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## Body representation does not lag behind in updating for the pubertal growth spurt

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### ABSTRACT

Both making perceptual judgments about your own body and successfully moving your body through the world depend on a mental representation of the body. However, there are indications that moving might be challenging when your body is changing. For instance, the pubertal growth spurt has been reported to be negatively correlated to motor competence. A possible explanation for this clumsiness would be that when the body is growing fast, updating the body representation may lag behind, resulting in a mismatch between internal body representation and actual body size. The current study investigated this hypothesis by testing participants ranging from aged 6 to 50 years on both a tactile body image task and a motor body schema task. Separate groups of participants, including those in the age range when pubertal growth spurt occurs, were asked to estimate the distance between two simultaneously applied tactile stimuli on the arm and to move their hand through apertures of different widths. Tactile distance estimations were equal between participants before, during, and after the age range where the pubertal growth spurt is expected. Similarly, Bayesian evaluation of informative hypotheses showed that participants in the age range of the growth spurt did not move through the apertures as if their representation of the hand was smaller than its physical size. These results suggest that body representations do not lag behind in updating for the pubertal growth spurt.

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## Introduction

Most of us can easily perform tasks such as reaching for our coffee while looking at our phone and stepping over a puddle without paying much attention. But for these seemingly simple tasks, you actually need to know quite a lot about your own body dimensions and about the position of your body parts in relation to the objects around you. Most of the time, we are unaware of this. Sensory information is unconsciously combined with mental body representations to perform the movement (Holmes & Spence, 2004). However, as an adult, your body is not changing in size very often and you have had much feedback about its size and form from the experience of moving it many times a day.

Healthy adults are indeed usually competent at moving their body through the world and can adequately change their movements depending on the current possibilities for action (e.g., Cole, Chan, Vereijken, & Adolph, 2013; Day, Wagman, & Smith, 2015) or affordances (Gibson, 1979). Some of your action possibilities are dependent on your body size and form. If you are very slender, you will fit through smaller doorways, and if you are very tall, you will need to be more careful about not hitting your head. However, your body size and form change considerably during your lifetime. This raises the question of how a veridical body representation is updated and maintained when your body is changing. Children in early puberty, when they are in the middle of a growth spurt, are often described as somewhat clumsy (Tanner, 1962). Indeed, Hirtz and Starosta (2002) found that the onset of the growth spurt was linked to an impairment in coordination in 75% (girls) to 90% (boys) of their participants. Visser, Geuze, and Kalverboer (1998) also found that being in a growth spurt was negatively related to motor competence. Starting at 11 years of age, they tested general motor skills of 16 boys, plus 15 relatively clumsy children, every 6 months for 2.5 years. They found that whereas the clumsy child group on average became less clumsy, for the control group the faster children had been growing in height, the worse their motor skills were (see Beunen & Malina, 1988, for a review of similar results). Bisi and Stagni (2016) reported less smooth walking patterns in teenagers that grew faster than in their similarly aged peers, but the difference between both groups on most measures was in fact nonsignificant.

At the same time, strength and speed of movements increase during the growth spurt (Beunen & Malina, 1988), suggesting that this apparent clumsiness does not originate at the level of the muscles. One possible explanation for the decline of motor competence, therefore, could be that updating the body representation during the pubertal growth spurt lags behind physical growth. With a fast growth rate, the body representation may get insufficient time to adapt, resulting in a body representation that is smaller than the actual body. This is actually often suggested in the media (e.g., “Teenagers shoot up so fast that their brains can’t keep up”; British Broadcasting Corporation, n.d.) and has been mentioned in the scientific literature (Longo, Azañón, & Haggard, 2010). Is there any support for this idea? The current experiment aimed to investigate this question while considering that body representation is in fact a collective term for many different concepts (De Vignemont, 2007). Thinking that you are smaller than you actually are does not immediately imply that you will move as if you are smaller than you actually are. The current study investigated both aspects in separate experiments. In body representation research, the mental representations of the body are often divided between *body schema*, the unconscious and constantly updated sensorimotor representations of the body that are directly used for making movements, and *body image*, which groups the more conscious and perceptual representations (Dijkerman & de Haan, 2007; Gallagher, 2005; Paillard, 1999; Rossetti, Rode, & Boisson, 1995). The term *body image* here includes all representations not directly used for making movements (covering all modalities), whereas the same term may be used in specific research areas to describe subsets (such as only visual representations or affective components) and has been used rather ambiguously in general (Tiemersma, 1989).

The current study focused on metric components of body image (i.e., representation of size, length, and width of body parts). Previous research on metric body image during development has mostly used visual tasks such as scaling an image on a computer screen to match the perceived body size (Neves et al., 2017). Results are variable and have shown slight over- and underestimations of body size as well as correct estimations, depending on the specific task, and no systematic differences between age groups (e.g., Gardner, Friedman, Stark, & Jackson, 1999; Gardner, Sorter, & Friedman,

1997; Gardner, Urrutia, Morrell, Watson, & Sandoval, 1990). However, you could solve these visual tasks using a visual memory snapshot of what you look like in the mirror, which is only a small part of your body image. In contrast to vision, tactile perception is inherently bound to the body. Therefore, a more direct method to test metric body image distortions may be by using tactile size estimations. Because the distribution of tactile receptors and the size of tactile receptive fields vary considerably over body parts (Johansson & Vallbo, 1979; Weinstein, 1968), they alone cannot give sufficient information about the distance between two tactile stimuli on the skin. The sensory input, therefore, will need to be combined with a mental representation of the touched body part (Serino & Haggard, 2010; Spitoni, Galati, Antonucci, Haggard, & Pizzamiglio, 2010). This means that if size of the touched body part is smaller in the mental representation than in reality, you will consequently underestimate tactile distances. Tactile distance estimations have indeed been shown to be a dependable measure of metric body image in clinical groups (Keizer, Smeets, Dijkerman, van Elburg, & Postma, 2012; Scarpina, Castelnuovo, & Molinari, 2014) and when using illusions to manipulate perceived body size (De Vignemont, Ehrsson, & Haggard, 2005).

