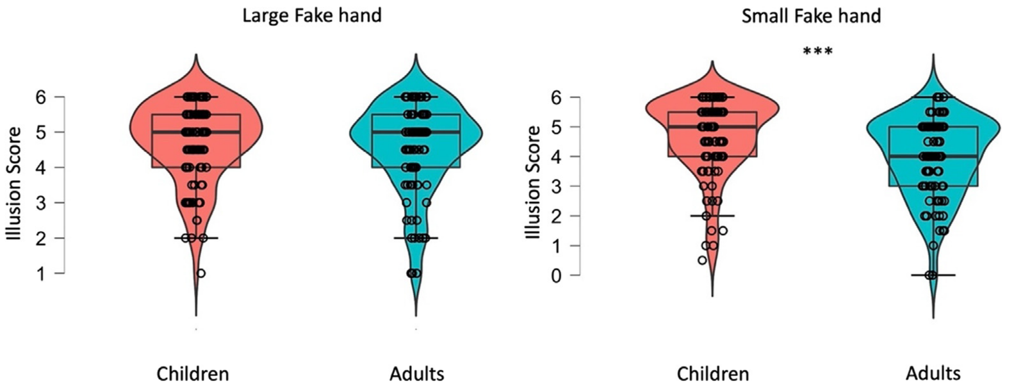

Fig. 2. Illusion scores from Experiment 1. (Left) Children and adults demonstrated statistically equivalent illusion scores for the large hand. (Right) Children reported stronger illusions compared with adults for the small hand. ***p <.001.

Ownership scores, however, were non-normally distributed and ordinal; therefore, relationships including this variable were analyzed using Spearman's rho.

The relationship between the difference score and illusion score for children was not significant [$r_s(96)$ =.048, p =.641] and remained nonsignificant when controlling for age in months [$r_s(94) = -.129$, p =.229]. The equivalent relationship in adults was also not significant [$r_s(95)$ =.18, p =.083].

The relationship between children's age in months and illusion scores was significant [$r_s(96) = -.209$, p =.041], such that as age increased illusion strength for the small hand decreased. This remained significant when controlling for difference score [$r_s(94) = -.227$, p =.029]. The equivalent correlation was not significant for the large hand [$r_s(97) = -.061$, p =.554]. These results suggest that illusion strength is related to children's age and not the relative difference in size between the real and fake hands.

Holes Task

First, we examined potential differences between hole size selected at baseline by calculating the difference between the smallest hole size selected and the actual hand width as a percentage of the actual hand width and then comparing children and adults with a paired-samples t test. This revealed a significant difference, $t(187) = 5.43$, p <.001, d =.79, BF = 70749, with children selecting a mean smallest hole size that was 16.8% (SD = 21) larger than the actual hand and adults selecting a mean smallest hole size that was 0.67% (SD = 23) smaller than the actual hand. We followed this up with Pearson's correlations to investigate further relationships between age and hole size choice in children and adults. The percentage difference between smallest hole selected and actual hand size correlated with children's age in months, $r(93) = -.54$, p <.001, such that as age increased the smallest hole sizes selected decreased relative to their actual hand size. The equivalent correlation in adults for age in years was also significant, $r(95) = -.24$, p =.019, such that as age increased the smallest hole size selected decreased relative to actual hand size. These results suggest that children have a bias in selecting a larger hole relative to their actual hand and that this may decrease developmentally across a lifespan (although this is only inferred given that this was not a longitudinal study).

We then calculated baseline-corrected scores for each condition by subtracting he smallest hole that participants judged they could fit their hand through at baseline from the same judgments after each condition. These data were then entered into a 2 $\times$ 2 $\times$ 2 mixed analysis of variance (ANOVA) with hand size (large vs. small) and synchrony (synchronous vs. asynchronous) as within factors and sample (children vs. adults) as a between factor. There was a significant main effect of hand size, $F(1, 187) = 13.77$, p <.001, η^2_p =.069, BF = 58.5, such that the large hand produced a mean increase in the smallest hole selected (M = 0.402, SE = 0.668) and the small hand led to a mean decrease in the smallest hole selected ($M = -1.276$, SE = 0.739). There was no main effect of synchrony, $F(1, 187) = 1.034$,

p =.31, η^2_p =.006, BF = 0.136. The main effect of sample approached significance, $F(1, 187) = 3.90$, p =.051, η^2_p =.02, BF = 3.20e-8 (children: $M = -1.76$, $SE = 0.63$; adults: $M = 0.88$, $SE = 1.17$), but the BF supported the null hypothesis. There was a significant Hand Size × Synchrony interaction, $F(1, 187) = 16.56$, p <.001, η^2_p =.081, BF = 211. All other interactions were nonsignificant, max $F(1, 187) = 0.59$, p =.442, η^2_p =.003, BF = 0.21.

To follow up the Hand Size × Synchrony interaction, planned paired-samples t tests were conducted between synchronous touch and asynchronous touch for large and small hand sizes. For the large hand, synchronous touch ($M = 1.39$, $SE = 0.668$) led to a larger hole being selected compared with asynchronous touch ($M = -0.59$, $SE = 0.79$), $t(191) = 3.34$, p =.001, d =.24, BF = 16.9. For the small hand, synchronous touch ($M = -1.858$, $SE = 0.812$) led to a smaller hole being selected compared with asynchronous touch ($M = -0.694$, $SE = 0.755$), $t(192) = -2.245$, p =.026, d =.16, BF = 0.93 (Fig. 3).

Discussion

The results of Experiment 1 support findings from previous studies showing that adults experience reduced illusions over smaller fake hands (Pavani & Zampini, 2007), whereas children demonstrated equivalent illusions for both hand sizes. Furthermore, we found that children have a stronger subjective experience of the illusion over small hands compared with adults and that this experience of ownership was related to children's age and not the relative incongruence in size between real and fake hands. This implies that stronger illusions for the small hand in children are a consequence of development and not just the fake hand being closer in size to children's hand.

Despite adults reporting lower subjective experience of the illusion for the small hand, they demonstrated equivalent responses for our indirect measure, such that after inducing the illusion over a small hand they thought that they could fit their hand through smaller holes and that after the illusion of owning a large hand the size of the smallest hole they selected increased. This may suggest fewer top-down constraints on representations of the body when measured by tasks more closely related to low-level processes. A previous study that found reduced illusions over a smaller hand reported this using an indirect measure of the illusion (proprioceptive drift) rather than subjective reports, the opposite to what we found in Experiment 1 (Pavani & Zampini, 2007). However, this previous study used proprioceptive drift to measure the illusions, which involves integration of proprioceptive and visual inputs. The current experiment, on the other hand, used the Holes Task, which involves integrating low-level information from the body (hand size) with visual information of external stimuli (hole size) to make a subjective judgment of whether participants could fit their hand

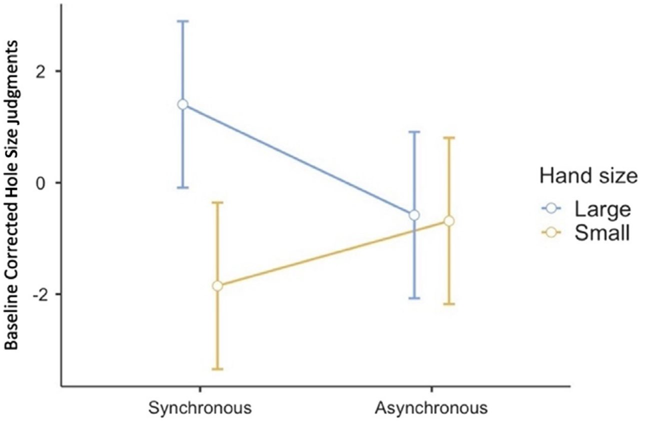

Fig. 3. Hole size judgments. Following synchronous touch over a large hand, participants selected a larger hole as the smallest they could fit their hand through, whereas following synchronous touch over a small fake hand, they selected a smaller size hole. This effect was not moderated by group (child vs. adult).

