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

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Author Note

This Project was funded by the British Academy SG163427

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Abstract

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, 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. 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 to adults using the Rubber Hand Illusion and a Monkey Hand Illusion. We found that children (5-17 years) exhibited more flexible body representations, showing stronger illusions for small and fantastical (monkey) fake hands compared to 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 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 to adults.

Keywords: Rubber Hand Illusion; Fantasy proneness; Development; Body Ownership; Multisensory Integration; Embodiment

Introduction

As humans our bodies afford us the capacity to explore and engage with our environment but also they are 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 hand 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 towards 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 to asynchronous touch (Filippetti et al. 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 old, after which children perform like adults (statistically optimal) (Gori et al. 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 the age of 10 years, children are found to perform like adults, demonstrating greater proprioceptive drift in the synchronous compared to asynchronous conditions (Cowie, Sterling, & Bremner 2013). However, children's bodies are still changing considerably through puberty along with substantial changes in synaptic density (Chechik et al. 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 our 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 et al. 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 (Tsakiris & Haggard 2005; Preston 2013; Lloyd 2007), size (Pavani & Zampini, 2007) and appearance (Tsakiris et al. 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), are physically plausible (Preston & Ehrsson 2014; Piryankova et al. 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 (Kilteni et al. 2012; Byrne & Preston 2019).

However, little is understood about how high-level body representations develop during childhood and how this impacts body ownership. Intuitively, children may have more flexible body representations because their body is undergoing more rapid change compared to adults. Additionally, 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 to 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 their own body (naming own body parts, meaningless gestures, dressing the self and a doll) (Brownell et al. 2010). Furthermore, using the RHI it has been found that children aged 6-8 years experienced ownership over both a regular and a 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 to adults.

Traditionally, children are thought to have more flexible boundaries between reality and imagination compared to adults. Therefore, constraints on body representations due to high-level cognitive knowledge may be less pronounced in 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 to adults (Woolley 1997), with an average age of ceasing pretence reported as 11 years old (Smith & Lillard 2012). Moreover, the act of pretence 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 towards fantasy in young children may also impact on 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 and thus 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 pretence (Smith & Lillard 2012) and retaining an IC (Seiffge-Krenke, 1997) well into young adulthood. Thus, it could be that differences between adult and child fantasy is less distinct (Subbotsky, 2004) and would therefore 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 to 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 bodies undergo more rapid changes in childhood compared to adulthood, we predicted that children will demonstrate greater flexibility of body representations by reporting stronger illusion experiences over fake hands which 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 are predicted to experience greater RHI compared to 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 will experience stronger illusions compared to children without an IC. We also predict that higher engagement in fantasy in adults will 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 dissociate 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 are 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 if their hand felt larger or smaller it may be less affected by high-level constraints in both children and adults.

Methods

For experiment one, two and four, participants were recruited from public venues, events, and summer activity clubs in the North East of the UK. Written parental consent was gained for children followed by verbal consent from the child. Written consent for adults (18+) was gained directly. For experiment three, participants were recruited via their primary school and parental consent was sought by sending information home to the parents. Individual verbal consent from the children was also taken. Ethical approval was obtained from the University Department ethics committee ref:604.

Experiment One

Participants

Children: N=100 (50 male, 50 female) mean age=9 years (111 months), range=5-16 years (63 – 200 months), SD=2.8 years (32.3 months).

Adults: N=99 (29 males, 70 female) mean age=35 years, range=19-72 years, SD=16.1 years.

Materials

Rubber Hand Illusion Participants sat at a table resting their right hand on the tabletop in front of them, underneath a wooden platform (35×30×13cm). 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 30cm from base of the wrist to the tip of the middle finger (22cm of hand and 8cm of wrist). The small fake hand measured 12cm in length (9cm of hand and 3cm 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 make-up brush.

The Holes Task This task was adapted from a previous study (Ishak et al. 2014), consisting of two 55x35cm Perspex test boards. Each test board contained 11 non-adjustable circular holes that varied in size (50-100mm in diameter, increasing in 5mm 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 - 13 years (N=7). Hole sizes were selected to ensure 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 ~500ms delay (asynchronously). Each trial lasted for one minute, timed by a second experimenter using a stopwatch. For each hand size there were four trials, two (one synchronous, one asynchronous) after which participants completed the Holes Task, and two following which they gave responses concerning the subjective experience of the illusion (see Table 1 and supplementary material). A baseline measure of the Holes Task was always completed first to measure participant's hand size judgments before experiencing the illusion. Participants then completed the RHI with both the small and large hand (the order of synchronous and asynchronous trials and large and small hands was counterbalanced), following which 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. This measurement was compared to the equivalent measurements on the large (75mm) and small (45mm) hands as well as the smallest hole selected.