With respect to the body schema, there may be a good argument why a delayed updating of the body representation leads to clumsiness. If you move as if you are smaller than you actually are, you may underestimate how close you get to objects in your environment, allow too little safety margin, and knock into things. On the other hand, because the body schema is responsible for online control of action, it needs to be constantly updated when moving your body (Schwoebel & Coslett, 2005; Wolpert, Goodbody, & Husain, 1998). This makes it unlikely that the body schema is lagging behind during relatively slow changes such as growth. Previous research on the development of the body schema has often used reaching movements (e.g., Gabbard & Caçola, 2014; Gabbard, Cordova, & Ammar, 2007; Ishak, Franchak, & Adolph, 2014; Yonas & Hartman, 1993) but has not found consistent over- or underestimations. For instance, when you ask participants to estimate whether reaching through a small aperture is possible, this gives an indication of how wide they think their hand is. Ishak et al. (2014) showed that children under 7 years old seem to underestimate what aperture size their hand will fit through. Estimated whole body width has previously been investigated in children with developmental dyspraxia, a DSM-5 (Diagnostic and Statistical Manual of Mental Disorders–Fifth Edition) neurodevelopmental disorder characterized by severely reduced motor coordination during childhood, not restricted to the growth spurt, and proceeding into adulthood. Wilmot, Du, and Barnett (2017) asked children with developmental dyspraxia to walk through an aperture and found that they initially underestimated the width needed to pass through, but when actually walking through the apertures, they started turning their shoulders at a larger aperture than their non-clumsy peers.

To summarize, no previous studies have yet looked at body size representations during the pubertal growth spurt or investigated inaccurate body representation as a possible cause of clumsiness in this group. The aim of the current study, therefore, was to bridge this gap in knowledge and compare a wide age range by testing participants between 6 and 50 years old in two experiments.

First, we investigated the accuracy of the tactile metric *body image* by examining the processing of spatial information of touch. In Experiment 1, we asked participants to estimate the distance between two stimuli on the skin (tactile) as well as the distance between two black dots on a paper (visual, as a non-body-related control condition). If indeed the metric body image is updated too slowly when you are growing faster, children experiencing the pubertal growth spurt would be expected to underestimate tactile presented distances compared with younger and older groups. These groups, however, would not be expected to differ on visual size estimations because these estimations do not rely on metric body image.

In Experiment 2, we investigated *body schema* at different ages. We asked participants to move their hand through narrow apertures of varying widths to see whether participants compensated for their hand width at different aperture widths. Reaching through apertures closely resembles the sort of situations in which teenagers might be clumsy (e.g., knocking over a glass of milk at the breakfast table). Based on the literature on clumsiness during a growth spurt (Beunen & Malina, 1988; Hirtz & Starosta, 2002; Visser et al., 1998), it could be expected that children who are in the age range of the pubertal growth spurt underestimate their body size and, as a consequence, think that their hand will fit through an aperture more easily than it actually can. If this is the case, they would be expected to

compensate less on average or start compensating at smaller aperture sizes (and so a smaller compensation threshold) than younger and older groups (before and after the growth spurt, respectively).

## General methods

All participants were recruited at NEMO Science Museum in Amsterdam, a science museum aimed at children approximately 6–12 years old. Through the Science Life research program (<http://www.sciencelife.nl>), the museum offers the possibility to recruit young visitors and their parents for participation in experiments in an experimental room within the museum.

Visitors could sign themselves up for experiments, so we had no control over the sizes of the groups or the male/female ratios. We allowed all visitors to participate in and experience the research. However, we included only individuals between 6 and 50 years old in the experiments because we were interested in body representations at the age of the growth spurt compared with adults and the tasks were too difficult for most children under 6 years old. Participants received no monetary or other compensation for their time. All participants were naive to the purpose of the study and gave their written informed consent prior to the experiment (in the case of minors, their parents gave consent). This study was done in accordance with the Declaration of Helsinki and was approved by the local ethics committee at Utrecht University.

## Experiment 1

### Method

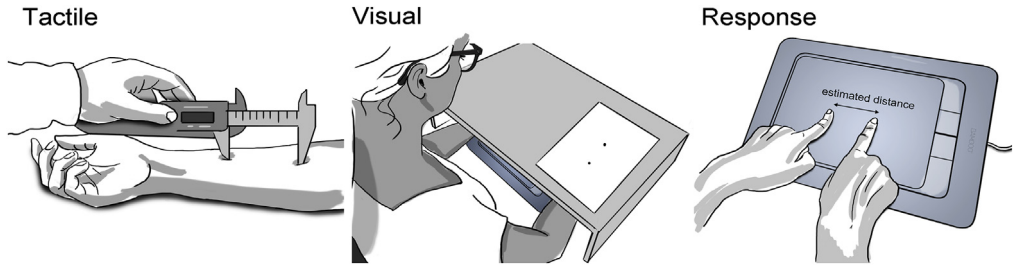
#### Participants

Experiment 1 had 71 participants; of these, 2 were excluded because they were older than the intended age range. The remaining 69 participants were divided into three groups: pre-growth spurt (Pre group), growth spurt (During group) and post-growth spurt (Post group). A growth spurt has been defined in the literature as a period in which an increase of 7–14 cm in length and 8–13 kg in weight is seen annually (Hirtz & Starosta, 2002). The growth spurt in girls (~10–14 years) starts earlier and ends a bit sooner than that in boys (~12–16 years) (Hågg & Taranger, 1982; Rauch, Bailey, Baxter-Jones, Mirwald, & Faulkner, 2004). We have no longitudinal data on the growth of our participants. Therefore, participants were assigned to groups based on their age and gender: Pre group (6–9 years for girls, 6–11 years for boys: 14 girls and 17 boys, mean age =  $8.5 \pm 1.4$  years, mean body height =  $134.4 \pm 8.1$  cm for girls and  $137.1 \pm 10.6$  cm for boys), During group (10–14 years for girls, 12–16 years for boys: 13 girls and 7 boys, mean age =  $12.8 \pm 1.5$  years, mean body height =  $157.9 \pm 8.8$  cm for girls and  $170.6 \pm 11.0$  cm for boys), and Post group (15–50 years for females [girls or women], 17–50 years for males [boys or men]: 12 females and 6 males, mean age =  $39.4 \pm 7.8$  years, mean body height =  $166.9 \pm 7.5$  cm for females and  $183.3 \pm 5.1$  cm for males). Of the 69 participants, 59 were right-handed (Edinburgh handedness questionnaire [Oldfield, 1971], cutoff score of 40), 4 were ambidexter, and 6 were left-handed. All participants had normal or corrected-to-normal vision (self-report).