through each hole. We know that visual–proprioceptive integration (proprioceptive drift) takes a different developmental trajectory compared with visual–tactile information (Cowie et al., 2013). Therefore, tasks that compare the body with external stimuli may also dissociate from and develop differently than what is recorded using proprioceptive drift measures. Indeed, another study that implemented the RHI over different hand sizes in adults and found similar recalibration of the hand for both large and small fake hands also used a task comparing the body with external stimuli (Bruno & Bertamini, 2010). In that study, participants needed to estimate the diameter of a disk relative to a reference disk using only haptics, which was found to be modulated by induction of the RHI over a small hand and a large hand. Body resizing illusions using the whole body have suggested that changing the size of the body in the illusion may actually lead to recalibration of size and distance of the external environment rather than own body dimensions. This is suggested to be because the body is used as a metric for space perception (van der Hoort et al., 2011). Therefore, the reason why we found equivalent illusory effects for adults and children for both hand sizes in the Holes Task could be that the task taps into external recalibration of the world relative to the body and not direct recalibration of body size.

Other studies that found asymmetric updating of changes in hand size reported this using grasping movements (Bernardi et al. 2013; Marino, Stucchi, Nava, Haggard, & Maravita, 2010). Whereas grasping also involves external stimuli, it has been shown that action body representations can dissociate from perceptual body representations during the RHI (Kammers, de Vignemont, Verhagen, & Dijkerman, 2009; Preston & Newport, 2011). Furthermore, these studies did not directly induce the RHI; instead, they visually shrank or enlarged the appearance of the hand during reaching and therefore might not have induced embodiment in the same way as in the current experiment.

In terms of the contradictory findings for subjective reports of the illusion, such that Pavani and Zampini (2007) found no differences in questionnaire scores between hand sizes but the current experiment did, Pavani and Zampini reported low subjective experience of the illusion across all conditions. Lower illusion experience (disagreement with illusion-relevant questions) may have caused a floor effect, such that it prevented identification of differences between the subjective experience of the illusion between conditions. For our experiment, however, even in the small hand condition, adults' average responses still corresponded to affirmation of an illusion (yes, a little), just to a lesser degree than for the large hand.

Interestingly, baseline responses to the Holes Task suggest that children on average select a larger hole relative to their own hand size as the smallest they can fit their hand through, whereas adults on average select a slightly smaller hole. In children, this is likely to reflect developmental changes in body size. Because their body is steadily growing in size, this may bias their responses to select a larger hole size. However, in a previous study (Cardinali, Serino, & Gori, 2019) where children were asked to make explicit judgments of actual hand size, it was found that children underestimate the size of their hand and this underestimation increases throughout childhood, such that older children make smaller hand size judgments relative to their actual hand compared with younger children, potentially due to over-compensation for misrepresentations of the hand in the somatosensory cortex. In our study, we showed overestimation of the size of the hole children judge they can fit their hand through and that this overestimation decreases with age throughout childhood into adulthood. Despite our results showing overestimations rather than underestimations, the results do reflect a similar pattern to the previous study, such that the relative size of the hole selected compared with the actual hand size decreases with age (equivalent to a relative decrease in hand size judgments throughout development). The difference between the underestimations found in Cardinali et al. (2019) and the overestimations with children in the current experiment is likely due to the nature of the task. In the current experiment, participants made estimations as to the size of a hole to fit their hand through, whereas the previous study asked participants to make smaller or larger judgments with direct respect to their actual hand size. For an object (hand) to fit through a hole, the hole needs to be larger than the object. Thus, if participants could not manipulate the posture of their hand, then they should always select a larger hole relative to their hand size to avoid damaging the hand.

The finding relating to baseline judgments of the Holes Task with adults is perhaps initially more surprising because they selected a smaller hole size compared with their actual hand, particularly given that adults are thought to have wider tactile representations of the hand compared with reality

(Longo & Haggard, 2011). One explanation may be age-related degrading in tactile acuity given that our adult sample had a large variation in age, including elderly participants. However, this has been associated with enlarged hand representations in the somatosensory cortex (Kalisch, Ragert, Schwenkreis, Dinse, & Tegenthoff, 2009), which may predict older adults to select larger hole sizes compared with younger participants. Alternatively, because instructions of how to position the hand were not provided, this finding may reflect increased experience with age (one can adjust the hand posture to fit through smaller holes sizes) and/or age-related changes of the hand (e.g., looser skin) that increase actual hand size but might not be adequately updated in the brain. However, because we did not measure whether participants could actually fit their hand through the holes selected, we cannot determine whether accuracy is influenced by aging.

Importantly, these results also validated our Holes Task as an effective measure of perceived change in hand size and as an indirect measure of the illusion for children and adults (although the difference between the hole sizes selected for synchronous touch and asynchronous touch for the small hand size had an inconclusive BF).

Our second experiment aimed to replicate the initial findings of Experiment 1 and to incorporate an additional measure of illusion onset time (Kalckert & Ehrsson, 2017). Previously, adolescents (16–20 years of age) were reported to have faster and stronger illusions compared with adults using a standard RHI paradigm (Ferracci & Brancucci, 2019). The authors suggested that this may be due to younger participants being less constrained by top-down cognitive representations and thus requiring less exposure to synchronous multisensory stimulation to experience changes in ownership. This would predict that children may experience the illusion faster than adults irrespective of fake hand size.

Experiment 2

Method

Participants

Participants were 120 children (46 male and 74 female; M_{age} = 9 years [112 months], *SD* = 2.7 years [31.8 months], range = 5–17 years [63–210 months]) and 108 adults (39 male and 69 female; M_{age} = 38 years, *SD* = 15.2, range = 18–82)].

Materials

The same experimental setup to elicit the RHI was used as described for Experiment 1.

Procedure

The RHI was delivered as described for Experiment 1 for a maximum of 1 min (duration for which most participants experience the illusion) (Kalckert & Ehrsson, 2017). Participants were asked to say "stop" when they felt as if the fake hand was their own hand. A second experimenter recorded the time with a stopwatch. This was conducted once with a small fake hand and once with a large fake hand (described for Experiment 1). After both trials, participants were asked about their feelings of ownership over the fake hand (Table 1), omitting the question on referral of touch. Ownership and referral of touch are associated but distinct components of the RHI (Reader, Trifonova, & Ehrsson, 2021). However, feelings of ownership are thought to be influenced more strongly by high-level cognitions (Marotta, Tinazzi, Cavedini, Zampini, & Fiorio, 2016) and therefore are more appropriate in this instance.

Results

Because the questionnaire data were ordinal and non-normally distributed, all questionnaire data were analyzed using nonparametric tests. To correct for multiple comparisons, we used a Bonferroni correction (critical p =.013). First, we wanted to examine whether hand size influenced ownership scores for both groups, so we conducted Wilcoxon signed ranks tests between feelings of ownership for the large and small fake hand sizes with both children and adults. For both groups, there was no significant effect of fake hand size on ownership (adults: $z = -1.34$, $p = .179$, $r = .13$, BF = 0.41, large hand *Mdn* = 5, interquartile range [IQR] = 4–5, small hand *Mdn* = 4, IQR = 4–5; children: $z = -0.801$, $p = .423$, $r = .07$, BF = 0.12, large hand *Mdn* = 5, IQR = 4–5, small hand *Mdn* = 5, IQR = 4–6).