Table 1.

Questions used to capture the experience of the illusion in each experiment

Question	Purpose	Experiment
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 (1-4).

The 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 the participant if they thought that they could fit their right hand through the hole, providing a verbal forced choice yes or no response. They were instructed not to physically try to fit their hand through, but to imagine if 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 which 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 a different board was used for synchronous and asynchronous trials.

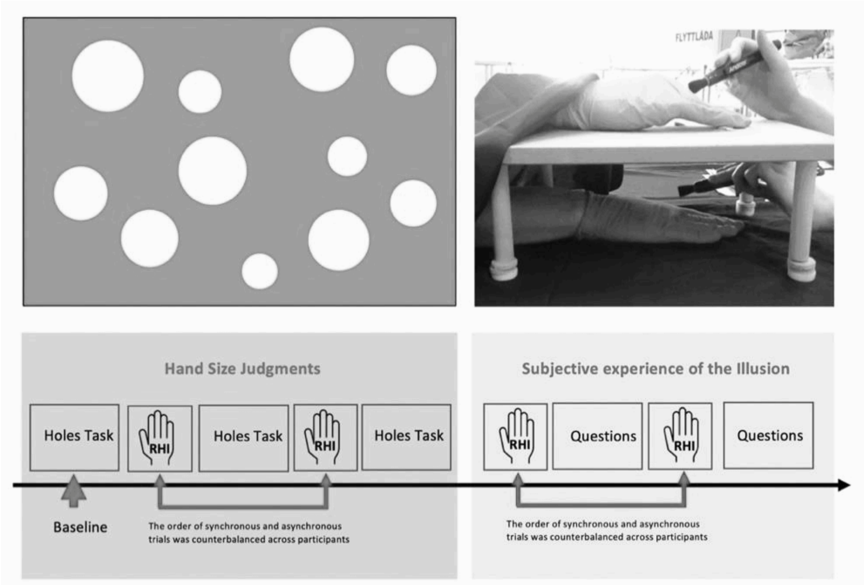

Fig.1.

Experimental set-up and procedure. (Top left) Diagram of one of the boards used for the Holes Task. (Top Right) The rubber hand illusion set-up. (Bottom) Schematic of trials for experiment one.

<u>Analysis</u>

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 materials). Because both small and large hand sizes were incongruent for children we analysed the data with small and large levels of hand size, rather than congruent and incongruent.

Ordinal data (Illusion questions) were analysed using non-parametric statistics (Mann-Whitney U for between comparisons, Wilcoxon signed ranks for within comparisons and Spearman's Rho for correlations). Bayes Factors (BF) for parametric and non-parametric data (van Doorn et al. 2020) were calculated where possible to supplement frequentist analysis. BF present likelihood ratios of the alternative relative the null hypotheses (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 1-3 provides anecdotal evidence for the alternative hypothesis and between .33-1 anecdotal evidence for the null (Assaf & Tsionas 2018). Analyses were conducted using IBM SPSS Statistics for macOS, Version 26.0 and Jasp Team (2020) Version 0.13.

Experiment One 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 if both of our samples experienced the illusion in line with synchrony of vision and touch, therefore we examined illusion scores for synchronous vs. 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 to asynchronous for the small hand (adults: $z=7.81$, $p<.001$, $r=.79$, BF=3.83e+18; synchronous Mdn=4; asynchronous Mdn=1.5; children: $z=8.09$, $p<.001$, $r=8.1$, 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 if the size of the hand affected illusion strength for either group. To 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 to 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=.562, p =.574, r=.06, BF=.11). This finding supports the idea that children's body representations are more flexible than adults'.

Then we explored potential differences between 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=.764, p =.445, r=.05, BF=.22). With the small hand children reported significantly stronger illusions (Mdn=5) compared to adults (Mdn=4) (z=4.32, p<.001, r=.31, BF=160.6). (Fig.2), indicating greater illusion susceptibility in children.