#### Experimental setup, procedure, and stimuli

Participants first completed the Edinburgh handedness questionnaire (Oldfield, 1971) as well as a form collecting demographic information (gender, date of birth, nationality, finished level of education, and current occupation), if necessary with help from an experimenter. Their body height and under arm length was measured, after which participants were seated next to the experimenter behind a table and the procedure was explained.

The experiment was divided into two blocks in random order: one with visual stimuli and one with tactile stimuli. In the tactile block, participants were asked to perform the tactile estimation task (TET; see Keizer et al., 2011), in which they needed to estimate the distance between the two pointers of a caliper that were pressed simultaneously on the ventral side of the right forearm for approximately 1 s (see Fig. 1). Participants were blindfolded using paper masks to prevent them from making the estimations based on visual information. For the visual block, participants needed to estimate the distance



**Fig. 1.** Experimental setup in Experiment 1. Depicted are the stimuli in the tactile estimation task (left), the visual estimation task (center, also showing wooden cover; the response tablet is below the cover, not visible to the participant), and the response method (right; note that the response tablet is not visible in the tactile condition either because participants wore paper masks).

between two black dots on white A4-sized paper. In both blocks, participants were allowed to respond only after the stimuli had disappeared.

Estimated distances in both the visual and tactile conditions were reported by varying the gap between the index fingers of both hands on a Wacom touch tablet (Model CTH-661). A laptop with Matlab software recorded 100 measurements of the coordinates of both index fingers and calculated the average distance between them per trial. Trials in which participants moved their hand during recording of the estimated distance were repeated. Between trials, participants were instructed to put their arms back on the table, ventral side up, and touch their thumb with their index finger.

Note that in both the visual and tactile conditions, participants had no visual feedback on their responses. During the visual block, both hands and arms and the Wacom touch tablet were covered from view by a wooden shelf. In the tactile block, participants wore paper masks. The visual stimuli were presented on top of the wooden shelf, above the right arm. For both the visual and tactile blocks, the presented distances were 50, 60, and 70 mm, and each distance was presented three times in random order within a block. In total, this yielded 18 trials, and the complete experiment, including instructions, took approximately 10 min.

Note that the tactile estimation task is not a two-point discrimination task, which would measure tactile acuity instead of metric body image. The presented distances in the current study are above the two-point discrimination threshold (Nolan, 1982), and the response requires participants to place the stimuli within a spatial reference frame, which requires including metric body image as was discussed in the Introduction.

#### Bayesian statistics

The current study uses Bayesian statistics. A priori, we considered it likely that children in the age range of the pubertal growth spurt would *not* respond differently from younger and older participants. In contrast to frequentist statistics, Bayesian methods allow for quantification of the evidence that the results from different groups do *not* differ from each other. Therefore, Bayesian statistics was a logical choice for our study.

#### Data analysis

Distance estimations that were more than three times the median absolute deviation from the median of all estimations of all participants for a certain presented distance were considered outliers (Leys, Ley, Klein, Bernard, & Licata, 2013). This resulted in exclusion of 38 of 1242 trials (3.06%). Next, average (mean) distance estimations for each presented distance were calculated per participant and expressed in percentages of the presented distance (so that > 100% is an overestimation). Two participants needed to be excluded because all three estimations for one condition were excluded and no average estimation could be calculated.

Distance estimations were separately analyzed per modality using a Bayesian mixed analysis of variance (ANOVA) in JASP Version 0.8.1.2 (which uses a linear mixed model) with within-factor presented distance (three levels: 50, 60, and 70 mm) and between-participants factor growth spurt group (three levels: Pre, During, and Post). This analysis uses Cauchy priors on effect size, centered on zero

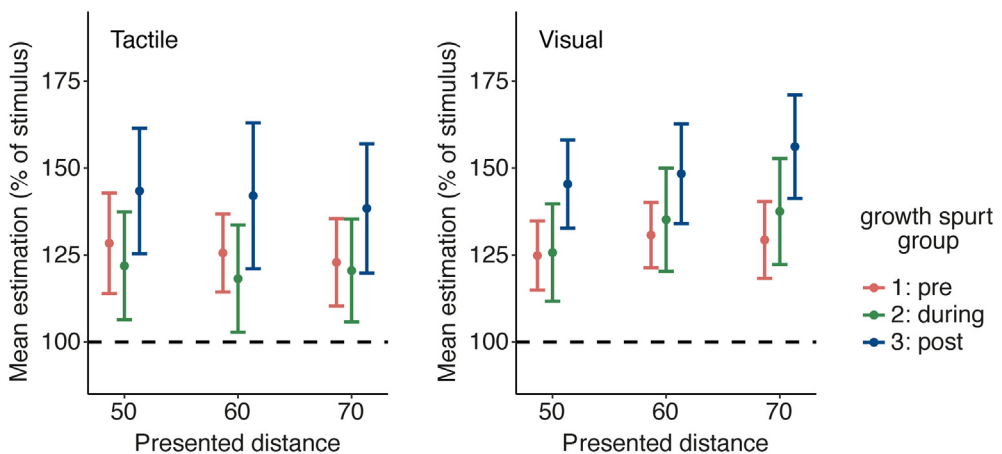
with  $r$  scale .50 for the fixed effects and  $r = 1$  for the random effect of participant. These are considered uninformative priors and are default in JASP. JASP ran 10,000 iterations.

## Results

Estimated distances at the applied distances in the visual and tactile condition were analyzed using Bayesian Presented Distance (3: 50, 60, or 70 mm)  $\times$  Group (3: Pre, During, or Post) mixed ANOVAs. Fig. 2 shows the average distance estimations in the three groups, expressed as percentages of the presented stimulus distance, on both the tactile and visual estimation tasks.

For tactile stimuli, there was evidence in favor of the null model, which had the highest posterior model probability [ $P(M) = 0.2$ ,  $P(M|data) = 0.449$ ]. This means that, given these data, it is most likely that there are no main effects or interactions. Inclusion Bayes factors were calculated for the possible main effects of presented distance and group and their interaction, which give a measure of the amount of evidence for or against an effect of a certain variable. Inclusion Bayesian factors showed moderate evidence *against* an effect of presented distance ( $BF_{inclusion} = 0.225$ ) on tactile distance estimations (in % of presented distance). This roughly means that there was  $1/0.225 = 4.4$  times more support in the data for *no effect* of presented distance than there was *for* an effect of presented distance. There was anecdotal evidence *against* an effect of group ( $BF_{inclusion} = 0.456$ ) and strong evidence *against* the interaction effect ( $BF_{inclusion}$  across matched models = 0.049). On average, stimuli were overestimated at  $126.6 \pm 30.88\%$ .

