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Alice in Wonderland: The effects of body size and movement on children's size perception and body representation in virtual reality

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ABSTRACT

Previous work shows that in adults, illusory embodiment of a virtual avatar can be induced using congruent visuomotor cues. Furthermore, embodying different-sized avatars influences adults' perception of their environment's size. This study ($N = 92$) investigated whether children are also susceptible to such embodiment and size illusions. Adults and 5-year-old children viewed a first-person perspective of different-sized avatars moving either congruently or incongruently with their own body. Participants rated their feelings of embodiment over the avatar and also estimated the sizes of their body and objects in the environment. Unlike adults, children embodied the avatar regardless of visuomotor congruency. Both adults and children freely embodied different-sized avatars, and this affected their size perception in the surrounding virtual environment; they felt that objects were larger in a small body and vice versa in a large body. In addition, children felt that their body had grown in the large body condition. These findings have important implications for both our theoretical understanding of own-body representation, and our knowledge of perception in virtual environments.

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Introduction

Representing one’s own body as distinct from other objects in the environment (Bermúdez, 2005) is thought to result from sensory information about the body, including visual, tactile, and proprioceptive signals (Blanke & Metzinger, 2009). The development of own-body representation is challenging because children must “keep track” of a body that is constantly changing and growing while their sensory systems also change substantially (de Klerk et al., 2021). Because of this, it is proposed that children have increased plasticity in own-body representation (de Klerk et al., 2021; Dewe et al., 2021). Insights into this area are important not only from a theoretical standpoint but also from a practical one because illusory embodiment of virtual bodies has potential applications in education (Hamilton et al., 2021), entertainment, and therapy (Won et al., 2017).

Bottom-up cues to body representation

The foundations of adult-like body representation are laid down early, with looking-time paradigms showing that infants as young as 5 months are sensitive to cross-modal correlations between visual feedback and either their own movements or felt touch (Bahrick & Watson, 1985; Filippetti et al., 2013). Despite this sensitivity to multisensory correlations, it has long been suggested that explicit self-awareness only develops later, at around 18 months of age (Bischof-Köhler, 2012), when mirror self-recognition and personal pronouns emerge (Brooks-Gunn & Lewis, 1984; Lewis & Ramsay, 2004).

Beyond the first 2 years of life, children are better able to respond verbally regarding their experiences, and studies during the primary years suggest that there is substantial experience-driven change in own-body representation at this age (de Klerk et al., 2021). This is often shown using bodily illusions where multisensory signals are manipulated to induce illusory embodiment over bodies or body parts other than one’s own. (Here *embodiment* is a common umbrella term that covers feelings of ownership or agency over a body and the perceived position of one’s body.) The best-known bodily illusion is the rubber hand illusion (RHI; Botvinick & Cohen, 1998) in which a fake hand is stroked at the same time and location as the participant’s own occluded hand. This congruency leads to embodiment of the fake hand. Likewise, researchers evoke illusory ownership of a full body by using motion capture to give participants a first-person perspective of a virtual body that moves spatially and temporally congruently with their own (Peck et al., 2013). These illusions can be conducted with body parts or with a whole body in the full-body illusion (FBI). In adults, embodiment ratings in all versions are significantly higher after congruent experiences than after incongruent experiences, suggesting that visuotactile congruency and visuomotor congruency are important cues to own-body representation in adults.

In children, these illusions likewise show that children aged 4–13 years use multisensory correlations to determine ownership of a body part. In the RHI, children experience an adult-like effect of visuotactile congruency on embodiment of a static hand (Cowie et al., 2013, 2016; Gottwald et al., 2021; Greenfield et al., 2015) and an adult-like effect of visuomotor congruency on the embodiment of a moving hand (Dewe et al., 2021). However, children younger than 9 years also show very exaggerated shifts in perceived hand position toward the fake hand regardless of congruency (Cowie et al., 2013, 2016; Filippetti & Crucianelli, 2019; Gottwald et al., 2021) and show some embodiment over nonhuman forms (Dewe et al., 2021). Therefore, visual capture is a particularly strong cue to embodiment for young children: the sight of the body in peripersonal space seems sufficient to evoke some embodiment of it even when that is also regulated by multisensory congruency.

This is particularly pronounced in the case of whole-body ownership. During hand illusions, participants still have “grounding” cues from the rest of the body; hands are also very prominent in the visual field from infancy (Fausey et al., 2016). Therefore, and in contrast to the early effects of visuotactile congruency for hands, children tended to embody a displaced static full-body irrespective of congruency, the effects of which steadily increased from 6 to 11 years of age (Cowie et al., 2018).

When slightly older children (8–12 years) viewed a moving virtual body from a first-person perspective (Weijs et al., 2021), visuomotor congruency did modulate ownership ratings; however, agency and affective responses were high in all conditions. Due to their different designs, these studies are difficult to compare, but visual capture again emerges as a powerful factor in children's own-body representation; in these whole-body illusions, multisensory correlations appear to regulate this effect only later during the primary years.

This work suggests several important directions for the current study in terms of understanding children's bottom-up multisensory cues to own-body representation. First, it is important to further investigate visuomotor congruency in children's embodiment; there are few existing studies with somewhat divergent results (Dewe et al., 2021; Weijs et al., 2021), moving bodies represent our most typical form of experience, and dynamic virtual embodied experiences are increasingly used in virtual reality (VR) applications. Second, we need to understand how whole-body ownership in particular emerges during childhood because existing data suggest that it may be more malleable than hand ownership. Finally, existing work suggests that the use of multisensory cues for own-body representation is developing, but not yet adult-like, during the primary years. Therefore, it is important to establish how multisensory cues ground own-body representation during early childhood. We suggest 5 years as a sensible age to examine; this is younger than in previous visuomotor studies and is the youngest age at which verbal responses have been elicited from participants in bodily illusion studies (Cowie et al., 2013) and an age at which children respond well to fully immersive VR (Negen et al., 2017).

Top-down cues to body representation

Bottom-up cues to embodiment are only part of the story of developing own-body representation. Adults also rely on top-down cues such as mental models of body form or size. For example, adults do not embody a wooden block even with congruent visuotactile stimulation (Lenggenhager et al., 2007). Body size is a less well-understood constraint to embodiment and is of particular interest in the context of bodily growth. The "rubber band hypothesis" (de Vignemont, 2018) states that body size is a key constraint on embodiment, in particular that adults can embody a smaller hand, but not a larger hand, than their own (Marino et al., 2010; Pavani & Zampini, 2007). Yet this literature is largely based on the hand alone. In contrast, adults have been shown to embody whole bodies that are either smaller or larger than their own (Banakou et al., 2013; van der Hoort et al., 2011). This may result from experience of the whole body changing size throughout the lifespan. We argue that for identification of one's own full body, size might not constrain embodiment even in adults.