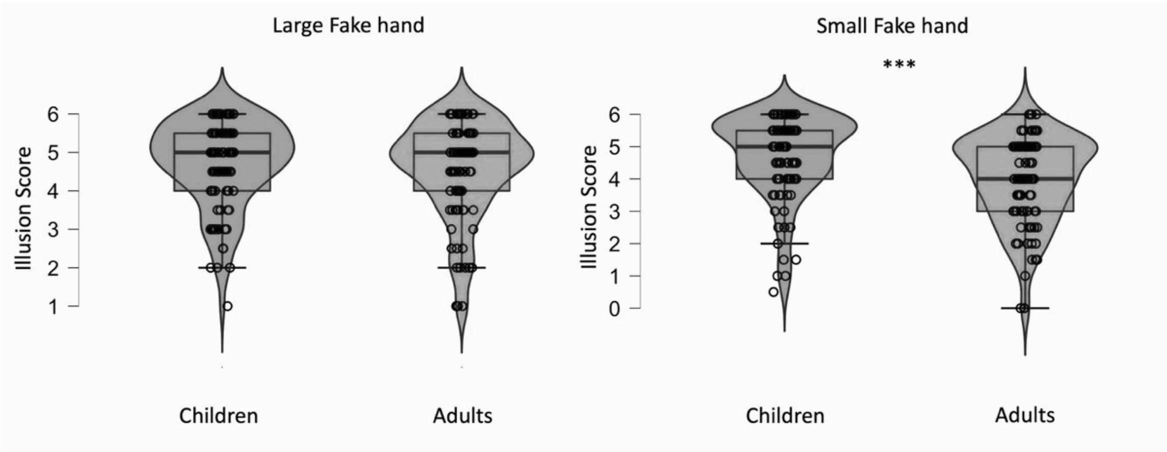

Fig.2.

Illusion scores from experiment one. (Left) Children and adults demonstrated statistically equivalent illusion scores for the large hand. (Right) Children reported stronger illusions compared to adults for the small hand. ***=p<.001.

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

The width of the fake small hand was subtracted from the equivalent measurement on 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 and so were analysed using Pearson's r correlation coefficient. Ownership scores, however, were non-normally distributed and ordinal, therefore relationships including this variable were analysed 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 non-significant 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 $(96)= -.209$, $p=.041$), as age increased, illusion strength for the small hand decreased. This remained significant 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 illusion strength is related to a child's age and not the relative difference in size between the real and fake hand.

The Holes Task First, we examined potential differences between hole size selected at baseline by calculating the difference between 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 percent difference between smallest hole selected and actual hand size correlated with a child'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 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 2x2x2 mixed ANOVA. Within factors: Hand Size (Large vs. Small), Synchrony (Synchronous vs. Asynchronous). Between factor: Sample (Child vs. Adult). There was a significant main effect of Hand Size ($F(1,187)=13.77$, $p<.001$, $\eta_p^2= .069$, BF=58.5), such that the Large hand produced a mean increase in the smallest hole selected (M=.402, SE=.668) and the small hand led to a mean decrease in the smallest hole selected (M=-1.276, SE=.739). There was no main effect of Synchrony ($F(1,187)= 1.034$, $p =.31$, $\eta_p^2= .006$, BF=.136). The main effect of Sample approached significance ($F(1,187)= 3.9$, $p=.051$, $\eta_p^2= .02$, BF=3.20e-8; children: M=-1.76 , SE=.63; adults: M=.88, SE=1.17) but the BF supported the null hypothesis. There was a significant Hand Size x Synchrony interaction ($F(1,187)=16.56$, $p<.001$, $\eta_p^2= .081$, BF=211). All other interactions were non-significant (max $F(1,187)=.59$, $p =.442$, $\eta_p^2= .003$, BF=.21).

To follow-up the Hand Size x Synchrony interaction, planned paired samples t-tests were conducted between synchronous and asynchronous touch for large and small hand sizes. For the large hand synchronous touch (M=1.39, SE=.668) led to a larger hole being selected compared to asynchronous touch (M=-.59, SE=.79) ($t(191)=3.34$, $p= .001$, *d*=.24, BF=16.9). For the small hand, synchronous touch (M=-1.858, SE=.812) led to a smaller hole being selected compared to asynchronous touch (M=-.694, SE=.755) ($t(192)=-2.245$, $p= .026$, *d*=.16, BF=.93) (Fig.3).

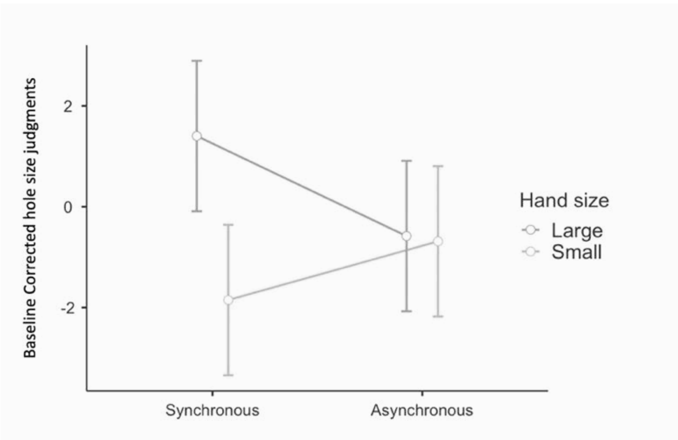

Fig.3.