For visual stimuli, the highest posterior model probability was for a model with a main effect of both group and presented distance on visual distance estimations (in % of presented distance) but no interaction. The  $BF_{10}$  for this model was 34.497 [ $P(M) = 0.2$ ,  $P(M|data) = 0.602$ ]. Inclusion Bayesian factors show moderate evidence for an effect of presented distance ( $BF_{inclusion} = 6.892$ ), anecdotal for group ( $BF_{inclusion} = 1.919$ ), and there was moderate evidence *against* the interaction effect ( $BF_{inclusion}$  across matched models = 0.125). Next, we performed post hoc Bayesian  $t$  tests to investigate the nature of these main effects. There was some evidence *in favor of* average distance estimations in the Post group (estimated mean =  $150.4 \pm 27.22\%$ ) being higher than those in the other two groups (vs. Pre: estimated  $128.3 \pm 25.12\%$ , moderate evidence,  $BF_{10} = 7.159$ ; vs. During: estimated  $132.8 \pm 28.64\%$ , anecdotal evidence,  $BF_{10} = 1.321$ ). There was anecdotal to moderate evidence *against* a difference between the Pre and During groups ( $BF_{10} = 0.330$ ). Furthermore, post hoc Bayesian paired-samples  $t$  tests showed that there was evidence *for* a difference in estimations of stimuli 50 mm (estimated  $130.8 \pm 28.93\%$ ) compared with 70 mm ( $138.7 \pm 32.25\%$ , strong,  $BF_{10} = 26.686$ ) and some indication



**Fig. 2.** Average distance estimations for tactile and visual stimuli in Experiment 1. Distance estimations are given in percentage of presented distance for tactile (left) and visually (right) presented stimuli for all three groups. Error bars depict the 95% confidence intervals. The dashed line at 100% indicates what would have been a correct estimation.

for a difference with 60 mm ( $136.6 \pm 28.84\%$ , anecdotal,  $BF_{10} = 1.487$ ) as well as moderate evidence against a difference in estimation of stimuli of 60 and 70 mm ( $BF_{10} = 0.208$ ).

### *Intermediate discussion, Experiment 1*

The tactile estimation task in Experiment 1 could be solved by comparing the tactile input with the mental representation of the length of your arm, which was not needed for the visual estimation task. Thus, because we expected children in the During group to underestimate their arm size, we expected them to underestimate tactile distances, but not visually presented distances, compared with the Pre and Post groups. However, in summary, the results show that tactile distances were not estimated differently in the three groups. Whereas the Bayes factor concerning this showed only anecdotal evidence against an effect of group, the evidence is pointing in the direction opposite to what was hypothesized. In addition, note that the Bayes factor is not really indecisive, which suggests that we had enough power to investigate our question, although not by a very large margin. For visual stimuli, the Post group overestimated presented distances slightly more than the other two groups, whereas overestimation of visual stimuli with a presented distance of 50 mm was slightly less than that of the two larger presented distances.

Experiment 1 shows evidence against our hypothesis that children in the During group underestimate tactile distances compared with the Pre and Post groups. This gives no support for the idea that their metric body image may lag behind on their growth. Nevertheless, their movements may still reflect a smaller body (part) representation. In Experiment 2, we investigated whether participants in the During group behave in an aperture task as if they are smaller than they actually are, which would indicate that their body schema lags behind.

## **Experiment 2**

### *Method*

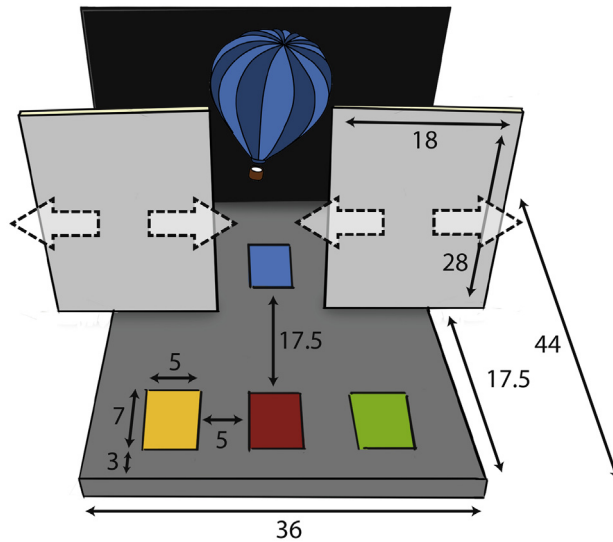
#### *Participants*

In total, 89 visitors participated in this experiment, none of whom participated in Experiment 1. The first 2 participated to optimize the test setting and were excluded from analysis. Furthermore, 5 participants were excluded due to equipment failure, 9 due to an experimenter error, and 2 because they were older than the intended age range. This was quite a hard task for children, especially those younger than 7 years. They often moved their hand from the start position before the beginning of a trial, scratched their nose or arms, moved their hand somewhere other than the target position or knocked into the panels, stopped looking at the monitor at all, or kept turning around to talk to siblings. The experimenter made a note when this was the case. In addition, the data were inspected visually to ensure that hand movements started at the start position and there was no collision with the setup. Participants who failed this in more than half of their trials were excluded. In total, we excluded 15 children because of these reasons.

The remaining 56 participants were divided into three groups, again based on their age and gender: Pre group (6–9 years for girls, 6–11 years for boys: 8 girls and 12 boys, mean age =  $9.3 \pm 1.5$  years, mean body height =  $134.1 \pm 10.2$  cm for girls and  $144.0 \pm 9.4$  cm for boys), During group (10–14 years for girls, 12–16 years for boys: 11 girls and 5 boys, mean age =  $12.4 \pm 1.6$  years, mean body height =  $159.5 \pm 11.3$  cm for girls and  $161.6 \pm 11.4$  cm for boys), and Post group (15–50 years for females, 17–50 years for males: 11 females and 9 males, mean age =  $28.5 \pm 10.9$ , mean body height =  $169.3 \pm 10.1$  cm for females and  $182.4 \pm 9.1$  cm for males). All participants were right-handed (Edinburgh handedness questionnaire scores  $> 40$ ), and all had normal or corrected-to-normal vision (self-report).