There is little data on how body size may constrain embodiment in children. Toddlers' "scale errors"—attempting to sit on a tiny doll's chair or in a toy car—are thought to result from an inability to inhibit automatic actions associated with certain objects and might not tell us much about early body size perception (Brownell et al., 2007; DeLoache et al., 2004). Using the RHI, Filippetti and Crucianelli (2019) found that 6- to 8-year-olds were able to embody a larger hand than their own. However, this study did not provide the comparison case of smaller bodies. Likewise, using an augmented-reality MIRAGE box, Newport et al. (2015) showed that 8- to 15-year-olds felt the illusion that their finger had been stretched. From these limited data, our prediction is that children would be at least as willing as adults to accept bodies of different sizes, but we note the need to test this empirically.

When the relative size between one's body and the environment changes, the observer can interpret this in one of two ways: Either the environment has changed size and one's body is the same size or the environment has stayed the same and one's body has changed. Previous investigations have found that participants tend toward the former; participants induced to inhabit a large body through visuotactile stimulation (van der Hoort et al., 2011) or visuomotor stimulation (Banakou et al. 2013) perceived objects in the environment as smaller and vice versa. Importantly, participants anecdotally reported being unaware that the virtual body was a different size than their own; instead, they felt surrounded by a different-sized world. It is important that, despite anecdotal and indirect evidence for this "body-relative scaling" (Linkenauger et al., 2010), to our knowledge there is little detail available from previous studies (Banakou et al., 2013; van der Hoort et al., 2011) on adults' subjective perception of own-body size during these experiences.

Likewise, no study has measured whether children engage in body-relative scaling during bodily illusions. Because young children encode their environment egocentrically instead of using external landmarks (Negen et al., 2017), one might predict that children's size perceptions would be affected by perceived body size to an even greater extent than those of adults. Further investigation into this area is needed.

The current study

Here we aimed to address outstanding questions regarding the bottom-up and top-down cues to own-body representation during childhood across two experiments. Experiment 1 addressed the following three questions. First, does full-body visuomotor congruency affect embodiment in young children? (We chose to examine 5-year-olds, which is the youngest group who have previously been shown to respond reliably to bodily illusions (Cowie et al., 2013). In contrast to other ages (Weijs et al., 2021), in this group there are no data on visuomotor congruency. Based on past work with visuotactile illusions (Cowie et al., 2013, 2018), one might predict differences between this age group and adults.) Second, does body size affect embodiment in children? Third, does body size affect size perception in children? We predicted that children of this age would embody a virtual body regardless of visuomotor congruency or size and that their size estimations would be more affected by perceived body size than those of adults. Experiment 2 was designed to directly address whether changes in body size lead to changes in the perceived size of the environment or of the body itself. We predicted that adults would perceive changes in their environment but not their body and that this effect would be magnified in children.

Across the two experiments, we used fully immersive VR to manipulate the visuomotor congruency (Experiment 1) and body size (Experiments 1 and 2) of a virtual body in 5-year-olds and adults. In Experiment 1, embodiment was assessed using a four-item questionnaire based on previous related studies (Cowie et al., 2018; Gottwald et al., 2021). The effect of body size on size perception was assessed by having participants estimate the size of unfamiliar and familiar objects before and after embodiment manipulations. In Experiment 1, participants estimated the sizes of unfamiliar objects manually, as in Banakou et al. (2013), to measure the implicit effects of the illusion, whereas the sizes of familiar objects were estimated by verbally stating whether the objects looked larger or smaller than usual to measure the explicit effect of body size on size estimation. In Experiment 2, the effect of body size on size perception was assessed using a four-item questionnaire probing the subjective perception of body and environment sizes.

Experiment 1: Effects of body size and visuomotor congruency on embodiment and size perception

Method

Participants

Power analyses were carried out in Erdfelder et al. (1996). Based on a predicted effect size of f = .50 and a desired power of.80, the minimum total sample size was calculated to be 48. Participants were 34 undergraduate students (M_{age} = 21.4 years, SD = 2.0; 14 male) and 34 children (M_{age} = 5.5 years, SD = 0.3; 18 male) living in the North-East of England. Participants were recruited from January 2018 to March 2019 and were tested from February 2018 to April 2019. All participants had normal or corrected-to-normal vision and no motor impairments. This investigation was approved by the local research ethics committee. Informed consent was obtained from all adult participants and the parents of all child participants included in the experiment.

Apparatus

All testing was carried out in a 5 × 9-m lab fitted with 16 Vicon Bonita cameras (Vicon, Oxford, UK). This motion capture system tracks small infrared reflective markers in real time at 240 Hz with millimeter accuracy. This allowed accurate tracking of live movement using "clusters" of reflective markers attached to the arms, legs, and torso using Velcro straps (Fig. 1A). Virtual bodies were created in MakeHuman (free modeling software used to create three-dimensional human avatars; https://www.makehumancommunity.org). The virtual body was mapped onto the participant's body using Vicon Pegasus software, such that the postures of the virtual body and participant's body were matched. The virtual "tea party" environment (Fig. 1B) was created and implemented using Unity (Unity Technologies, San Francisco, CA, USA) and was viewed by participants through an Oculus Rift head-mounted display (HMD; Oculus, Menlo Park, CA, USA).

Design

Virtual body size had three levels and was manipulated between participants. These were small, normal, and large, operationalized as 50%, 100%, and 150% of the participant's body size, respectively. As an index of body size, we took body height, but the whole body was enlarged or reduced, not merely its height (Fig. 1C–E). Proportions for both the small and large body conditions were determined in piloting to be sufficiently noticeable size changes. Visuomotor congruency had two levels (congruent and incongruent) and was manipulated within participants with conditions counterbalanced to avoid order effects. Therefore, each participant experienced one virtual body size with both congruent and incongruent movements. We measured subjective embodiment using a questionnaire