Next, to determine whether age was a factor in illusion strength, we examined differences in feelings of ownership between children and adults for each hand size using Mann–Whitney *U* tests. With the small hand, children reported significantly stronger ownership (*Mdn* = 5, IQR = 4–6) compared with adults (*Mdn* = 4, IQR = 4–5) ($z = -3.80$, $p < .001$, $r = .25$, BF = 98.3). For the large hand, the difference between children (*Mdn* = 5, IQR = 4–5) and adults (*Mdn* = 5, IQR = 3–5) did not survive Bonferroni correction, although an effect was indicated by the BF ($z = -1.95$, $p = .051$, $r = .13$, BF = 5.15; children's *Mdn* = 5, IQR = 4–5; adults' *Mdn* = 5, IQR = 3–5) (Fig. 4). See Table S1 in supplementary material for mean hand size differences of children and adults from Experiments 1 and 2.

Next, partial correlations were conducted to examine the relationship between children's age and the illusion. The relationship between the hand size difference score (see above) and ownership for children was significant, $r(120) = .210$, $p = .021$. This relationship was no longer significant when controlling for age, $r(94) = -.129$, $p = .229$. The equivalent relationship in adults was not significant, $r(97) = -.046$, $p = .654$.

The relationship between children's age in months and ownership was significant for the small hand [$r_s(119) = -.306$, $p < .001$], such that as age increased ownership decreased. This remained significant when controlling for difference score [$r_s(116) = .242$, $p = .008$]. The equivalent correlation was not significant for the large hand [$r_s(119) = -.119$, $p = .198$].

These results replicate findings from Experiment 1, suggesting that ownership over a small hand is related to children's age and not their real hand size.

Next, the time in milliseconds recorded to experience an illusion with each hand size for children and adults was entered into a 2 × 2 mixed ANOVA with hand size (large vs. small) as a within factor and sample (children vs. adults) as a between factor.

There was no significant main effect of hand size, $F(1, 217) = 0.096$, $p = .757$, $\eta_p^2 < .001$, BF = 0.08. There was a significant main effect of sample, $F(1, 217) = 21.10$, $p < .001$, $\eta_p^2 = .09$, BF = 2234, with children having a shorter onset time (M = 15.8 s, SE = 1.18) compared with adults (M = 26.0 s, SE = 1.93) (Fig. 5). The Hand Size × Sample interaction was not significant, $F(1, 217) = 1.76$, $p = .187$, $\eta_p^2 = .008$, BF = 0.34.

Participants not reporting an illusion within 60 s for the small hand were 22 adults and 5 children and for the large hand were 22 adults and 4 children (17 adults and 2 children reported no illusion for either hand).

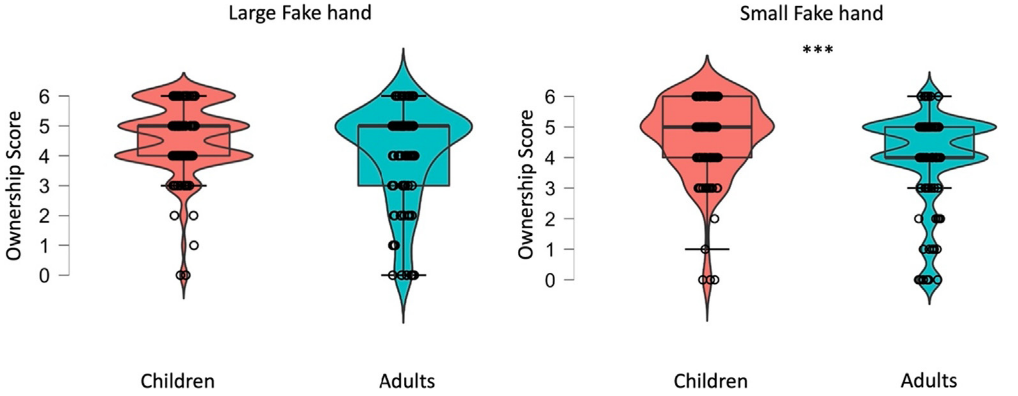

Fig. 4. Ownership scores from Experiment 2. (Left) Children and adults demonstrated statistically equivalent ownership scores for the large hand. (Right) For the small fake hand, children reported stronger feelings of ownership compared with adults. ***$p < .001$.

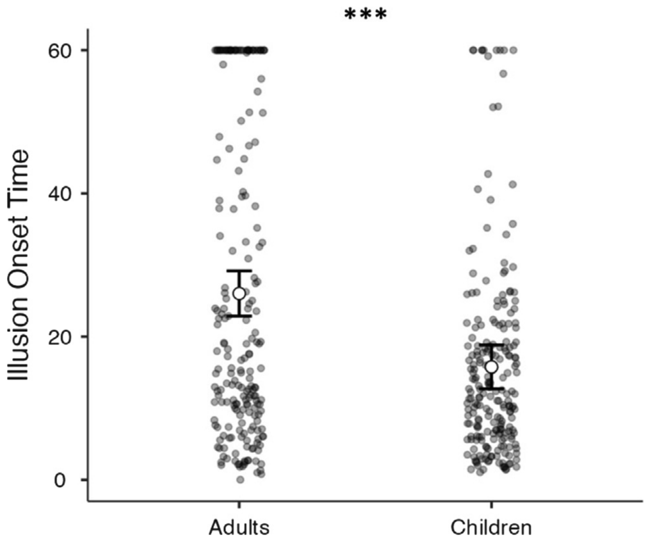

Fig. 5. Illusion onset times. When verbally reporting when they began to feel ownership over the fake hand, children reported faster illusion onset times compared with adults irrespective of hand size. ***p <.001.

Participants reporting an illusion in less than 10 s for the small hand were 30 adults and 48 children and for the large hand were 29 adults and 45 children (22 adults and 29 children reported an illusion in <10 s for both hands).

Discussion

The results from Experiment 2 largely replicate those from Experiment 1, suggesting that children have a stronger experience of the illusion (ownership) over small hands compared with adults. Furthermore, reductions in ownership felt for the small hand are related to children's age and not the size difference between the actual and fake hands. In addition, onset times show that children experience the illusion faster compared with adults irrespective of hand size. This finding supports previous findings that speed of illusion onset is related to age (Ferracci & Brancucci, 2019), extending this to demonstrate the effect with young children. However, because there was no difference between onset times for small and large hands, we cannot determine whether these mechanisms are a result of differences in high-level constraints. Although our mean onset times in adults are similar to those reported previously (Kalckert & Ehrsson, 2017), other studies reported faster onset times (Ehrsson, Spence, & Passingham, 2004; Lloyd 2007) and others reported longer onset times (Ferracci & Brancucci, 2019). Directly comparing illusion onset times between studies may be difficult due to methodological differences. The quicker subjective reports of feelings of ownership for both hand sizes in children may represent a general enhanced flexibility of body representations compared with adults linked to development.