#### *Experimental setup and stimuli*

Participants were seated behind a table with a custom-made experimental setup (see Fig. 3). This consisted of a black floorboard with two gray panels ( $18 \times 28$  cm at 17.5 cm from the front edge of the table) that could be moved inward and outward to adjust the width of the aperture between them.



**Fig. 3.** Experimental setup for the reaching movements. Two panels could be moved inward and outward to adjust the width of the aperture between them.

Four colored patches were attached to the floorboard as start (red) and target (green, yellow, or blue) positions for the right hand during the experiment. The aperture setup was placed in front of a monitor (HP Compaq LA2006x) at table level (44 cm from the edge of the table) on which visual stimuli were presented.

Reaching trajectories of the right hand were recorded continuously during the whole experiment at two locations (sensors at the second phalange of the thumb and in between the knuckles of the ring finger and the pinkie) using an electromagnetic motion analysis system (MiniBIRD, Ascension Technology, Shelburne, VT, USA) that recorded  $x$ ,  $y$ , and  $z$  positions at a frequency of 103.3 Hz.

### Procedure

As in Experiment 1, participants first completed the Edinburgh handedness questionnaire (Oldfield, 1971) as well as a form collecting demographic information (gender, date of birth, nationality, finished level of education, and current occupation), if necessary with help from an experimenter. Their body height and width of their right hand (while lifted above the table) were measured, after which participants were seated behind the experimental setup, the procedure was explained, and the sensors were attached.

During each block, participants were asked to pay attention to the monitor on which a sequence of colored drawings of air balloons were presented for 1750 ms each (target colors: green, yellow, and blue), alternated with a drawing of a red air balloon for 1250 ms (start position color). Participants were to cover—with a flat right hand—the colored patch on the board in front of them corresponding to the color presented on the monitor. This resulted in them moving their hand from the red patch to a random target color and back to the red patch 12 times during a block (each target color 4 times). Participants were instructed that the speed of the movement was not important as long as they responded correctly and covered the target patch in time to respond to the next color. They were told not to touch the panels because pilot experiments showed that some participants would otherwise try to smash through the panels instead of moving their hand between them. In the first block, the aperture between the panels was set at 1.6 times the width of the right hand of participants. Between blocks, the experimenter changed the aperture to one of the other seven ratios (0.9, 1.0, 1.1, 1.2, 1.3, 1.4, or 1.5 times the hand width) in a random order. In total, participants completed 8 blocks of 12 trials.



### Data analysis

Because the blue target patch was located behind the panels, participants needed to move their hand through the aperture when a blue air balloon was presented. We analyzed only these reaching movements. The possibility to move to the green and yellow patches was included to keep the task entertaining for young children and to ensure that the movements were not initiated without any conscious effort. For the analyses, this leaves 4 trials per ratio per participant. Trials in which participants failed to reach the target (4.69%), did not start their movement from the start position (0.22%), or knocked into the panels (3.29%) were excluded from further analysis, as were 1.28% of trials due to recording errors.

Three-dimensional reaching trajectory recordings were filtered with a one-dimensional lowpass Butterworth filter (fourth order, cutoff frequency = 20 Hz). The exact point at which the hand passed the position of the aperture on the  $y$  axis for each trial was interpolated using the five data points before moving through the aperture and the five data points after doing so. At this point in the trajectory, the distance on the  $x$  axis between the two sensors was calculated.

*Average hand compensation at the different apertures.* A decrease in  $x$ -axis distance between the two sensors with narrower apertures (and so smaller ratios) would indicate that participants compensated by either rotating the hand or moving the little finger and/or thumb below the hand palm to fit through (which we group under “hand compensation”; see Fig. 4). Scrunched hand width strongly correlates with affordance thresholds in adults (Ishak, Adolph, & Lin, 2008). We analyzed average  $x$ -axis distance at the different aperture widths using a Bayesian mixed ANOVA in JASP (which uses a linear mixed model and 10,000 iterations) with within-factor aperture width (8 levels: 0.9, 1.0, 1.1, 1.2, 1.3, 1.4, 1.5, and 1.6 times hand width) and between-participants factor group (3 levels: Pre, During, and Post) (see Method section for Experiment 1). JASP uses Cauchy priors on effect size, centered on zero with  $r$  scale = .50 for the fixed effects and  $r = 1$  for the random effect of participant. These are considered uninformative priors and are default in JASP.

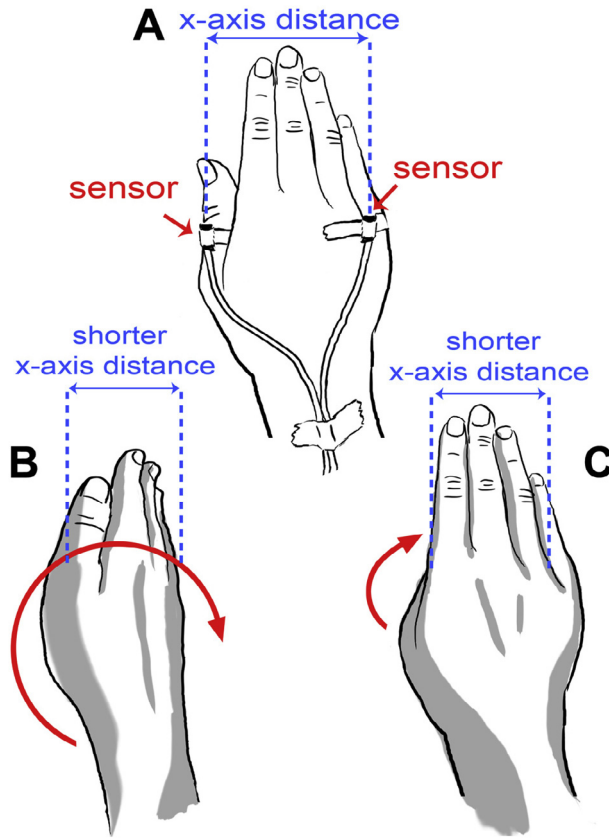
*Compensation thresholds.* The distance between the sensors on the  $x$  axis as a function of aperture width was expected to follow a sigmoid curve (Franchak & Adolph, 2014). With the largest aperture, participants were expected to not compensate or to compensate very little (baseline compensation set at 100%). With decreasing aperture width, at some point participants were expected to start compensating. The compensation threshold (CT) was defined as the aperture width at which the hand compensation would be at 90% of hand compensation at the largest aperture.