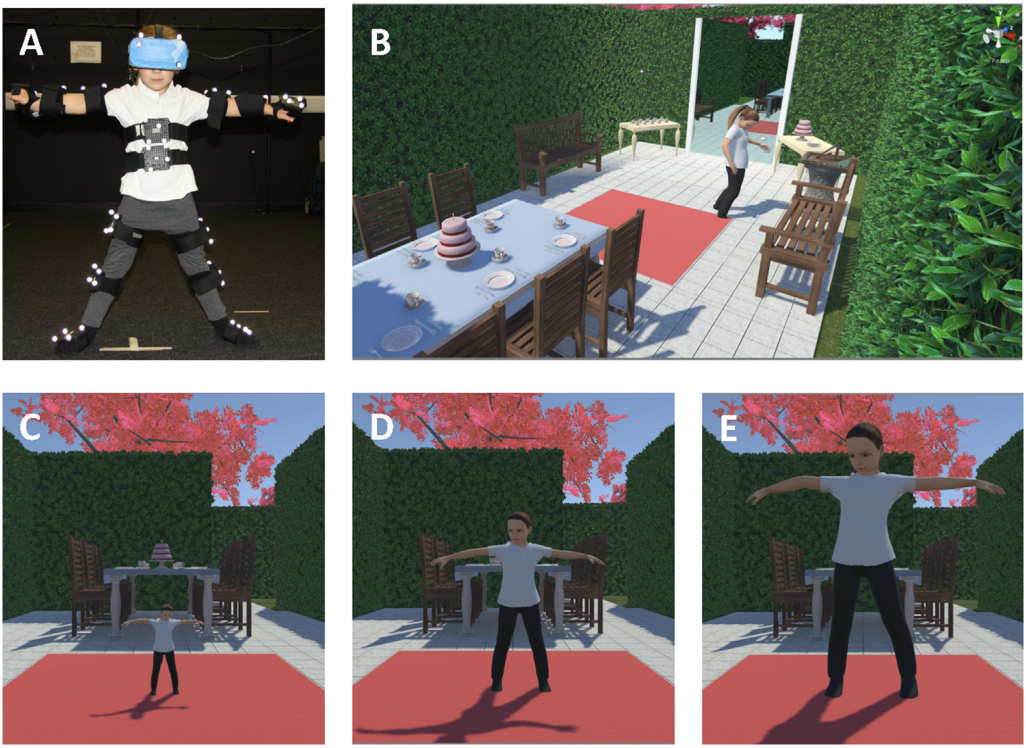

Fig. 1. Method. (A) Child participant wearing motion capture clusters and the head-mounted display. (B–E) The virtual "tea party" scene (B) with the child participant in the small body condition (C), normal body condition (D), and large body condition (E).

displayed within the VR environment. To measure the effect of body size on size estimation, we measured both manual size estimations of unfamiliar objects, and verbal size estimations of familiar objects. All measures are described in detail below.

Procedure

We used a procedure that has been established in literature describing embodiment in adults (Banakou et al., 2013) with seven steps, each described in detail below: (a) setup, (b) size estimation training, (c) baseline size estimations, (d) embodiment, (e) post-embodiment size estimations, (f) embodiment questionnaire, and (g) second embodiment phase, post-embodiment size estimations, and embodiment questionnaire.

(a) Setup. Before entering the virtual environment, participants were shown example real objects to demonstrate the size estimation tasks. The first was a 30-cm white cube and the second was a familiar object (football), 22 cm in diameter. Participants were not told the metric size of the ball but were instructed to remember its size because they would need to recall it later.

Participants' height was measured to the nearest centimeter so that body size could be manipulated relative to participants' actual height. Participants were then fitted with "clusters" of reflective markers, used by motion capture cameras to track participants' live movements, and an HMD to allow participants to view a virtual body from a first-person perspective (Fig. 1A). The experimenter taught participants a well-known standardized set of full-body movements that therefore placed minimal demands on attention and memory (the "hokey cokey" children's dance), which they would carry out while inhabiting a virtual body. During the setup phase, the experimenter took a motion capture recording of these movements lasting approximately 2 min for use in the incongruent motor condition.

(b) Size estimation training. Participants carried out the size estimation phase in a virtual outdoor scene resembling a large empty field. During this phase, participants had no visible body to prevent estimations from being made based on visible hand position. The only objects in the scene were a scoreboard behind participants indicating how many trials had been completed and a white cube "floated" at eye level 30 cm away from participants. Pilots showed that participants found the size estimations difficult in the absence of any cues to size or distance. Therefore, a plastic pole that could not be seen in VR was placed 30 cm in front of participants. They could reach out to touch the pole, giving a distance cue that made size estimations easier. Cubes were one of three sizes: 15 cm, 25 cm, or 35 cm. Each cube size appeared three times in a random order for each participant.

For each cube, participants were instructed to hold their hands out in front of them to estimate the size of the cube as if they were aiming to grasp it. The experimenter manually measured the distance between participants' palms to the nearest centimeter (this could not be easily done through the software). Participants were given feedback with words appearing in VR reading "TOO SMALL," "CORRECT," or "TOO BIG" (estimations were classified with ±20% tolerance so that for a 15-cm cube estimates ranging from 12 to 18 cm were classed as correct). This feedback was also given verbally by the experimenter, for example, "You guessed too big that time! Try a little smaller." Participants attempted the same cube until their estimation was rated as correct, at which point the next cube would appear.

After this, a virtual football the same size as the one presented in real life appeared at the same height and distance as the cubes. Participants were asked whether the football was larger than, smaller than, or the same size as the real-life ball and were given feedback on their response.

(c) Baseline size estimations. Baseline size estimations were carried out in the same outdoor environment as training, again with no visible virtual body. Participants saw three cubes (10 cm, 20 cm, and 30 cm) three times each in a random order. Each was viewed at eye level and at a 30-cm distance for 5 s before disappearing. Participants made their estimates, this time without feedback. Following this, another virtual football of the same size appeared and participants rated its size as before but without feedback.

(d) Embodiment. During the embodiment phase, participants were located in a virtual outdoor environment designed as a "tea party." Participants were given an age- and gender-matched virtual body that was 50%, 100%, or 150% of participants' actual height. The body could be seen both by looking down from a first-person perspective and in a mirror located in front of participants (Fig. 1).

Participants were instructed to carry out the movements taught to them at the beginning of the procedure. In the congruent condition, the virtual body's movements were driven by participants' own live movements. In the incongruent condition, the motion capture recording of participants from the beginning of the experiment was used to move the virtual body incongruently to participants' own movements so that the felt and seen movements did not match. We achieved this by playing the recording from halfway through and then looping it so that it played approximately 1 min behind or in front of participants' live 2-min sequence. Importantly, as visually monitored by the two experimenters in the test room, participants did not try to synchronize their movements with that of the virtual body in the incongruent condition. Often, they were moving their upper limbs while the body moved its lower limbs or vice versa. Visuomotor incongruency therefore was clearly perceptible to all participants. Participants were exposed to the virtual body for approximately 2 min during each embodiment phase.