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

Experiment One Discussion

The results of experiment one support findings from previous studies showing adults experience reduced illusions over smaller fake hands (Pavani & Zampini 2007) whilst 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 to adults and that this experience of ownership was related to the child'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 hands.

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 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 which 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 one (Pavani & Zampini, 2007). However, this previous study used proprioceptive drift to measure the illusions, which involves integration of proprioceptive and visual inputs. The current study, 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 the participant could fit their hand through each hole. We know that visual-proprioceptive integration (proprioceptive drift) takes a different developmental trajectory compared to visual-tactile information

(Cowie et al., 2013). Therefore, tasks which compare the body with external stimuli may also dissociated from and develop differently to what is recorded using proprioceptive drift measures. Indeed, a further study which 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 to external stimuli (Bruno & Bertamini (2010). In their study participants had 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 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 metric for space perception (Van Der Hoort, Guterstam, & Ehrsson, (2011). Therefore, the reason that we find equivalent illusory effects for adults and children for both hand sizes in the holes task, could be because the task taps into external recalibration of the world relative to the body and not direct recalibration of body size.

Other studies which find asymmetric updating of changes in hand size report this using grasping movements (Marino, Stucchi, Nava, Haggard, & Maravita, 2010, Bernardi et al. 2013;). Whilst grasping also involves external stimuli, it has been shown that action body representations can dissociate from perceptual body representations during the RHI (Kammers, dr 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 may not have induced embodiment in the same way as in the current study.

In terms of the contradictory findings for subjective reports of the illusion, such that Pavani & Zampini (2007) found no differences in questionnaire scores between hand sizes, but the current study did, Pavani & Zampini (2007) 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 study, 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) in which 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 to younger children, potentially due to over compensation for misrepresentations of the hand in the somatosensory cortex. In our study, we show that overestimate of the size of the hole children judge that they can fit their hand through and this overestimation decreases with age through 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 to the actual hand size decreases with age (equivalent to a relative decrease in hand size judgments through development). The difference between the underestimations found in Cardinali et al. (2019) and the current overestimations with children in the current study is likely to be due to the nature of the task. In the current study, participants were making 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 respect directly to their actual hand size. In order for an object (hand) to fit through a hole, that hole needs to be larger than the object. Thus, if participants could not manipulate the posture of their hand, then they should always be selecting 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 as they select a smaller hole size compared to their actual hand, particularly given that adults are thought to have wider tactile representations of the hand compared to reality (Longo & Haggard, 2016). One explanation may be due to age related degrading in tactile acuity as 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 to younger participants. Alternatively, because instructions of how to position the hand were not provided, this finding may reflect increased experience with age (you 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 may not be adequately updated in the brain - However, as 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 size selected for synchronous and asynchronous touch for the small had an inconclusive BF).

Our second experiment aimed to replicate the initial findings of experiment one and to incorporate an additional measure of illusion onset time (Kalckert & Ehrsson 2017). Previously, adolescents (16-20 years) were reported to have faster and stronger illusions compared to adults using a standard rubber hand illusion paradigm (Ferracci & Brancucci 2019). The authors suggested 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 Two

Participants

Children: N=120 (46 males, 74 female) mean age=9 years (112 months), range=5-17 years (63 – 210 months), SD=2.7 years (31.8 months).

Adults: N=108 (39 males, 69 female) mean age=38 years, range=18-82 years, SD=15.2 years.

Materials

The same experimental set-up to elicit the RHI was used as described above.

Procedure

The RHI was delivered as described for experiment one for a maximum of one minute (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 above). 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 et al. 2021). However, feelings of ownership are thought to be influenced more strongly by high-level cognitions (Marotta et al. 2016) and therefore more appropriate in this instance.

Experiment Two Results

Because there questionnaire data was ordinal and non-normally distributed all questionnaire data was analysed using non-parametric 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=.41; large hand Mdn=5, IQR=4-5; small hand Mdn=4, IQR=4-5; children: $z=-.801$, $p =.423$, $r=.07$, BF=.12; large hand Mdn=5, IQR=4-5; small hand; Mdn=5, IQR=4-6).

Next, to determine if 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 to adults (Mdn=4, IQR=4-5) ($z=-3.8$, $p<.001$, $r=.25$, BF=98.3). The difference between children (Mdn=5, IQR=4-5) and adults (Mdn=5, IQR=3-5) for the large hand did not survive Bonferroni correction although an effect was indicated by the BF ($z=-1.95$, $p =.051$, $r=.13$, BF=5.15; Children Mdn=5 IQR=4-5; Adults Mdn=5; IQR=3-5). (Fig.4). See Table S1 for mean hand size differences of children and adults from experiments one and two.