For participants who did indeed compensate more at smaller apertures, the data were better described by a sigmoidal cumulative Weibull function than by a linear model in both the During and Post groups, but not in the Pre group (difference in penalized deviance: Pre group, 1.40; During group, -17.1; Post group, -95.9). Therefore, we compared only the CTs of the During and Post groups. For these participants, we normalized the average distance between the sensors at the different aperture widths to the average distance at an aperture width of 1.6 times hand width. Next, we fitted scaled Weibull sigmoidal affordance functions (Franchak & Adolph, 2014) and used the likely fitted distributions to find estimations of the CT. Likely distributions were fitted using JAGS within R. A hierarchical structure allowed for the repeated measures at different apertures within each participant. The  $x$ -axis distance was defined by a Weibull psychometric function as proposed by Kuss, Jäkel, and Wichmann (2005) [Formula (1)]:

$$y = 1 - \exp\left(-\exp\left(\frac{2sm}{\ln(2)}(\ln(x) - \ln(m)) + \ln(\ln(2))\right)\right) \text{ with } x > 0 \quad (1)$$

With location parameter  $m$  and slope parameter  $s$ ,  $x$  is the aperture width divided by the hand width and  $y$  is the  $x$ -axis distance normalized to the  $x$ -axis distance at the largest aperture (1.6 times hand width).

JAGS ran three chains, running 30,000 iterations burn-in, followed by 40,000 iterations with thinning at 25. Separate but identical priors were set for the (hyper)parameters of both groups. Priors on the hyperparameters (hyperpriors) for the mean of location and slope were normal distributions with



**Fig. 4.** Placement of the sensors and possible types of hand compensation. The top drawing shows the hand of a participant from above in normal position (and so no hand compensation) as well as the placement of the sensors (A). The lower two drawings depict the possible ways in which participants may compensate for their hand width if they think that their hand will not fit through the aperture: by rotating the hand (B) or by placing the thumb (C) or little finger (not depicted) under the hand palm. For clarity reasons, the sensors are not drawn in Panels B and C, but the dotted lines indicate their position. As is illustrated, both types of hand compensation will lead to a shorter x-axis distance between the two sensors.

mean 0 and precision 0.001 (broad uninformative priors), and hyperpriors on the standard deviations were uniform distributions from 0 to 1000. Priors on location and slope parameters were normal distributions with mean and standard deviation taken from the corresponding hyperparameters. The prior and hyperprior on location were truncated at zero because the Weibull psychometric function is defined for  $x > 0$  (in addition, you cannot reach through an aperture of zero width). Parameter estimates for both groups were obtained through MCMC (Markov chain Monte Carlo) sampling (see Spiegelhalter & Rice, 2009). All chains converged (potential scale reduction factor estimates for the hyperparameters between 1.00 and 1.01).

The CT was calculated at every iteration for both groups. This was defined as the  $x$  value at which  $y = 0.9$  and was calculated using Formula (2):

$$x = \exp\left(\frac{A}{2sm} + \ln(m)\right) \text{ with } A = \ln(2) * (\ln(\ln(10)) - \ln(\ln(2))) \quad (2)$$

For each iteration, we counted which estimated group CT was higher. We formulated two informative hypotheses (Hojtink, 2011). First, if growing faster results in underestimation of body size, the During group will start compensating at smaller apertures than the Post group, with Pre growth spurt

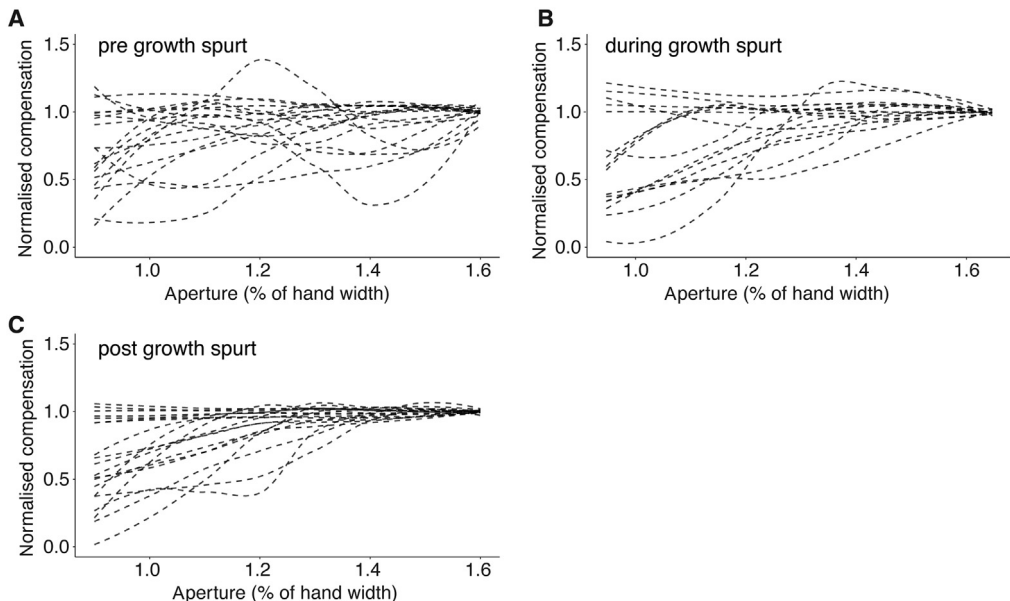
children somewhere in between. Unfortunately, participants in the Pre group could not be compared on CT because their data were better described by a linear model than by a sigmoidal one, which suggests that they do not show a clear threshold at some point. Therefore, Hypothesis 1 (H1) is  $CT_{\text{During}} < CT_{\text{Post}}$ . Alternatively, if the amount of safety margin is related to how much experience you have with moving your body near potential obstacles, the effect will be the other way around. Hypothesis 2 (H2) is  $CT_{\text{During}} > CT_{\text{Post}}$ . We compared the evidence in favor of these hypotheses with an unrestricted null model (using JAGS within R).