(e) Post-embodiment size estimations. Post-embodiment size estimations followed the same procedure as at baseline. In this way, we determined whether inhabiting the virtual body had an effect on the perceived size of surrounding objects.

(f) Embodiment questionnaire. Participants were shown a virtual outdoor environment with a large blackboard presented in front of them. The blackboard showed one of four statements (Table 1) adapted from a previous adult article with the same visual scene (Keenaghan et al., 2020). Of the four statements, one related to ownership of the virtual body, one related to agency over the virtual body's movements, and two were control questions designed to refer to the body but not the effects one would predict in the current experiment. Participants indicated their agreement with each statement by moving a line on a continuous scale with their hand. The scale ranged from "NO" (0% agreement) to "YES" (100% agreement). Statements were read aloud by the experimenter. The next statement appeared, after participants gave their response, in a randomized order for each participant. Before the first statement, participants were trained to use the full range of the answer scale by asking them questions such as "How much do you like chocolate?" and "How much do you like mushrooms?".

(g) Second embodiment phase, post-embodiment size estimations, and embodiment questionnaire. Steps (d)–(f) were then repeated for the second visuomotor condition (congruent or incongruent depending on the order for each participant). Children received a small reward for taking part, and adults were awarded course credit if applicable.

Results

We carried out all analyses using IBM SPSS 22 or JASP. The Bayes factor (BF_{10}) is reported for all parametric tests, indicating the likelihood of the alternative hypothesis (H_1) compared with the null hypothesis (H_0). In accordance with Kass and Raftery (1995), BF_{10} of 3.2 or lower is considered extremely weak evidence against H_0, whereas BF_{10} of 10 or higher is considered strong evidence against H_0.

Table 1
Embodiment questionnaire statements.

Statement	Category	Label
While I was doing the hokey cokey, I felt as though the virtual body I saw was my own body or belonged to me	Ownership	Own
While I was doing the hokey cokey, I felt like I was controlling the movements of the virtual body	Agency	Agency
While I was doing the hokey cokey I felt like I had a tail	Control	Tail
While I was doing the hokey cokey I felt like my hair was turning blue	Control	Hair

Data from 6 participants (3 adults and 3 children) were excluded due to technical issues with the virtual environment, leaving data from 62 participants for analysis. Of these participants, 22 (11 adults and 11 children) experienced the normal body size condition, 20 (10 adults and 10 children) experienced the large body size condition, and 20 (10 adults and 10 children) experienced the small body condition.

Questionnaire

We examined the effects of visuomotor congruency and body size on agreement ratings using a mixed analysis of variance (ANOVA) with age (child or adult) and body size (small, normal, or large) as between-participants factors and congruency (congruent or incongruent) and questionnaire statement (hair, tail, ownership, or agency) as within-participants factors. Questionnaire statement was included as a factor in order to identify differences in ownership and agency ratings. Where assumptions of sphericity were violated, Greenhouse–Geisser corrections were applied. A summary of the results is shown in Fig. 2.

There was a significant effect of statement on agreement ratings, $F(2.28, 122.85) = 119.9$, $p < .001$, $\eta_p^2 = .689$, $BF_{10} = 4.608e+46$. Pairwise comparisons using the Bonferroni correction revealed that ratings for the two control statements did not significantly differ ($p = 1.0$, $BF_{10} = 0.113$) but were significantly lower than ratings for both embodiment questions ($p < .001$, $BF_{10} > 1.649e+15$). Agency ratings were significantly higher than ownership ratings ($p = .032$, $BF_{10} = 9.66$). Agreement ratings were further affected by visuomotor congruency, $F(1, 54) = 45.6$, $p < .001$, $\eta_p^2 = .458$, $BF_{10} = 536.18$, with ratings higher in the congruent condition than in the incongruent condition, and age, $F(1, 54) = 23.0$, $p < .001$, $\eta_p^2 = .298$, $BF_{10} = 28.34$, with children's mean ratings significantly higher than those of adults. However, body size did not significantly affect agreement ratings, $F(2, 54) = 0.2$, $p = .815$, $\eta_p^2 = .008$, $BF_{10} = 0.04$.

There was a significant three-way interaction of congruency, questionnaire statement, and age, $F(3, 162) = 18.44$, $p < .001$, $\eta_p^2 = .208$, $BF_{10} = 9.691e+71$. For adults, congruency did not affect agreement ratings for the hair questionnaire statement, $t(30) = -1.04$, $p = .307$, $BF_{10} = 0.31$, or the tail questionnaire statement, $t(30) = -1.73$, $p = .095$, $BF_{10} = 0.72$. Adults' agreement ratings were significantly higher in the congruent condition than in the incongruent condition for both the ownership statement, $t(30) = 8.46$, $p < .001$, $BF_{10} = 6.037e+6$, and the agency statement, $t(30) = 12.77$, $p < .001$, $BF_{10} = 6.228e+10$. However, children's agreement ratings were not affected by congruency for any of the four questionnaire statements [hair: $t(28) = -0.25$, $p = .806$, $BF_{10} = 0.20$; tail: $t(28) = 0.62$, $p = .544$, $BF_{10} = 0.24$; ownership: $t(28) = 0.48$, $p = .638$, $BF_{10} = 0.22$; agency: $t(28) = -0.98$, $p = .337$, $BF_{10} = 0.30$].

Size estimation

We examined size estimations of both unfamiliar objects (manual estimations of cube size) and familiar objects (verbal estimations of football size—"smaller than," "same as," or "larger than" a real object). Two "difference" variables were calculated for both unfamiliar and familiar object size estimations. These variables indicated the change in size estimation from baseline to post-embodiment in both congruent and incongruent conditions.

We first examined differences in unfamiliar size estimations across conditions (Table 2) using a mixed ANOVA with the factors age (adult or child), body size (small, normal, or large), and visuomotor congruency (congruent or incongruent). There were no significant effects of congruency, $F(1, 55) = 0.19$, $p = .665$, $\eta_p^2 = .003$, $BF_{10} = 0.22$, age, $F(1, 55) = 0.50$, $p = .484$, $\eta_p^2 = .009$, $BF_{10} = 0.47$, or body size, $F(2, 55) = 0.27$, $p = .765$, $\eta_p^2 = .010$, $BF_{10} = 0.30$, and no significant interactions.