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 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 whilst 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 one, suggesting that ownership over a small hand is related to a child's age and not their real hand size

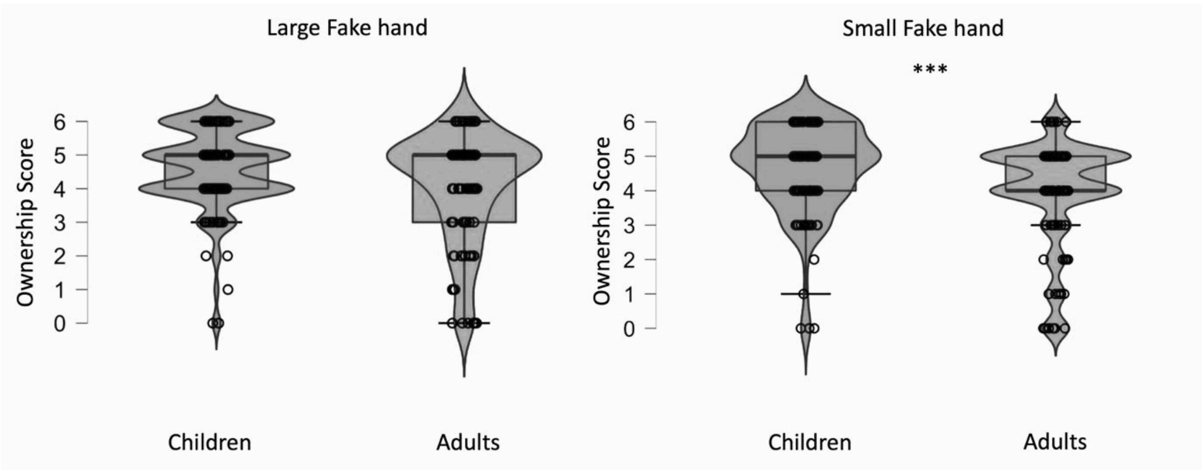

Fig.4.

Ownership scores from experiment two. (Left) Children and adults demonstrated statistically equivalent ownership scores for the large hand. (Right) For the small fake hand children reported a stronger feelings of ownership compared to adults. ***=p<.001.

Next, the time in milliseconds recorded to experience an illusion with each hand size for children and adults was entered into a 2x2 mixed ANOVA. Within factor: Hand Size (large vs. small). Between factor: Sample (children vs. adults).

There was no significant main effect of Hand Size ($F(1,217)=.096$, $p=.757$, $\eta_p^2<.001$, BF=.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 seconds, SE=1.18s) compared to adults (M=26.0 seconds, SE=1.93s) (Fig.5). The Hand Size x Sample interaction was not significant ($F(1,217)=1.76$, $p=.187$, $\eta_p^2=.008$, BF=.34).

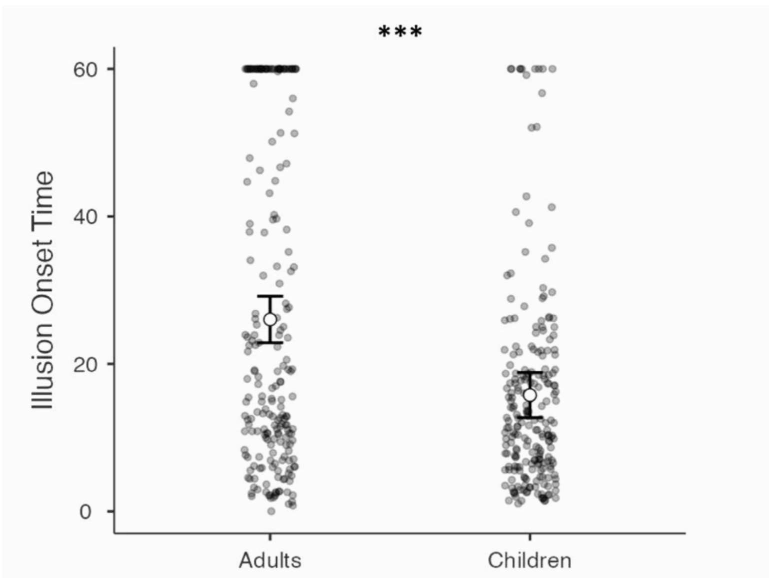

Fig.5.

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

Participants not reporting an illusion within 60s: Small hand: 22 adults, 5 children; Large hand: 22 adults, 4 children (17 adults and 2 children reported no illusion for either hand). Participants reporting an illusion <10s: Small hand: 30 adults, 48 children; Large hand: 29 adults, 45 children. (22 adults and 29 children reported an illusion in <10s for both hands).