## Results

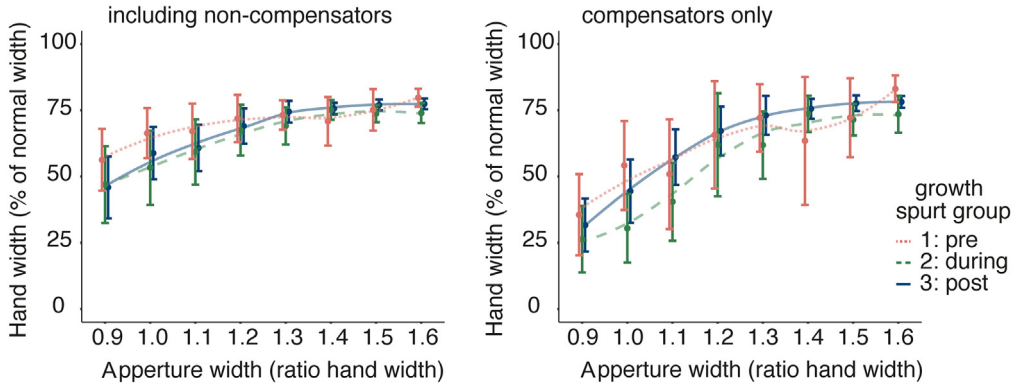
### Average hand compensation

Fig. 5 shows the average hand compensation for each participant at the eight ratios compared with the hand compensation at an aperture width of 1.6 times the hand width (the largest aperture used). All groups already decreased their hand width to about 75% of their normal hand width at an aperture of 1.6 times hand width (see also Fig. 6: Pre group, 79.5%; During group, 73.5%; Post group, 78.2%). This was unexpected and did not happen in pilot testing. As a result, an aperture width of 0.9 times hand width would not require additional hand compensation. Indeed, approximately half of the participants did not further decrease their hand width more than 10% when the aperture width was equal to or smaller than their normal hand width (non-compensators: Pre group, 11 of 19; During group, 8 of 16; Post group, 9 of 20). In the During and Post groups, it seems to be one of two patterns, with the other pattern being the expected increase of hand compensation at smaller apertures (compensators). In the Pre group, patterns are less clear because there is more variance in the movements.

Average hand compensation at the different apertures was investigated with a Bayesian Aperture (8)  $\times$  Group (3) mixed ANOVA. If children in the During group would underestimate what size



**Fig. 5.** Individual hand compensation. Local polynomial regression fits for the individual participants' average hand compensation at the eight ratios in the Pre growth spurt group (A), the During growth spurt group (B), and the Post growth spurt group (C). Hand compensation is normalized to the hand compensation at an aperture size of 1.6 times hand width to increase visibility of different patterns. The black dotted lines are local polynomial regression fits for the individual participants, which were added to increase visibility of different patterns.



**Fig. 6.** Average hand compensation. Shown are average hand compensations at the eight ratios for all three groups for all participants (left) and for only the compensators (right). Error bars depict the 95% confidence intervals. The fitted lines are local polynomial regression fits for the separate groups, which were not used in analyses but were added to increase visibility of the patterns.

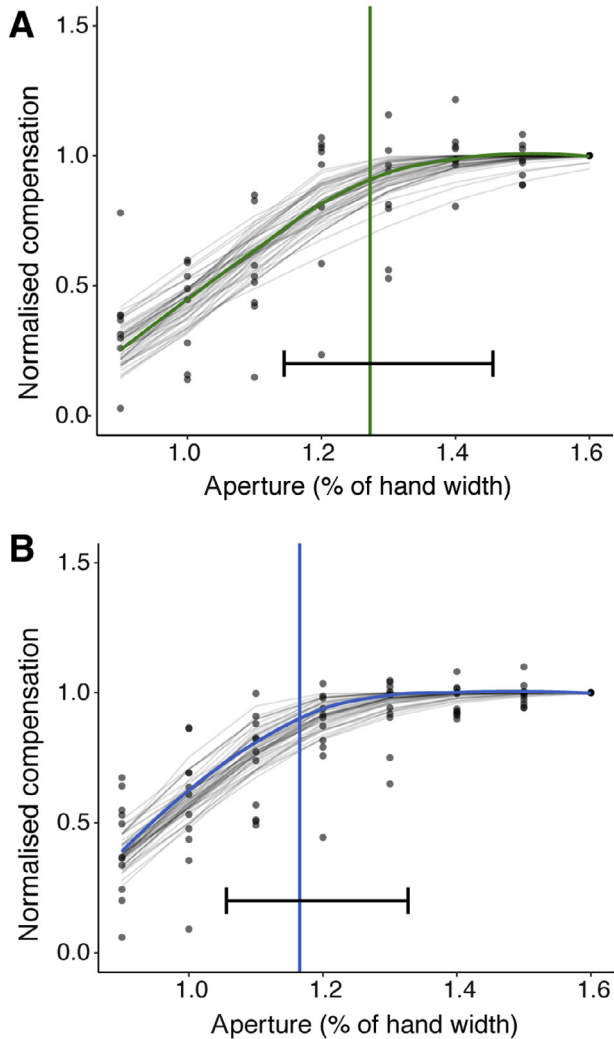
aperture their hand would fit through, you could expect an interaction between group and aperture or perhaps a main effect of group. We performed this analysis twice: once with the non-compensators and once without them. Fig. 6 shows the average hand compensation for each group at the eight ratios expressed in percentage of hand width (not normalized to the largest aperture).

When including non-compensators, a Bayesian Aperture (8)  $\times$  Group (3) mixed ANOVA showed that the posterior model probability was largest for the model with only a main effect of aperture [ $P(M) = 0.2$ ,  $P(M|data) = 0.819$ ,  $BF_{10} = 5.527e+24$ ]. This means that—given these data—it is most likely that there is a main effect of aperture but no other main effects or interactions. Hand width decreased with smaller apertures. We calculated inclusion Bayes factors for the possible main effects of aperture and group and their interaction, which give a measure of the amount of evidence for an effect of a certain variable. The inclusion Bayes factor for aperture was larger than JASP can handle ( $>1e+305$ ), indicating that there was decisive evidence *in favor of* hand compensation being dependent on aperture. There was moderate evidence *against* an effect of group ( $BF_{inclusion} = 0.148$ ) and very strong evidence *against* an interaction ( $BF_{inclusion}$  across matched models = 0.023). When including only the compensating participants, the results were similar (model with aperture effect only,  $BF_{10} = 2.560e+33$ ; aperture,  $BF_{inclusion} > 1e+305$ ; group,  $BF_{inclusion} = 0.438$ ; interaction,  $BF_{inclusion} = 0.285$ ). So, both analyses show evidence for an effect of aperture and evidence against an effect of group or interaction.