Because the familiar object size estimation measure produced nominal-level data, we used chi-square tests to investigate any differences in this variable across conditions. We examined the relation between body size and familiar size estimation separately for each age group and movement condition. There was no relation between body size and familiar size estimation in the incongruent condition [adults: $\chi^2(4) = 0.65$, $p = .957$, $BF_{10} = 3.70$; children: $\chi^2(4) = 5.13$, $p = .274$, $BF_{10} = 0.16$] or in the congruent condition [adults: $\chi^2(4) = 5.00$, $p = .288$, $BF_{10} = 0.29$; children: $\chi^2(4) = 1.50$, $p = .823$, $BF_{10} = 0.10$].

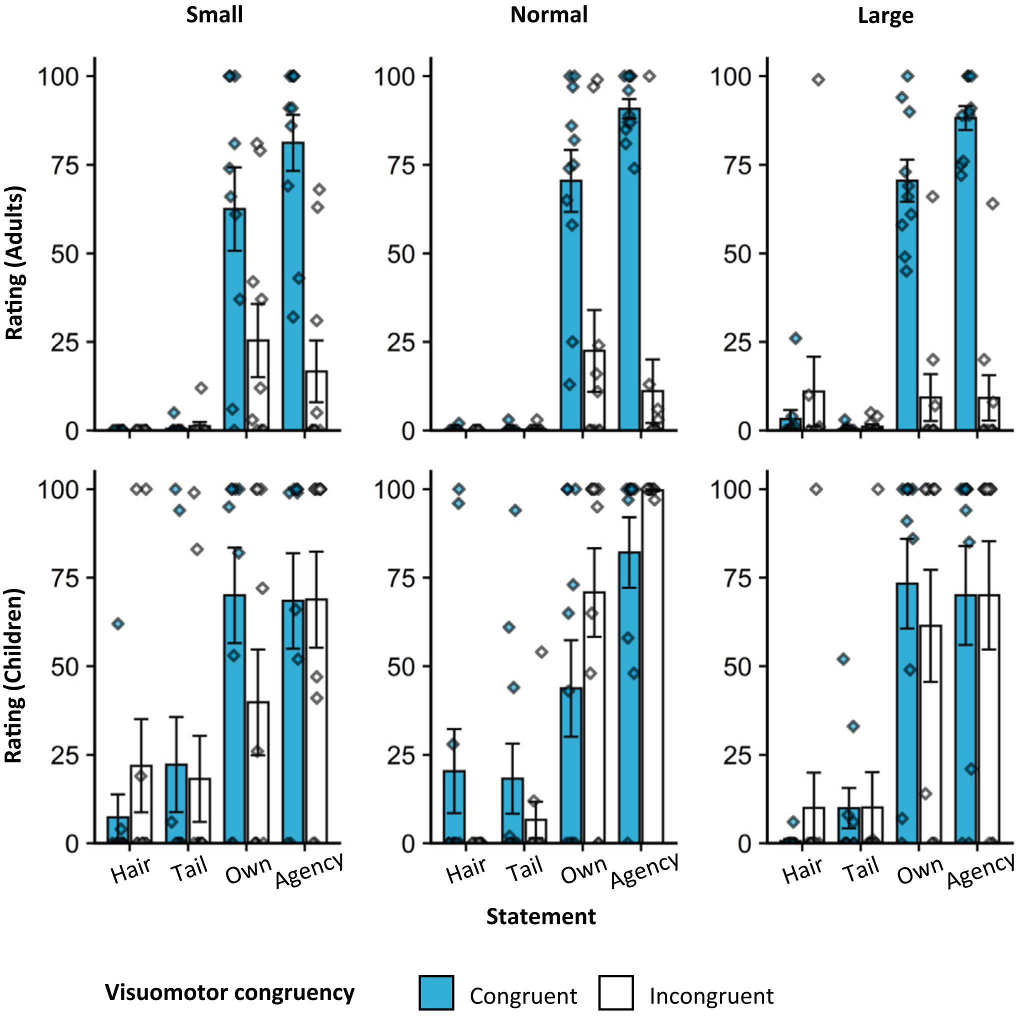

Fig. 2. Experiment 1 questionnaire results. Shown are mean (bars) and individual (scatter points) responses by virtual body size (small, normal, or large), age group (children or adults), and movement congruency (congruent or incongruent) to control (hair or tail) and experimental (ownership or agency) questionnaire items (see Table 1 for details). Error bars represent standard errors.

Table 2
Mean differences in unfamiliar size estimation error (cm) across conditions.

	Body size and age					
	Small		Normal		Large	
Visuomotor congruency	Child	Adult	Child	Adult	Child	Adult
Congruent	−2.2	1.4	1.8	1.7	0.5	0.8
Incongruent	0.2	0.7	0.1	1.0	0.3	0.4

Discussion

Experiment 1 had three main findings. First, we replicated well-established adult findings regarding visuomotor cues to embodiment; that is, adults accept a body that moves congruently with their own, but not one that moves incongruently (Kokkinara et al., 2016; Peck et al., 2013; Steptoe et al., 2013). However, we found that 5-year-olds reported high levels of ownership and agency over the virtual body regardless of visuomotor congruency. This may reflect a primacy of perspective over visuomotor congruency in young children's motor representations, allowing them to accept incongruent multisensory information when the first-person perspective signals that the body is theirs. Because children did give very distinctively low ratings for control questions, we do not believe that this reflects a propensity for children to always agree with the statements given.

Second, we found that adults and children embodied virtual bodies of all three virtual body sizes, supporting previous adult work (Banakou et al., 2013; van der Hoort et al., 2011) and extending the findings to 5-year-olds. Because both adults and children were able to embody virtual bodies of different sizes than their own (both smaller and larger), it appears that neither age group holds strong top-down representations of body size. Anecdotally, children taking part in all conditions consistently referred to their virtual body as "I" rather than using other third-person pronouns.

Lastly, we found no evidence of body size affecting size perception in either adults or children. This is in contrast to previous adult work, which has shown that illusory body size affects perception of the environment (Banakou et al., 2013; Tajadura-Jiménez et al., 2017; van der Hoort et al., 2011). This result was unexpected given that our method closely replicated that of Banakou et al. (2013). The main difference in our procedure was the inclusion of a tactile distance cue to help participants in their size estimations, which may have eliminated any effects of virtual body size. In Experiment 2, we further investigated the effect of body size on size estimation by asking participants about their subjective perceptual experience of their body and the environment.