Experiment Two Discussion

The results from experiment two largely replicate those from experiment one, suggesting that children have a stronger experience of the illusion (ownership) over small hands compared to adults. Furthermore, reductions in ownership felt for the small hand are related to the age of the child and not the size difference between the actual and fake hands. Additionally, onset times show that children experience the illusion faster compared to 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 hand 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 that reported previously (Kalckert & Ehrsson 2017), other studies report faster onset times (Ehrsson et al. 2004; Lloyd 2007), and others 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 to adults, linked to development.

Despite clear replications in our findings, study limitations mean that our results and interpretations from experiments one and two must be taken 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. We thus implemented the RHI in a fantastical (non-human) fake monkey hand. If children have stronger illusions due to less clear boundaries between fantasy and reality, then their experiences will be more equivalent for monkey and humanlike hands. Adults, however, who do not engage in pretence to the same degree as children, are predicted to show reduced illusions for a fantastical monkey hand compared to children.

It is possible that opposed to 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 three a control question was introduced, predicted to elicit reduced agreement compared to ownership. Here we selected a control question (Table 1) asking about feelings of disownership, predicted to induce lower levels of agreement compared to illusion questions, but is 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 age 6, children are thought to have developed sophisticated strategies of reputation management to appear favourable others (Jakubowska et al. 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. Additionally, neurological cases of disturbances in limb ownership are predominantly found over the left side of the body (Vallar & Ronchi 2009). Experiments one and two induce the illusion only on the right hand. Although hand laterality is not thought to affect the subjective strength of the illusion (Smit et al. 2017; Ocklenburg et al. 2011), it has been found to influence other outcome measures (Ocklenburg et al. 2011; Dempsey-Jones and Kritikos 2019) 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 Three

Participants

58 six (n=53) and seven (n=5) year olds (23 female, 35 male) were recruited via their school and tested individually in their classroom.

Materials

The same experimental set-up to elicit the RHI was used as described above for experiment one, 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 of the participants had their right hand stimulated and the other half their left hand (along with the corresponding laterality of fake hand)

Fig.6.

Monkey hand illusion set-up. (Left) Vertical Rubber Hand Illusion set-up with Monkey hand that was used for Experiment 3. (Right) Lateral Rubber Hand Illusion set-up with Monkey hand (as viewed from above) that was used for Experiment 4.

Procedure

The RHI was delivered as describe for experiment one, for one minute. This was completed four times in total, twice with the fake monkey hand (once synchronous, once asynchronous) and twice with the fake human hand (once synchronous, once asynchronous). The order of the fake hand type and synchrony of touch was counterbalanced between 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).

Experiment Three Results

To examine whether the 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 we would expect similar levels of agreement for both questions. Conversely, if the children were truly experiencing the illusion we would expect higher agreement for the ownership question. Significantly stronger agreement was found for the ownership (Mdn=5, IQR=4.38-6) compared to control (Mdn=4, IQR=3-5.63) question ($z=4.1$, $p< .001$, $r=.55$, 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 ($z=-.734$, $p=.461$, $r=.098$, BF=.38) between those who had their right hand stimulated (Mdn=5, IQR=4.5-6) compared the left hand (Mdn=4.75, IQR=4-6).

Finally, we wanted to see if 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 and hand the human hand ($z=-.725$, $p=.469$, $r=.07$, BF=.27). Thus, the monkey hand was successful in eliciting an illusion of ownership to a statistically equivalent degree as the human hand in six and seven year olds.

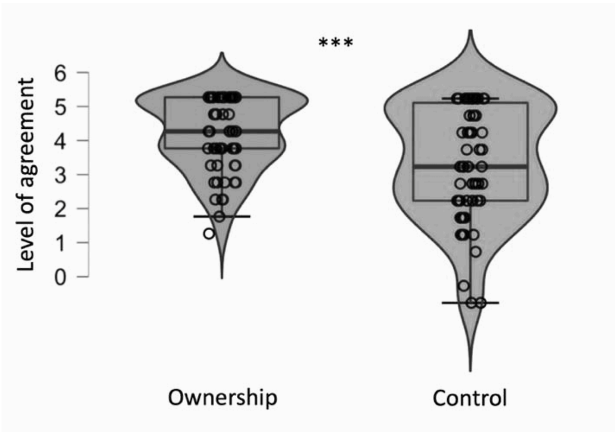

Fig.7.

Ownership and control question. Children reported significantly higher levels of agreement for the ownership compared to the control question. ***=p<.001.

Experiment Three Discussion

The results from experiment three support the prediction that children are responding in accordance to their perceptual experience of the illusion and not simply complying with the experimenter. Moreover, no significant difference in the illusion between left and right hands, (supported by a relatively low BF and a small effect size), suggests there is no meaningful difference in the illusion based on hand laterality in children.