Despite clear replications in our findings, study limitations mean that our results and interpretations from Experiments 1 and 2 must be viewed with caution. Therefore, our third experiment was designed to control for some potential confounds. Although our results so far are consistent with developmental differences in high-level constraints of body ownership, the incongruent (small) hand sizes may still be perceived as physically more similar to the hands of children. Thus, we implemented the RHI in a fantastical (nonhuman) fake monkey hand. If children have stronger illusions due to less clear boundaries between fantasy and reality, then their experiences should be more equivalent for monkey and humanlike hands. Adults, however, do not engage in pretense to the same degree as chil-

Fig. 6. Monkey hand illusion setup. (Left) Vertical rubber hand illusion setup with monkey hand that was used for Experiment 3. (Right) Lateral rubber hand illusion setup with monkey hand (as viewed from above) that was used for Experiment 4.

dren and so were predicted to show reduced illusions for a fantastical monkey hand compared with children.

It is possible that, instead of capturing differences in high-level constraints on body ownership, the differences we observed may reflect a greater readiness to comply in children. Young children are thought to be more susceptible to social demand characteristics (Bjorklund et al., 2000), such that rather than experiencing a stronger illusion during the RHI they may just be complying with the researchers. Therefore, in Experiment 3 a control question was introduced, predicted to elicit reduced agreement compared with ownership. Here, we selected a control question (Table 1) asking about feelings of disownership (Longo et al., 2008), predicted to induce lower levels of agreement compared with illusion questions but not as distant from the illusion experience as other traditional control questions (e.g., “It felt like my real hand was turning rubbery”).

To target potential compliance, we selected a specific age range (6–7 years). By 6 years, children are thought to have developed sophisticated strategies of reputation management to appear favorable to others (Jakubowska, Filip, & Białecka-Pikul, 2021) and are still strongly susceptible to suggestibility when responding to questioning from adults (Bjorklund et al., 2000). Therefore, if differences between adults and children are driven by compliance, social demand characteristics, or wanting to please the experimenter, this age group should be optimal for capturing it. In addition, neurological cases of disturbances in limb ownership are predominantly found over the left side of the body (Vallar & Ronchi, 2009). Experiments 1 and 2 induced the illusion only on the right hand. Although hand laterality is not thought to affect the subjective strength of the illusion (Ocklenburg, Rüther, Peterburs, Pinnow, & Güntürkün, 2011; Smit, Kooistra, van der Ham, & Dijkerman, 2017), it has been found to influence other outcome measures (Dempsey-Jones & Kritikos, 2019; Ocklenburg et al., 2011) and has not been examined in children. Therefore, we also varied the hand to which the illusion was delivered, anticipating equivalent feelings of ownership for both hands.

Experiment 3

Method

Participants

Participants were 58 children (53 6-year-olds and 5 7-year-olds; 23 female and 35 male) who were recruited via their school and tested individually in their classroom.

Materials

The same experimental setup to elicit the RHI was used as described for Experiment 1 except that instead of a small fake hand, a large fake monkey hand (Fig. 6) was used in addition to the large humanlike hand. Half the participants had their right hand stimulated, and the other half had their left hand stimulated (along with the corresponding laterality of the fake hand).

Procedure

The RHI was delivered as described for Experiment 1 for 1 min. This was completed four times in total: twice with the fake monkey hand (once synchronous and once asynchronous) and twice with the fake human hand (once synchronous and once asynchronous). The order of the fake hand type, hand laterality and synchrony of touch was counterbalanced across participants. The two trials (synchronous and asynchronous) of the same hand type were always completed together. Only for human hand trials were participants asked to wear a matching rubber glove. After each trial, participants were asked questions about their experience of the illusion and a control question (Table 1).

Results

To examine whether children were truly experiencing the illusion, we compared ownership and the control responses irrespective of fake hand type using a Wilcoxon signed ranks test. For all questionnaire comparisons, we used Bonferroni correction (critical p =.017). If children were complying, then we would expect similar levels of agreement for both questions. Conversely, if children were truly experiencing the illusion, we would expect higher agreement for the ownership question. Significantly stronger agreement was found for the ownership question (*Mdn* = 5, IQR = 4.38–6.00) compared with the control question (*Mdn* = 4, IQR = 3.00–5.63) (z = 4.10, p <.001, r =.55, BF = 926) (Fig. 7).

To verify whether there was an effect of which hand was stimulated, we conducted a Mann–Whitney U test between those who had the RHI delivered to their right hand and those who had it delivered to their left hand. No significant difference was found (z = −0.734, p =.461, r =.098, BF = 0.38) between those who had their right hand stimulated (*Mdn* = 5, IQR = 4.5–6.0) and those who had their left hand stimulated (*Mdn* = 4.75, IQR = 4–6).

Finally, we wanted to see whether there was a difference in ownership experienced depending on the type of fake hand used. A Wilcoxon signed ranks test revealed no significant difference between strength of ownership for the monkey hand and that for the human hand (z = −0.725, p =.469, r =.07, BF = 0.27). Thus, the monkey hand was successful in eliciting an illusion of ownership to a statistically equivalent degree as the human hand in 6- and 7-year-olds.

Discussion

The results from Experiment 3 support the prediction that children are responding in accordance with their perceptual experience of the illusion and not simply complying with the experimenter.

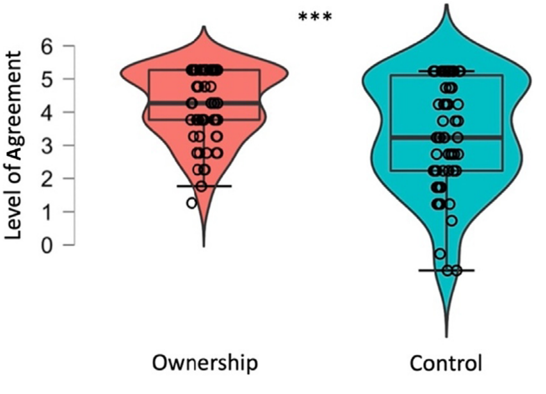

Fig. 7. Ownership and control questions. Children reported significantly higher levels of agreement for the ownership question compared with the control question. ***p <.001.

Moreover, no significant difference in the illusion between the left and right hands (supported by a relatively low BF and a small effect size) suggests that there is no meaningful difference in the illusion based on hand laterality in children.

These results also support our prediction that children would show equivalent illusions for the human and monkey hands, a result supported by the Bayesian statistics. This finding is consistent with the suggestion that children have more flexible body representations, which may be partially driven by fewer high-level constraints on body appearance. Our final experiment aimed to directly compare ownership over a fantastical monkey hand in children with that in adults, predicting that adults would report lower ownership compared with children. We also examined whether self-reported levels of fantasy proneness in children and adults is related to illusion strength over the monkey hand.

Experiment 4

Method

Participants

Participants were 84 children (40 male and 44 female; M_{age} = 8.5 years, *SD* = 1.89, range = 5–12), among which 32 were high fantasy (14 male and 18 female; M_{age} = 8.5 years, SD = 1.69, range = 5–11) and 52 were low fantasy (26 male and 26 female; M_{age} = 8.7 years, *SD* = 2.01, range = 5–12), and 42 adults (7 male and 35 female; M_{age} = 22 years, *SD* = 4.50, range = 18–38).

Materials and measures

Creative Experiences Questionnaire. The Creative Experiences Questionnaire (CEQ) is a 25-item self-report measure of fantasy proneness, capturing three aspects of fantasy proneness: developmental antecedents, intense elaboration of and profound involvement in fantasy and daydreaming, and the concomitants and consequences of fantasizing. Responses are given as yes or no, with the yes answers summed to obtain a total score (0–25). The CEQ demonstrates adequate test–retest stability and internal consistency (Merckelbach, Horselenberg, & Muris, 2001).