Experiment 2: How body size affects body and environment size perception

Method

Participants

Power analyses were carried out in G*Power. Based on a predicted medium effect size of $f = .50$ and a desired power of.80, the total required sample size was calculated to be 24. Participants were 12 undergraduate students ($M_{\text{age}} = 19.9$ years, $SD = 1.3$; 10 female) and 12 5-year-old children ($M_{\text{age}} = 5.4$ years, $SD = 0.3$; 2 female) recruited from the North-East of England. Participants were recruited from November 2018 to March 2019 and were tested from December 2018 to April 2019. All participants had normal or corrected-to-normal vision and no motor impairments. This investigation was approved by the local research ethics committee. Informed consent was obtained from all adult participants and the parents of all child participants included in the experiment.

Apparatus

The apparatus was the same as in Experiment 1.

Design

In Experiment 2, virtual body size had two levels (small and large; operationalized as 50% and 150% of participants' body height, respectively) and was manipulated within participants. The order in which body size conditions were presented was counterbalanced to avoid order effects. Subjective size estimations were measured using a virtual questionnaire with a similar structure to the embodiment questionnaire in Experiment 1. In Experiment 2, the virtual body always moved congruently with participants' own body.

Procedure

As in Experiment 1, participants' height was measured to the nearest centimeter in order to accurately manipulate virtual body size. Participants were then fitted with clusters of motion-tracking markers and were taught the same set of movements as in Experiment 1 (the "hokey cokey" children's dance).

Participants were immersed in the same "tea party" virtual environment with a mirror. In each body size condition, participants performed the movements taught to them by the experimenter, which lasted approximately 2 min. After this phase, participants were shown a large blackboard that sequentially showed one of four statements in a random order (statements are shown in Table 3). Participants rated their agreement with each statement in the same manner as in Experiment 1. These steps were then repeated for the second body size condition.

Results

For Experiment 2, we were interested in agreement ratings for each questionnaire statement but not their comparison. Therefore, ratings were examined for each statement separately using four mixed ANOVAs, with each having the within-participants factor body size (small or large) and the between-participants factor age (adult or child). Ratings for each question are shown in Fig. 3.

For the "body smaller" question, there was no effect of body size, $F(1, 22) = 0.08$, $p = .787$, $\eta_p^2 = .003$, $BF_{10} = 0.30$, or age, $F(1, 22) = 0.55$, $p = .464$, $\eta_p^2 = .025$, $BF_{10} = 0.41$, on agreement ratings, and there was no interaction, $F(1, 22) = 0.09$, $p = .767$, $\eta_p^2 = .004$, $BF_{10} = 0.05$.

"Body larger" agreement ratings were significantly affected by body size, $F(1, 22) = 9.55$, $p = .005$, $\eta_p^2 = .303$, $BF_{10} = 7.79$, with ratings higher in the large body condition than in the small body condition. Ratings were not significantly affected by age, $F(1, 22) = 1.88$, $p = .184$, $\eta_p^2 = .079$, $BF_{10} = 0.60$, but there was a significant interaction of body size and age, $F(1, 22) = 7.36$, $p = .013$, $\eta_p^2 = .251$, $BF_{10} = 30.07$. Paired t tests revealed that children rated "body larger" higher in the large body condition than in the small body condition, $t(11) = 3.73$, $p = .003$, $BF_{10} = 14.72$, whereas adults did not, $t(11) = 0.30$, $p = .770$, $BF_{10} = 0.30$.

"Objects smaller" ratings were significantly higher in the large body condition than in the small body condition, $F(1, 22) = 23.29$, $p < .001$, $\eta_p^2 = .514$, $BF_{10} = 2194.41$, but they were not significantly affected by age, $F(1, 22) = 1.19$, $p = .287$, $\eta_p^2 = .051$, $BF_{10} = 0.44$. There was no significant interaction of body size and age for this question according to the p value, although the Bayes factor indicated some evidence of an interaction, $F(1, 22) = 1.54$, $p = .228$, $\eta_p^2 = .065$, $BF_{10} = 809.23$. Investigating this further, adults' ratings were significantly higher in the large body condition than in the small body condition ($t = 5.34$, $p < .001$, $d = 1.54$, $BF_{10} = 136.50$), whereas this difference was marginal for children ($t = 2.18$, $p = .052$, $d = 0.63$, $BF_{10} = 1.61$).

Finally, "objects larger" agreement ratings were also significantly affected by body size, $F(1, 22) = 20.17$, $p < .001$, $\eta_p^2 = .478$, $BF_{10} = 1976.56$, with ratings higher in the small body condition than in the large body condition. There was no significant effect of age on this question, $F(1, 22) = 1.14$, $p = .297$, $\eta_p^2 = .049$, $BF_{10} = 0.42$. Again, although the p value indicated that there was no significant interaction, the Bayes factor suggested otherwise, $F(1, 22) = 2.05$, $p = .166$, $\eta_p^2 = .085$, $BF_{10} = 850.59$. And again, adults rated this question higher in the small body condition ($t = -5.40$, $p < .001$, $d = -1.56$, $BF_{10} = 147.34$), and the difference was marginal in children ($t = -1.83$, $p = .095$, $d = -0.53$, $BF_{10} = 1.03$).

Table 3
Size questionnaire statements.

Statement	Category
When I was at the tea party, it felt as though the body I saw was smaller than my own body	Body smaller
When I was at the tea party, it felt as though the body I saw was bigger than my own body	Body larger
When I was at the tea party, it felt as though objects around me were smaller than normal	Objects smaller
When I was at the tea party, it felt as though objects around me were bigger than normal	Objects larger