These results also support our prediction that children will 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 to adults, predicting that adults will report lower ownership compared to 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 Four

<u>Participants</u>

Children: Total: N=84 (40 males, 44 female) mean age = 8.5 years, range=5-12, SD=1.89 years. High-fantasy: N=32 (14 males, 18 female) mean age=8.5 years, range=5-11, SD=1.69 years. Low-fantasy: N=52 (26 males, 26 female) mean age = 8.7 years, range = 5-12, SD=2.01 years. Adults: N=42 (6 males, 37 female) mean age=22 years, range=18-38 years, SD=4.5 years.

Materials and measures

Creative Experiences Questionnaire (CEQ): The CEQ is a brief 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 (IC) interview: To delineate between children with high and low fantasy we used an interview protocol to assess the presence (or history) of an IC in children (Davis et al. 2014) originally based on an interview assessment by Taylor & Carlson (1997). Children were asked if 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 them. A lateral set-up, in which the real and fake hands were displaced along the horizontal plane was chosen for logistical purposes. Participants were asked to keep their hand still whilst watching the fake hand as the experimenter then brushed both the real hand and the corresponding location of the fake hand for one minute. 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 of the children completed the IC interview before taking part, the other half were asked afterwards. Our adults complete the CEQ, half before the RHI and half afterwards.

Experiment Four Results

Firstly, we wanted to examine whether children and adults experienced the illusion over a monkey hand so we conducted Wilcoxon signed ranks tests between 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 (Mdn=5, IQR=3-6) compared to asynchronous Mdn=2.5, IQR=1-4) touch ($z=-5.43$, $p<.001$, $r=.59$, 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 to the control question in children and adults using Wilcoxon signed ranks tests. Children gave greater agreement to the illusion (Mdn=5) compared to control (Mdn=4) questions ($z=-3.74$, $p< .001$, $r=.41$, BF=373). The equivalent comparison for adults was non-significant ($z=-.223$, $p=.837$, $r=.03$, BF=.18), with agreement for the ownership (Mdn =3) and control (Mdn=3) questions 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 the control question. Although this may be a result of increased compliance in our adult sample. In context of results from the previous studies and the relatively low means (corresponding average neutral response rather than an affirmation of the illusion) compared to 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, the children were divided into two groups, those reporting an IC (n=32) and those who did not (n=52). An independent samples t-test was then used to determine if there was a difference in age between the two groups. No significant difference was found ($t(79)=-.452$, $p=.653$, d=, BF=.26).

Next, to compare the strength of the illusion (level of agreement to the illusion question) between 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, child without IC, adult). A significant difference was revealed for the ownership question ($X^2(2)=8.34$, $p=.015$, $\varepsilon^2= .07$). Follow-up Dwass-Steel-Critchlow-Fligner pairwise comparisons revealed that low imaginary children (Mdn=5) had higher ownership scores compared to adults (Mdn=3) (W=-3.75, $p=.02$, BF=3.16). There was no significant difference between high and low-fantasy groups for children (W=.207, $p=.988$, BF=.23). The difference between adults and the high-fantasy children approached significance (W=3.2, $p=.061$, BF=2.45), with the high-fantasy children reporting stronger illusions (Mdn=4) compared to 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, child without IC, adult) revealing no significant effect of group ($X^2(2)=2.37$, $p=.31$, $\varepsilon^2= .02$).

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 ($r(43)=.038$, $p=.810$).

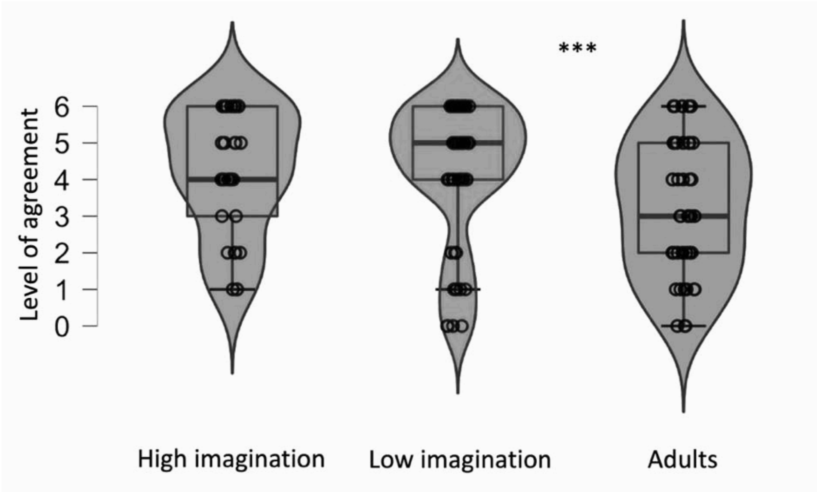

Fig.8.