Imaginary companion interview. To delineate between children with high fantasy and those with low fantasy, we used an interview protocol to assess the presence (or history) of an IC in children (Davis & Meins, 2014) originally based on an interview assessment by Taylor and Carlson (1997). Children were asked whether they had an IC and to further elaborate on details. Corroboration was sought from parents/guardians where possible. See supplementary material for details.

Procedure

Participants' real right hand was placed on a tabletop hidden from view behind a vertical screen (Fig. 6). A fake monkey hand was placed on the table directly in front of participants. A lateral setup, in which the real and fake hands were positioned along the horizontal plane, was chosen for logistical purposes. Participants were asked to keep their hand still while watching the fake hand as the experimenter then brushed both the real hand and the corresponding location of the fake hand for 1 min. This was done once synchronously and once asynchronously, the order of which was counterbalanced across participants. At the end of each trial, participants were asked about their experience of ownership and a control question (Table 1). Half the children completed the IC interview before taking part, and the other half were asked afterward. Our adults complete the CEQ, half before the RHI and half afterward.

Results

First, we wanted to examine whether children and adults experienced the illusion over a monkey hand, so we conducted Wilcoxon signed ranks tests between the synchronous and asynchronous conditions for children and adults independently. For all questionnaire responses, we used Bonferroni correction (critical p =.013). Children gave higher scores for synchronous touch (*Mdn* = 5, IQR = 3–6) compared with asynchronous touch (Mdn = 2.5, IQR = 1–4) (z = −5.43, p <.001, r =.59, BF = 3.72e+6). The same effect was found with adults (z = −4.72, p <.001, r =.73, BF = 244209; synchronous Mdn = 3, IQR = 2–5; asynchronous Mdn = 1, IQR = 0–2).

Next, we wanted to examine the strength of agreement for the illusion question compared with the control question in children and adults using Wilcoxon signed ranks tests. Children gave greater agreement to the illusion question (Mdn = 5) compared with the control question (Mdn = 4) (z = −3.74, p <.001, r =.41, BF = 373). The equivalent comparison for adults was nonsignificant (z = −0.223, p =.837, r =.03, BF = 0.18), with agreement for the ownership question (Mdn = 3) and control question (Mdn = 3) being relatively low. This suggests that adults, unlike children, were not on average experiencing a strong sense of ownership over the monkey hand because their responses to the ownership question were statistically equivalent to their responses to the control question, although this may be a result of increased compliance in our adult sample. In the context of results from previous studies and the relatively low means (corresponding average neutral response rather than an affirmation of the illusion) compared with children, this finding is more likely to represent reduced illusion for the monkey hand.

To examine the effect of fantasy/imagination in children's experience of the illusion, children were divided into two groups: those who reported having an IC (n = 32) and those who did not (n = 52). An independent-samples t test was then used to determine whether there was a difference in age between the two groups. No significant difference was found, $t(79)$ = −0.452, p =.653, d = .103, BF = 0.26.

Next, to compare the strength of the illusion (level of agreement to the illusion question) among the three groups, and because the data were ordinal, we conducted a Kruskal–Wallis test for ownership questions in the synchronous condition with the between factor of group (child with IC vs. child without IC vs. adult). A significant difference was revealed for the ownership question, $\chi^2(2)$ = 8.34, p =.015, ε^2 =.07. Follow-up Dwass–Steel–Critchlow–Fligner pairwise comparisons revealed that low-imaginary children (Mdn = 5) had higher ownership scores compared with adults (Mdn = 3) (W = −3.75, p =.02, BF = 3.16). There was no significant difference between the high- and low-fantasy groups for children (W = 0.207, p =.988, BF = 0.23). The difference between adults and the high-fantasy children approached significance (W = 3.20, p =.061, BF = 2.45), with the high-fantasy children reporting stronger illusions (Mdn = 4) compared with adults (Mdn = 3) (see Fig. 8). A second Kruskal–Wallis test was conducted on the control scores with the between factor of group (child with IC vs. child without IC vs. adult), revealing no significant effect of group, $\chi^2(2)$ = 2.37, p =.31, ε^2 =.02.

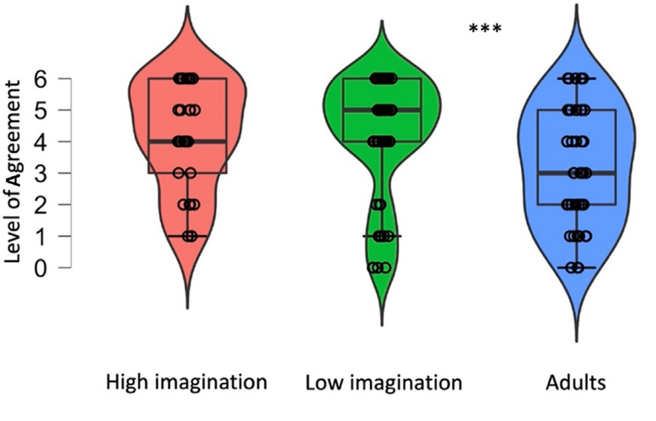

Fig. 8. There was no significant difference between levels of ownership over the fake monkey hand for children with low and high imagination. Children in the low-imagination group reported significantly higher levels of ownership over the fake monkey hand compared with adults. The difference between children with high imagination and adults approached significance. ***p <.001.

Finally, we examined whether fantasy proneness scores in adults related to feelings of ownership for the monkey hand. No significant relationship was found between synchronous ownership scores and CEQ scores, $r(43)$ =.038, p =.810.

Discussion

The results from Experiment 4 suggest that children experience a stronger illusion for the monkey hand than adults. However, high-fantasy children reported statistically equivalent ownership scores when compared with adults, and there was no difference in illusion strength between children with and without ICs. Equivalent illusions for high-fantasy children and adults may be due to differences in sample sizes, with a smaller sample of high-fantasy children compared with low-fantasy children and adults. Other high-level cognitions have previously been related to strength of the RHI (Marotta et al., 2016; Mussap & Salton, 2006). Our results are not consistent with this given that ownership over a monkey hand illusion did not relate to fantasy proneness. Instead, our results support high-level cognitions constraining RHI strength based on body appearance to a greater extent for adults than for children irrespective of level of fantasy. However, a limitation of this experiment is that we did not compare the monkey hand with the humanlike hand, the difference of which is likely to be predominantly driven by high-level constraints. On a related point, because we did not directly compare illusion strength for a monkey hand and a human hand in adults, we cannot fully discount the possibility that the nonsignificant difference between control and illusion scores in adults may reflect greater suggestibility in adults for this experiment rather than a reduction in illusion for a monkey hand. However, given the results of the previous experiments, the lower agreement scores (suggesting that on average adults did not affirm the ownership question), and the significant difference between children and adults, we feel that this statistical equivalence between ownership and control scores likely reflects a reduced illusion.

General discussion

The current study investigated high-level contributions to feelings of body ownership in children compared with adults across four different experiments using variants of the RHI. We examined how differences in the appearance of the to-be-embodied fake hand modulated the experience of the RHI in children and adults and explicitly examined individual differences in fantasy proneness. We also developed a novel adaptation to a previous paradigm, the Holes Task, to indirectly capture perceived hand size and how this was modulated by the illusion. The results indicate that children have reduced high-level constraints on body ownership compared with adults for subjective feelings of ownership. Specifically, adults showed reduced feelings of ownership compared with children over hands that were incongruent compared with their own in terms of visual appearance (small and fantastical hands). However, our Holes Task, in which participants made judgments about the size of holes they could fit their hand through after illusion induction over both small and large hands, revealed no significant difference between children and adults, with both showing effects of the illusion. Children selected larger hole sizes relative to their actual hand size compared with adults at baseline, the current results suggest that this may change developmentally across a lifespan. Explicit measures of fantasy proneness/imagination were not found to relate to the experience of the RHI with children or adults. Together, these results suggest that children have a less rigid structural body description and so can more readily accept greater changes to their body representations compared with adults (i.e., accept more unrealistic hands as their own in the RHI).