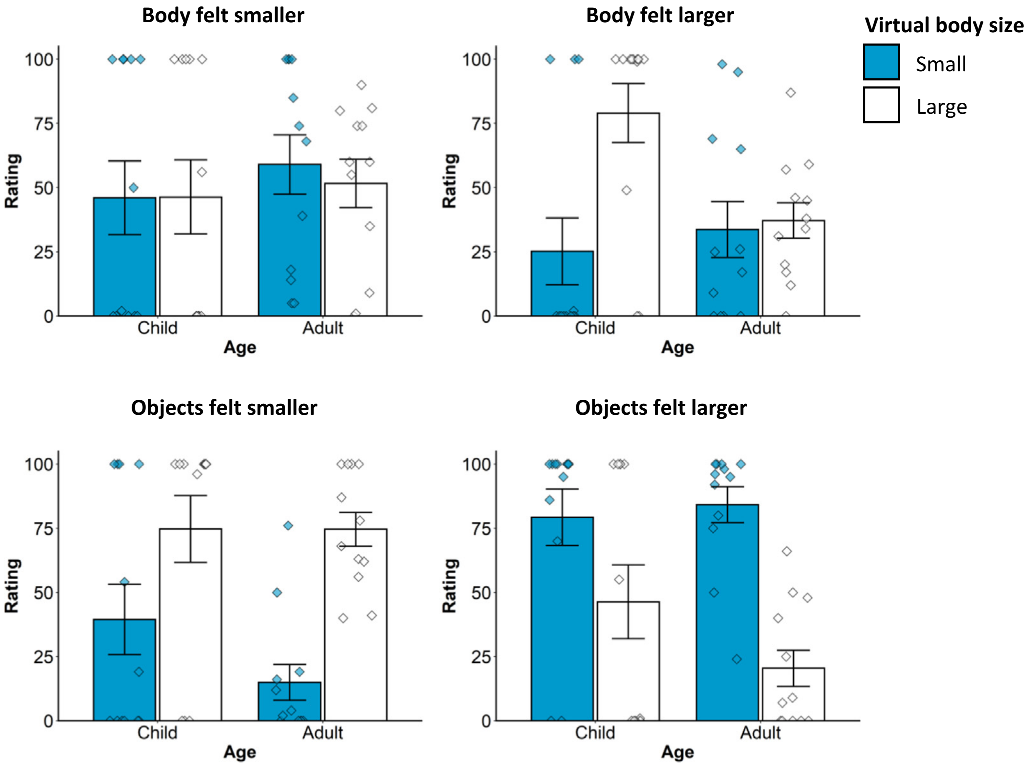

Fig. 3. Experiment 2 questionnaire results. Shown are mean (bars) and individual (scatter points) ratings for questionnaire items "body smaller," "body larger," "objects smaller," and "objects larger" (see Table 3 for details). Results are shown by age (children or adults) and virtual body size (large or small). Movement was always congruent. Error bars represent standard errors.

Discussion

In Experiment 2, we aimed to better understand the perceptual experience of participants when inhabiting a virtual body that was a different size than their own. Specifically, do adults and children perceive their body to have changed size or rather their environment? Here we found that in the small body condition, neither adults nor children reported a change in perceived body size; rather, both age groups reported that objects in the environment appeared larger (although this effect was somewhat weaker in children than in adults). However, in the large body condition, adults did not report a change in perceived body size, whereas children did report perceiving their body as larger. Both age groups also reported that objects in the environment seemed smaller than usual (although again this was slightly more apparent in adults than in children).

In summary, when presented with a virtual environment where the relative sizes of body and environment are different than usual, both adults and children primarily reported that objects in the environment changed size, whereas their own body size remained stable. The notable exception is that children in the large body size condition did report their body as larger than usual. It may be that 5-year-old children are accustomed to their body growing and so are more willing to accept a body size change in this direction. In contrast, neither adults nor children reported their body as smaller in the small body condition, potentially because our bodies do not normally shrink at any age.

General discussion

Here we examined, for the first time, the effect of full-body visuomotor congruency on own-body representation in young children as well as the effect of body size on their own-body representation and size perception. We found that whereas adults showed higher levels of embodiment over a virtual body that moved congruently with their own body than one that moved incongruently, 5-year-old children embodied an avatar regardless of visuomotor congruency. It was also found that both adults and children embodied, to an equal extent, virtual bodies that were smaller than, larger than, or the same size as their own body. Finally, we found that both adults and children reported that objects in the environment were smaller after experiencing a large body and were larger after experiencing a small body. Whereas adults did not report changes in body size in either condition, children did report that their body was larger in the large body condition. These findings and their implications are discussed in more detail below.

The role of visuomotor congruency in embodiment

Adults gave higher embodiment ratings when a virtual body moved congruently with their own movements than when felt and seen movements were incongruent. These results are in accordance with the well-replicated finding that adults rely on the congruency of multisensory cues for own-body representation (Kokkinara et al., 2016; Peck et al., 2013; Steptoe et al., 2013) and therefore provide further support to this idea. Replicating this result in adults provides assurance that the experimental manipulation of visuomotor congruency worked as expected, allowing us to place confidence in the results of the younger group.

As hypothesized, children's embodiment ratings were not affected by visuomotor congruency, as supported by *p* values and Bayes factors. Remarkably, children embodied an avatar even when it moved completely randomly compared with children's own movements, often moving entirely different limbs than participants. It is important to note that these questions are comprehensible to children and have previously produced differential responses from children of this age for changes in, for example, visuotactile synchrony (Cowie et al., 2013, 2016, 2018) or hand posture (Gottwald et al., 2021). We took care in training to have children use the full range of the answer scale, and they successfully did this before testing commenced. As the results show, children did use the lower and upper ends of the scale during the test phases; indeed, the responses were somewhat bimodal, and it may be that a Likert scale would have allowed a more nuanced picture to emerge. Nevertheless, this does not explain the absence of a synchrony effect. Furthermore, in the test session, children's ratings on the critical embodiment questions were always significantly higher than their ratings on the control questions. Therefore, we can rule out the possibility that children responded positively to all questions. Likewise, it is also unlikely that the results were caused by a lack of sensitivity to the visuomotor discrepancy in the incongruent condition. Although young children do show a wider temporal binding window for multisensory cues than older children and adults, this is still on the order of hundreds of milliseconds (Lewkowicz & Flom, 2014) rather than the approximately 1-min discrepancy between proprioceptive and visual cues in the current study. Therefore, it is more likely that the 5-year-olds did notice the discrepancy but that this did not diminish their feelings of embodiment.

This result suggests for the first time that, at 5 years of age, children do not substantially use the congruency of visuomotor cues in embodying a full body when strong perspective cues to body ownership are present. Indeed, in judging whether a viewed body is their own, they discounted large perceptible visuomotor discrepancies to conclude that the viewed body was their own and that they could control its movement. This contrasts with recent work showing that movement synchrony affects ownership over a virtual hand during mid-childhood (Dewe et al., 2021) and over a virtual body at 8 to 12 years of age (Weijs et al., 2021). However, we note that our participants were substantially younger than those in these studies and that we have previously found development from 6 to 11 years of age in full-body embodiment (Cowie et al., 2018). Furthermore, in one of these studies, even at 8 years of age children viewing 1-s delayed movements did show strong threat responses as well as persistently high agency compared with adults (Weijs et al., 2021). Finally, the result is in line with previous research showing that perspective is a very strong cue to own-body representation in adults; merely viewing a body from a first-person perspective can be sufficient to induce a sense of embodiment (Keenaghan et al., 2020; Kokkinara et al., 2016; Slater et al., 2010).