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 adults. The difference between the children with high imagination and adults approached significance. *** = p<.001.

Experiment Four Discussion

The results from experiment four suggest that children experience a stronger illusion for the monkey hand than adults. However, high-fantasy children reported statistically equivalent ownership scores when compared to 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 to low-fantasy children and adults. Other high-level cognitions have previously been related to strength of the RHI (Mussap & Salton 2006; Marotta et al. 2016). 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 study is that we did not compare the monkey hand to the humanlike hand, the difference between which is likely to be predominantly driven by high-level constraints. On a related point, because we did not compare directly illusion strength for a monkey and human hand in adults we cannot fully discount the possibility that the non-significant 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 this statistical equivalence between ownership and controls scores is likely to reflect a reduced illusion.

General Discussion

The current study investigated high-level contributions to feelings of body ownership in children compared to adults across four different experiments utilizing variants of the rubber hand illusion (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 to adults for subjective feelings of ownership. Specifically, adults showed reduced feelings of ownership compared to children over hands that were incongruent compared to their own in terms of visual appearance (small and fantastical hands). Our Holes Task however, in which participants made judgments about the size of hole they could fit their hand through after illusion induction over both small and large hands, revealed no significant difference between children and adults, both showing effects of the illusion. Although children selected larger hole sizes relative to their actual hand size compared to adults at baseline and 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 so can more readily accept greater changes to their body representations compared to adults (i.e. accept more unrealistic hands as their own in the RHI).

Our results support previous findings demonstrating 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 was not directly replicated in experiment two (Bayesian statistics were inconclusive), however, children had stronger illusions than adults for the small but not the large fake hand. This difference in our findings might be due to the nature of the task. In experiment two, participants were providing subjective reports of the illusion at illusion onset, which may not be as developed as after experiencing the illusion over a longer period of time. Botvinick & Cohen (1998) found that illusion strength (indexed by proprioceptive drift) increased as duration of illusion induction increased. Therefore, this enhancement of illusion strength may not occur to the same degree in adults with a small fake hand compared to an adult sized fake hand, but illusion strength at the initial illusion onset are more equivalent. Additionally, illusion strength in experiment two only measured ownership, whereas experiment one considered ownership and referral of touch. Whilst 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 to 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.

Whilst 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 isn't 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 as 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 five for the current study and because it was portable, the task was also highly suited to our testing environment. Future variations of the Holes Tasks 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 towards 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, adults would be expected to experience stronger illusions for the large hand compared to children, rather than demonstrating statistically equivalent effects. An alternative explanation is that even though both fake hands differ significantly in size compared to our children's actual hands, this is not to the same extent as the difference between the adults and small fake hands. However, we also found that it is the age of the child 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. Additionally, in experiments three and four we used a monkey hand. This fake monkey hand was equally implausible for both children and adults (or even more implausible for children as 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 experiment, still resembles a human hand in terms of the overall features and shape. 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 a greater flexibility of body representation to adapt to rapid body changes, this may not be developmentally optimal for non-corporeal 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 and colleagues (2013), who did not include control questions. Control questions are important in body illusion studies, as they attempt to control for demand characteristics (Botvinick & Cohen 1998), therefore, in experiments three and four we included a control question. Greater agreement for the illusion compared to control question in both experiments suggests that the ownership responses do reflect the illusion and not a propensity to agree.

However, not all of our results can discount compliance. In experiment two 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 et al. 2019). Therefore, very fast responses may 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 not just governed by high-level processing, but also multisensory integration. Therefore, inter-individual differences in weighting of multisensory information, such as the relative weighting of vision vs. proprioception may also influence feelings of ownership towards any non-corporeal object, realistic or not. Future studies should aim to examine potential relationships between fantasy proneness and a relative difference between illusion strength for a fantastical and humanlike hand. There are also limitations in the way we have measured fantasy in children. Our samples were recruited at public engagement events and so, although when testing each child there was an attempt at privacy, they may have felt embarrassed reporting ICs, especially older children. Indeed, our percentage of children reporting ICs was lower than studies examining similar age ranges (Pearson et al. 2001; Taylor & Mottweiler 2008). Also, 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 not subject to the same experimental control as lab studies. However, we were able to replicate our key findings across different experiments. Additionally, 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 in adolescence (Sánchez-Bernardos & Avia 2006) which may relate to onsets of psychopathologies that most commonly occur during this time (Fossati et al. 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 to adults, which may be driven by a less rigid representation of what the own body looks like. We suggest that this increased flexibility of body representations in 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) is 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.

Declarations

Not applicable

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