Our results support previous findings demonstrating that adults experience reduced RHI over small fake hands (Pavani & Zampini, 2007) and that children report equivalent RHI over different hand sizes (Filippetti & Crucianelli, 2019). Reduced feelings of ownership for adults over the small hand were not directly replicated in Experiment 2 (Bayesian statistics were inconclusive); however, children had stronger illusions than adults for the small fake hand but not for the large fake hand. This difference in our findings might be due to the nature of the task. In Experiment 2, participants were providing subjective reports of the illusion at illusion onset, which might not be as developed as after experiencing the illusion over a longer period of time. Botvinick and Cohen (1998) found that illusion strength (indexed by proprioceptive drift) increased as duration of illusion induction increased. Therefore, this enhancement of illusion strength might not occur to the same degree in adults with a small fake hand compared with an adult-sized fake hand, but illusion strengths at the initial illusion onset are more equivalent. In addition, illusion strength in Experiment 2 only measured ownership, whereas Experiment 1 considered ownership and referral of touch. Although ownership and referral of touch are often examined together (Preston, 2013), they can show different effects, with ownership being generally lower than referral of touch (Kalckert, Bico, & Fong, 2019). It is possible that referral of touch and ownership take different developmental trajectories or that because ownership scores are lower there is less sensitivity to detect differences. Interestingly, children in our study experienced the illusion faster compared with adults irrespective of hand size, which may reflect a greater readiness to embody the illusion per se and not just with incongruent fake hands. A stronger tendency to update body representations could be an important mechanism in children, allowing them to adapt to more rapid and significant bodily changes occurring at this stage of development.

Whereas adults verbally reported weaker experiences of the illusion than children, they demonstrated equivalent responses to children on the Holes Task. Thus, after experiencing the illusion with a hand smaller than their own, they then judged that their own hand could fit through smaller holes, yet they rated their experience of the illusion as weaker than children. One explanation for this is perceived social constraints in adults for explicitly reporting illusion experience. Although traditionally children are thought to have a more blurred boundary between fantasy and reality, it has been suggested that adults may also engage in fantasy but are less likely to admit to these thoughts (Smith & Lillard 2012), such that in today's modern (Western) technological world, adults are primed to revert to the dominant scientific paradigm (Subbotsky 2004). Similarly, dissociations in illusion strength have been found when asking participants to report what they *feel* rather than what they *believe* (Tamè, Linkenauger, & Longo 2018). Therefore, a high-level belief that it is not their hand might inhibit the illusion on a subjective level, but not on indirect measures of embodiment that may be driven more by low-level signals.

The development of our adapted Holes Task was an important aspect of the current study because it is important to continually re-assess and develop new measures of the illusion. This method supported embodiment over the fake hands, but because the pattern of results differed from what was found with the subjective responses, our results also suggest that indirect judgments of hand size are less influenced by high-level constraints and as such are less susceptible to potential subjective bias. Because childhood is an important time for body development, simple and effective ways to capture bodily experience in young children are essential to understand how different aspects of body ownership develop. The Holes Task is an easy and effective measure to deliver to children as young as 5 years for the current study, and because it was portable the task was also highly suited to our testing environment. Future variations of the Holes Task could incorporate smaller holes and adapt instructions for testing younger children. Indeed, our piloting involved children aged 18 months.

A limitation with our study is that the incongruent hand size for adults was small, whereas our planned incongruent hand size for children was large. Previous studies suggest that adults can take ownership over larger fake hands (Pavani & Zampini, 2007) and that the human body representation may be more adapted to increases in size opposed to decreases in size, in line with developmental changes (Byrne & Preston, 2019), which is supported by our finding of a bias toward selecting larger hand sizes in children relative to their actual hand at baseline, but not in adults. However, the average hand size of children was smaller than the large fake hand *and* larger than the small fake hand. Therefore, both fake hands were incongruent for children, whereas only the small hand was incongruent for adults. If the strength of the illusion was purely down to similarity between the actual and fake hands, then adults would be expected to experience stronger illusions for the large hand compared with children rather than demonstrating statistically equivalent effects. An alternative explanation is that even though both fake hands differed significantly in size compared with our children's actual hands, this was not to the same extent as the difference between the adults and the small fake hands. However, we also found that it is children's age and not the similarity between the size of the fake and real hands that relates to the illusion for the small hand. Similarly, we did not find a relationship between the difference in hand size between the small fake hand and the actual hand and ownership/illusion scores in adults. Thus, our results are compatible with the notion that susceptibility to the illusion for a smaller hand decreases developmentally. In addition, in Experiments 3 and 4, we used a monkey hand. This fake monkey hand was equally implausible for both children and adults (or even more implausible for children because the hand was also adult sized), and yet the illusion was still stronger for children. However, a monkey hand, and certainly the fake monkey hand used in the current experiments, still resembles a human hand in terms of the overall features and shape, with the main difference between the two hands being texture (fur on the monkey hand). Therefore, although the current study suggests fewer constraints on body appearance in children, we do not know whether this extends beyond a humanoid shape. Although it makes sense for children to have greater flexibility of body representation to adapt to rapid body changes, this might not be developmentally optimal for noncorporeal objects that do not resemble a living body.

A possible alternative explanation for higher illusion scores in children is that children are more likely to agree to the statements proposed by the experimenter due to greater susceptibility to social demand characteristics (Bjorklund et al., 2000). The illusion questions chosen for these experiments were based on those previously developed for young children by Cowie et al. (2013), who did not include control questions. Control questions are important in body illusion studies because they attempt to control for demand characteristics (Botvinick & Cohen, 1998); therefore, in Experiments 3 and 4, we included a control question. Greater agreement for the illusion question compared with the control question in both experiments suggests that the ownership responses do reflect the illusion and not a propensity to agree. However, not all our results can discount compliance. In Experiment 2, when measuring illusion onset times, we did not exclude participants for responding too quickly. This is because some people have been found to experience strong bodily illusions driven purely by visual capture without synchronous touch (Carey, Crucianelli, Preston, & Fotopoulou, 2019). Therefore, very fast responses might not be false positives. However, it is possible that children respond quickly due to compliance; therefore, future studies should aim to confirm illusion responses following verbally reported onset times.

We found no direct relationship between illusion strength and fantasy proneness (CEQ). However, current theories of body ownership suggest that the RHI is governed not just by high-level processing but also by multisensory integration. Therefore, interindividual differences in weighting of multisensory information, such as the relative weighting of vision versus proprioception, may also influence feelings of ownership toward any noncorporeal object, whether realistic or not. Future studies should aim to examine potential relationships between fantasy proneness and a relative difference between illusion strength for a fantastical hand and a humanlike hand. There are also limitations in the way we have measured fantasy in children. Our samples were recruited at public engagement events; therefore, although when testing each child there was an attempt at privacy, children may have felt embarrassed reporting ICs, especially older children. Indeed, our percentage of children reporting ICs was lower than percentages in studies examining similar age ranges (Pearson et al., 2001; Taylor & Mottweiler, 2008). In addition, although those reporting ICs are found to show greater creativity (Hoff, 2005) and more vivid imagination (Bouldin, 2006), the presence of an IC as a boundary between reality and fantasy has been questioned (Bouldin & Pratt, 2001). Therefore, future studies should confirm the results using a more reliable measure of fantasy in children.