Further work is needed that uses the same paradigm to measure own-body representation across a wide age range of children. This should give a fuller picture of the developmental trajectory of how children weight perspective and movement cues for embodiment, how children might use synchrony in finer-grained ways or when perspective cues point less strongly to ownership, how synchrony might affect aspects of embodiment not measured here (e.g., affective response), how specific embodiment is to one's own body form or to biological motion, and how explicit embodiment responses are linked to developing perceptual sensitivities to multisensory information.

The role of body size in embodiment

We found that the size of a virtual avatar did not alter adults' ratings of embodiment. This supports and extends previous findings that adults embody smaller or larger bodies than their own in congruent multisensory conditions (Banakou et al., 2013; van der Hoort & Ehrsson, 2014; van der Hoort et al., 2011). We can now conclude that adults not only accept bodies of different sizes but also accept these bodies to an equal extent.

The current study also provided the first investigation into the effect of body size on own-body representation in children. Based on the premise that children's bodies are naturally and rapidly changing size during development, it was hypothesized that children would show a similar effect to adults and embody an avatar regardless of body size. The current results support this hypothesis; embodiment ratings did not differ across body size conditions for either age group. One possibility is that rather than feeling that their body had changed size, participants felt that it had moved in depth relative to the mirror. However, this would contradict motor cues indicating a stationary body as well as the results from Experiment 2 indicating that surrounding objects had changed size, and we received no reports of perceived depth or position changes. We conclude that both children and adults perceived different-sized bodies to be their own, basing their judgments on the viewed avatar body rather than on any internal representations of body size.

This finding demonstrates considerable flexibility in body representation for both adults and children, in accordance with the whole-body literature. Adults hold certain top-down representations of body form, meaning that embodiment is restricted by an object's appearance as "body-like"; for example, adults do not embody objects such as wooden blocks and sticks (Lenggenhager et al., 2007; Tsakiris & Haggard, 2005). In contrast, the fact that both adults and children embody avatars of different sizes suggests that own-body representation is not restricted by internal representations of body size. Indeed, van der Hoort et al. (2011) speculated that the range of body sizes that adults are able to embody may be unlimited as long as the body remains in proportion (i.e., basic body form remains the same). The current findings support this view and extend its scope to children as well as adults. Alongside other recent work (Hoyet et al., 2016), the data also fail to support the "rubber band hypothesis" (de Vignemont, 2018), which states that the body map may be stretched but not compressed. Future investigations should aim to identify whether children also hold similar representations of body form as adults or whether they are more adaptable regarding the forms that they can inhabit.

Size perception in different-sized avatars

In Experiment 1, neither children nor adults showed any effect of body size on size estimations of either unfamiliar or familiar objects. Although this effect had not previously been investigated in children, our findings are inconsistent with previous work in adults. Previous findings have shown that inducing illusory ownership over a smaller or larger body than one's own led to an increase or decrease, respectively, in size estimations of objects in the environment (Banakou et al., 2013; van der Hoort et al., 2011), which is referred to as body-relative scaling (Linkenauger et al., 2010). Our result was unusual because the methods were a partial replication of those used by Banakou et al. (2013). However, we did include a touch reference, allowing participants to feel how far away the virtual objects were. This was introduced during piloting because without it participants were unable to give consistent and accurate size estimations even with extensive training. This may have reduced uncertainty to an extent where body size no longer affected size estimations. Indeed, Chen et al. (2018) found that unseen tactile cues to distance provided a sense of size constancy in the absence of other cues.

In Experiment 2, however, questions showed that both children and adults demonstrated evidence of body-relative scaling given that the environment was perceived to be smaller in the large body condition and vice versa for both age groups. These results support the previous findings on size perception from implicit measures like size estimation in adults (Banakou et al., 2013; Linkenauger et al., 2010; van der Hoort et al., 2011). Importantly, this was also the first study to examine the effect of body size on size perception in children. This question was of theoretical interest because, of course, children's bodies are continuously changing size, as opposed to adult bodies whose sizes stay mostly constant. This could feasibly mean that children would not use their body size as a reference due to its lack of reliability. However, we did not find this to be the case. The 5-year-old group responded in much the same manner as the adults, suggesting that they do in fact use body size as a cue to size perception in the environment. However, notably, in the large body condition, children did report their body to have grown, whereas adults did not. We suggest that this could be due to young children being more "tuned in" to their body growth because this is something they must account for as they develop; therefore, they may be more likely than adults to notice such a change. Further work should test a broader age range in order to confirm whether this effect does diminish as body growth slows. This finding was also complemented by the fact that neither adults nor children reported their body to have shrunk in the small body condition. Participants may be less sensitive to changes in body size in this direction because it does not normally occur naturally during the lifespan.

Practical implications

Overall, the current findings demonstrate that the full-body illusion can be elicited in children as young as 5 years and that children embody avatars regardless of visuomotor congruency and body size. We also showed that both 5-year-olds and adults are susceptible to body-relative scaling, whereby their perception of the size of their environment is affected by the size of their embodied avatar. It is important to note that our sample was drawn from a predominantly WEIRD (Western, educated, industrialized, rich, and democratic) population (Rad et al., 2018) given that the North-East of England comprises 92% White British populates, according to the British Office for National Statistics (2009). Therefore, we must be conscious of avoiding overgeneralization of the results. However, our findings add a great deal to our theoretical understanding of the development of own-body representation. Practically, we have also confirmed that full-body motion tracking and immersive VR can be used successfully in young children (see also Weijs et al., 2021). Such technology is being widely used in adults to investigate social interactions (e.g., Peck et al., 2013) and may be useful in physical rehabilitation (Levin et al., 2015). Based on the current findings, it is plausible that these important applications could now be used with children as young as 5 years.

Conclusion

The findings of the current study make a valuable contribution to current understanding of own-body representation and its development. We showed that children embody a moving avatar regardless of its visuomotor congruency, highlighting both the flexibility of motor representations in young children and the potential importance of perspective in children's body representation. We also showed that both adults and children can embody avatars of different sizes, supporting and extending previous findings that body representation is not restricted by representations of body size (e.g., van der Hoort et al., 2011). Although we did not replicate previous findings that body size affects implicit size perception, we did find that both adults and children explicitly report the environment to appear smaller when they inhabit a large body and vice versa, with children also reporting a change in body size in the large body condition. Therefore, we have provided evidence of body-relative scaling in 5-year-olds. Although much is still unknown about the development of own-body representation (e.g., the effect of perspective and importance of body form), the current study provides an essential starting point for future investigations.

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