A further limitation is the nature of the recruitment, such that the majority of testing was done in a public event and so was not subject to the same experimental control as lab studies. However, we were able to replicate our key findings across different experiments. In addition, although our samples incorporated a spread of ages, children in adolescence were underrepresented. These children were more likely to be attending the public events without their parents but still required parental consent. During early adolescence, multisensory integration is thought to be in line with adults (Cowie et al., 2016), but the body is still changing significantly. Furthermore, fantasy proneness is found to have different properties during adolescence (Sánchez-Bernardos & Avia, 2006), which may relate to onsets of psychopathologies that most commonly occur during this time (Fossati, Raine, Carretta, Leonardi, & Maffei, 2003) and can include disorders in bodily experience (e.g., Klaver & Dijkerman 2016).

In summary, the current results demonstrate that children have stronger experiences of the RHI over incongruent hands compared with adults, which may be driven by a less rigid representation of what one's own body looks like. We suggest that this increased flexibility of body representations during early life allows children to quickly adapt to greater and more rapid bodily changes occurring during childhood. We did not find evidence that high-level cognitions (fantasy proneness) are related to differences in illusion susceptibility for a fake monkey hand in adults or children; however, such relationships may be masked by individual differences in multisensory integration. Together, our results demonstrate the importance of high-level processes in the experience and flexibility of the human body representations throughout development into adulthood.

Acknowledgment

We would like to thank Chole Robinson, Molly Bowns, Ailish Byrne, Ella White and Caitlin Woods for their help with data collection. We would also like to thank Knavesmire Primary School, Askham Bryan Wildlife Park, York Castle Museum, York Festival of Ideas and Manchester Science Festival for allowing us to collect data are you venues.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jecp.2022.105477.

References

Assaf, A. G., & Tsionas, M. (2018). Bayes factors vs. p-values. *Tourism Management, 67*, 17–31.
Bernardi, N. F., Marino, B. F., Maravita, A., Castelnuovo, G., Tebano, R., & Bricolo, E. (2013). Grasping in wonderland: Altering the visual size of the body recalibrates the body schema. *Experimental Brain Research, 226*, 585–594.
Bjorklund, D. F., Cassel, W. S., Bjorklund, B. R., Brown, R. D., Park, C. L., Ernst, K., & Owen, F. A. (2000). Social demand characteristics in children's and adults' eyewitness memory and suggestibility: The effect of different interviewers on free recall and recognition. *Applied Cognitive Psychology, 14*, 421–433.
Botvinick, M., & Cohen, J. (1998). Rubber hands "feel" touch that eyes see. *Nature, 391*, 756.
Bouldin, P. (2006). An investigation of the fantasy predisposition and fantasy style of children with imaginary companions. *Journal of Genetic Psychology, 167*, 17–29.
Bouldin, P., & Pratt, C. (2001). The ability of children with imaginary companions to differentiate between fantasy and reality. *British Journal of Developmental Psychology, 19*, 99–114.
Brownell, C. A., Nichols, S. R., Svetlova, M., Zerwas, S., & Ramani, G. (2010). The head bone's connected to the neck bone: When do toddlers represent their own body topography? *Child Development, 81*, 797–810.
Bruno, N., & Bertamini, M. (2010). Haptic perception after a change in hand size. *Neuropsychologia, 48*, 1853–1856.
Byrne, A., & Preston, C. (2019). Mr. Fantastic meets The Invisible Man: An illusion of invisible finger stretching. *Perception, 48*, 185–188.
Cardinali, L., Serino, A., & Gori, M. (2019). Hand size underestimation grows during childhood. *Scientific Reports, 9*, 13191.
Carey, M., Crucianelli, L., Preston, C., & Fotopoulou, A. (2019). The effect of visual capture towards subjective embodiment within the full body illusion. *Scientific Reports, 9*, 2889.
Chechik, G., Meilijson, I., & Ruppin, E. (1998). Synaptic pruning in development: A computational account. *Neural Computation, 10*, 1759–1777.
Cowie, D., Makin, T. R., & Bremner, A. J. (2013). Children's responses to the rubber hand illusion reveal dissociable pathways in body representation. *Psychological Science, 24*, 762–769.
Cowie, D., Sterling, S., & Bremner, A. J. (2016). The development of multisensory body representation and awareness continues to 10 years of age: Evidence from the rubber hand illusion. *Journal of Experimental Child Psychology, 142*, 230–238.
Davis, P. E., & Meins, E. (2014). Children with imaginary companions focus on mental characteristics when describing their real-life friends. *Infant and Child Development, 23*, 622–633.
Dempsey-Jones, H., & Kritikos, A. (2019). Handedness modulates proprioceptive drift in the rubber hand illusion. *Experimental Brain Research, 237*, 351–361.
Dienes, Z. (2014). Using Bayes to get the most out of non-significant results. *Frontiers in Psychology, 5*. https://doi.org/10.3389/fpsyg.2014.00781.
Ehrsson, H. H., Spence, C., & Passingham, R. E. (2004). That's my hand! Activity in premotor cortex reflects feeling of ownership of a limb. *Science, 305*, 875–877.
Ferracci, S., & Brancucci, A. (2019). The influence of age on the rubber hand illusion. *Consciousness and Cognition, 73*, 102756.
Filippetti, M. L., & Crucianelli, L. (2019). If I were a grown-up: Children's response to the rubber hand illusion with different hand sizes. *Journal of Experimental Child Psychology, 185*, 191–205.
Filippetti, M. L., Johnson, M. H., Lloyd-Fox, S., Dragovic, D., & Farroni, T. (2013). Body perception in newborns. *Current Biology, 23*, 2413–2416.
Fossati, A., Raine, A., Carretta, I., Leonardi, B., & Maffei, C. (2003). The three-factor model of schizotypal personality: Invariance across age and gender. *Personality and Individual Differences, 35*, 1007–1019.
Gori, M., Del Viva, M., Sandini, G., & Burr, D. C. (2008). Young children do not integrate visual and haptic form information. *Current Biology, 18*, 694–698.

Heron, M., & Slaughter, V. (2008). Toddlers' categorization of typical and scrambled dolls and cars. *Infant Behavior and Development, 31*, 374–385.
Hoff, E. V. (2005). Imaginary companions, creativity, and self-image in middle childhood. *Creativity Research Journal, 17*, 167–180.
Ishak, S., Franchak, J. M., & Adolph, K. E. (2014). Perception–action development from infants to adults: Perceiving affordances for reaching through openings. *Journal of Experimental Child Psychology, 117*, 92–105.
Jakubowska, J., Filip, A., & Białecka-Pikul, M. (2021). The coin that is most current is flattery? Stability and discontinuity of false praise-telling from 5 to 7 years of life. *Journal of Experimental Child Psychology, 207*, 105128.
JASP Team (2020). *JASP* (Version 0.13) [computer software].
Kalckert, A., Bico, I., & Fong, J. X. (2019). Illusions with hands, but not with balloons—Comparing ownership and referral of touch for a corporal and noncorporal object after visuotactile stimulation. *Perception, 48*, 447–455.
Kalckert, A., & Ehrsson, H. H. (2017). The onset time of the ownership sensation in the moving rubber hand illusion. *Frontiers in Psychology, 8*. https://doi.org/10.3389/fpsyg.2017.00344.
Kalisch, T., Ragert, P., Schwenkreis, P., Dinse, H. R., & Tegenthoff, M. (2009). Impaired tactile acuity in old age is accompanied by enlarged hand representations in somatosensory cortex. *Cerebral Cortex, 19*, 1530–1538.
Kammers, M. P., de Vignemont, F., Verhagen, L., & Dijkerman, H. C. (2009). The rubber hand illusion in action. *Neuropsychologia, 47*, 204–211.
Kilteni, K., Maselli, A., Kording, K. P., & Slater, M. (2015). Over my fake body: Body ownership illusions for studying the multisensory basis of own-body perception. *Frontiers in Human Neuroscience, 9*. https://doi.org/10.3389/fnhum.2015.00141.
Kilteni, K., Normand, J. M., Sanchez-Vives, M. V., & Slater, M. (2012). Extending body space in immersive virtual reality: A very long arm illusion. *PLoS One, 7*(7), e40867.
Klaver, M., & Dijkerman, H. C. (2016). Bodily experience in schizophrenia: Factors underlying a disturbed sense of body ownership. *Frontiers in Human Neuroscience, 10*. https://doi.org/10.3389/fnhum.2016.00305.
Lloyd, D. M. (2007). Spatial limits on referred touch to an alien limb may reflect boundaries of visuo-tactile peripersonal space surrounding the hand. *Brain and Cognition, 64*, 104–109.
Longo, M. R., & Haggard, P. (2011). Weber's illusion and body shape: Anisotropy of tactile size perception on the hand. *Journal of Experimental Psychology: Human Perception and Performance, 37*, 720–726.
Longo, M. R., Schüür, F., Kammers, M. P. M., Tsakiris, M., & Haggard, P. (2008). What is embodiment? A psychometric approach. *Cognition, 107*, 978–998.
Marino, B. F., Stucchi, N., Nava, E., Haggard, P., & Maravita, A. (2010). Distorting the visual size of the hand affects hand pre-shaping during grasping. *Experimental Brain Research, 202*, 499–505.
Marotta, A., Tinazzi, M., Cavedini, C., Zampini, M., & Fiorio, M. (2016). Individual differences in the rubber hand illusion are related to sensory suggestibility. *PLoS One, 11*(12), e168489.
Merckelbach, H., Horselenberg, R., & Muris, P. (2001). The Creative Experiences Questionnaire (CEQ): A brief self-report measure of fantasy proneness. *Personality and Individual Differences, 31*, 987–995.
Mussap, A. J., & Salton, N. (2006). A "rubber-hand" illusion reveals a relationship between perceptual body image and unhealthy body change. *Journal of Health Psychology, 11*, 627–639.
Ocklenburg, S., Rüther, N., Peterburs, J., Pinnow, M., & Güntürkün, O. (2011). Laterality in the rubber hand illusion. *Laterality, 16*, 174–187.
Pavani, F., & Zampini, M. (2007). The role of hand size in the fake-hand illusion paradigm. *Perception, 36*, 1547–1554.
Pearson, D., Rouse, H., Doswell, S., Ainsworth, C., Dawson, O., Simms, K., ... Faulconbridge, J. (2001). Prevalence of imaginary companions in a normal child population. Child: Care. *Health and Development, 27*, 13–22.
Piryankova, I. V., Wong, H. Y., Linkenauger, S. A., Stinson, C., Longo, M. R., Bülthoff, H. H., & Mohler, B. J. (2014). Owning an overweight or underweight body: Distinguishing the physical, experienced and virtual body. *PLoS One, 9*(8), e103428.
Preston, C. (2013). The role of distance from the body and distance from the real hand in ownership and disownership during the rubber hand illusion. *Acta Psychologica, 142*, 177–183.
Preston, C., & Ehrsson, H. H. (2014). Illusory changes in body size modulate body satisfaction in a way that is related to non-clinical eating disorder psychopathology. *PLoS One, 9*(1), e85773.
Preston, C., & Newport, R. (2011). Evidence for dissociable representations for body image and body schema from a patient with visual neglect. *Neurocase, 17*, 473–479.
Reader, A. T., Trifonova, V. S., & Ehrsson, H. H. (2021). The relationship between referral of touch and the feeling of ownership in the rubber hand illusion. *Frontiers in Psychology, 12*. https://doi.org/10.3389/fpsyg.2021.629590.
Sánchez-Bernardos, M. L., & Avia, M. D. (2006). The relationship between fantasy proneness and schizotypy in adolescents. *Journal of Nervous and Mental Disease, 194*, 411–414.
Seiffge-Krenke, I. (1997). Imaginary companions in adolescence: Sign of a deficient or positive development. *Journal of Adolescence, 20*, 137–154.
Smith, E. D., & Lillard, A. S. (2012). Play on: Retrospective reports of the persistence of pretend play into middle childhood. *Journal of Cognition and Development, 13*, 524–549.
Smit, M., Kooistra, D. I., van der Ham, I. J. M., & Dijkerman, H. C. (2017). Laterality and body ownership: Effect of handedness on experience of the rubber hand illusion. *Laterality, 22*, 703–724.
Sobel, D. M., & Lillard, A. S. (2001). The impact of fantasy and action on young children's understanding of pretence. *British Journal of Developmental Psychology, 19*, 85–98.
Subbotsky, E. (2004). Magical thinking in judgments of causation: Can anomalous phenomena affect ontological causal beliefs in children and adults? *British Journal of Developmental Psychology, 22*, 123–152.
Tamè, L., Linkenauger, S. A., & Longo, M. R. (2018). Dissociation of feeling and belief in the rubber hand illusion. *PLoS One, 13*(10), e206367.
Taylor, M., & Carlson, S. M. (1997). The relation between individual differences in fantasy and theory of mind. *Child Development, 68*, 436–455.
Taylor, M., & Mottweiler, C. M. (2008). Imaginary companions: Pretending they are real but knowing they are not. *American Journal of Play, 1*(1), 47–54.

Tsakiris, M. (2010). My body in the brain: A neurocognitive model of body-ownership. *Neuropsychologia, 48*, 703–712.
Tsakiris, M. (2017). The multisensory basis of the self: From body to identity to others. *Quarterly Journal of Experimental Psychology, 70*, 597–609.
Tsakiris, M., Carpenter, L., James, D., & Fotopoulou, A. (2010). Hands only illusion: Multisensory integration elicits sense of ownership for body parts but not for non-corporeal objects. *Experimental Brain Research, 204*, 343–352.
Tsakiris, M., & Haggard, P. (2005). The rubber hand illusion revisited: Visuotactile integration and self-attribution. *Journal of Experimental Psychology: Human Perception and Performance, 31*, 80–91.
Vallar, G., & Ronchi, R. (2009). Somatoparaphrenia: A body delusion. A review of the neuropsychological literature. *Experimental Brain Research, 192*, 533–551.
van der Hoort, B., Guterstam, A., & Ehrsson, H. H. (2011). Being Barbie: The size of one's own body determines the perceived size of the world. *PLoS One, 6*(5), e20195.
van Doorn, J., Ly, A., Marsman, M., & Wagenmakers, E.-J. (2020). Bayesian rank-based hypothesis testing for the rank sum test, the signed rank test, and Spearman's ρ. *Journal of Applied Statistics, 47*, 2984–3006.
Woolley, J. D. (1997). Thinking about fantasy: Are children fundamentally different thinkers and believers from adults? *Child Development, 68*, 991–1011.