#### Affordance threshold

Next, we wanted to test our hypotheses regarding hand compensation in the aperture task more directly by comparing at which aperture the different groups start compensating for their hand width. Because this analysis was specifically investigating CT, we selected only the compensating participants. In addition, because participants in the Pre group did not show the predicted sigmoidal pattern, they are not included in this analysis (see Method section). Fig. 7 shows the average fitted sigmoidal curves and estimated CTs.

Estimated median group CT for the During group was 1.27 (95% confidence interval [CI] = 1.14–1.45) and for the Post group was 1.17 (95% CI = 1.06–1.33). Given the Bayes factor for our H1 ( $CT_{During} < CT_{Post}$ ) over the null model, the support in the data for the During group having a smaller CT than the Post group (which would be hypothesized if participants in the During group moved as if they were smaller than they actually are) was only 0.257, indicating moderate evidence *against* this hypothesis. The Bayes factor for our H2 ( $CT_{During} > CT_{Post}$ ) over the null model was  $BF_{10} = 1.744$ , which indicates anecdotal evidence.



**Fig. 7.** Average fitted sigmoidal models and estimated compensation thresholds (CTs). Shown are fitted sigmoidal models for the During group (A) and the Post group (B), with 50 likely sigmoidal curves in light gray and a thicker line for the final estimated curve. Darker gray dots are individual data points. The estimated CTs for the During and Post groups are indicated with the vertical lines, with the error bars indicating the 95% confidence intervals.

## General discussion

The current cross-sectional study aimed to bridge the gap in the literature on body size representation in teenagers and investigate whether there is evidence in favor of claims that body representation during the growth spurt lags behind. We differentiated between the question of whether children in the pubertal growth spurt *perceive themselves* as smaller than they actually are (metric body image, Experiment 1) and *move* as if they are smaller than they actually are (body schema, Experiment 2).

### *Summary of main results*

In Experiment 1, children in the age range of the pubertal growth spurt did not underestimate tactile distances compared with participants before and after the growth spurt. In all groups, the three presented tactile distances were equally overestimated with approximately 25%. This means that estimations increased with larger applied distances, suggesting that participants in all groups could differentiate between the different applied distances. Therefore, not finding a difference among the three groups was not caused by all participants just reporting random guesses. In our visual control condition, children in the age range of the pubertal growth spurt did underestimate visual distances compared with the Post growth spurt participants but not compared with the Pre growth spurt participants. Our results, thus, show evidence against a lag in at least tactile metric body image during the growth spurt. All groups on average overestimated both tactile and visual distances with the current response method.

In Experiment 2, targeting body schema, we administered a task that most resembles the kind of situations in which you could expect children to be clumsy: moving their hands near potential obstacles, in this case through an aperture. Whereas average hand compensation increased with smaller apertures, showing that participants on average could perform the task and adapt their movements to the changes in affordance, there were no differences among the three groups. There was evidence against the expected interaction between aperture size and group. Moreover, our data show moderate evidence against the hypothesis that children in the growth spurt would start compensating for their hand width at smaller apertures than Post growth spurt participants. There is actually anecdotal evidence that children in the growth spurt start compensating at larger apertures than Post growth spurt participants, which is opposite to what you would expect if children in the growth spurt would move as if they are smaller than they actually are. Therefore, our Experiment 2 shows evidence against a lag in body schema during the growth spurt.

### *Measuring metric body image*

We found no difference between the groups on our metric body image task. This is in line with previous studies on visual body image size in children, which have also shown no difference between different age groups (Gardner et al., 1990, 1997, 1999). For instance, Gardner et al. (1997, 1999) asked children aged 6, 9, and 12 years to adjust the width of visual images of a body until they thought it matched their own body and, in separate trials, their ideal body size. They repeated this after 1 year. Girls showed a discrepancy between their perceived and ideal body sizes already at 7 years of age, with increasingly higher discrepancies in older girls. Overall, however, children tended to be quite accurate in visual body size estimations, with (similar to the current study) no difference between children in the different age groups. Children overestimated, rather than underestimated, their average body size with only around 2%.

Our results in Experiment 1 show large overestimations of the presented distances. We asked participants to respond by indicating a distance between the two index fingers of both hands because the fact that younger participants have smaller hands would have compromised our results if we had used the traditional response method between thumb and index finger. With this new method, we find overestimations as large as 56%. In previous experiments with the TET, average estimations have varied greatly (e.g., Anema, Wolswijk, Ruis, & Dijkerman, 2008; Keizer et al., 2011, 2012; Longo & Sadibolova, 2013; Scarpina et al., 2014). This might be partly caused by differences in which reference frame is employed to encode the response. In the current study, the response distance between the index fingers of both hands depended on the positions of the hands in space, which is not the case for the more commonly used response method between thumb and index finger of one hand. Given the dependency on specific response method, our results do not necessarily indicate that participants in all groups in our study largely overestimated the length of their forearm even though on average estimations were larger than the presented stimuli. These effects of response method on overall over- or underestimation, however, do not restrict between-group comparisons on the TET within an experiment.

Also in other paradigms investigating metric body image, estimations have varied largely between methods. Body image is not one monolithic mental representation but rather depends on the task at hand. Large distortions in localization judgments of body parts are not necessarily reflected when you need to select the image of a body or body part that most resembles yours from an array of possibilities (Fuentes, Longo, & Haggard, 2013). Linkenauger et al. (2015) found that length estimations of body parts are specifically distorted when participants are asked to estimate the length of a body part in amount of hand lengths rather than compare a body part with a neutral object. In addition, Longo and Haggard (2011) showed that when the back of the hand is touched at two points, the perceived distance between them is larger when they were oriented across the width of the hand rather than along the length. However, this was not found when touches were applied to the palm of the hand. Thus, different methods have been used to test metric body image and have yielded different results. This shows that “perceiving yourself as smaller than you actually are” is not as simple a statement as it appears to be. It might, therefore, be possible that a lag in metric body image will be visible in other measures than our tactile distance estimations, although we consider this unlikely because tactile perception is inherently bound to the body and, thus, is particularly suitable for measuring metric body image.

#### *Development of affordance perception and action*

Our body schema task could be considered a classical example of affordance experiments; to solve the task, you need to estimate the match between the body and the environment (Gibson, 1979). If you estimate the body to be too large to make the required action possible, you will need to compensate by changing your movement. The body size estimation here is what we were particularly interested in (and within a body representation framework this would be considered the body schema). Previous research shows that adults are rather good at estimating affordances, especially for movements that are more restrained by the body proportions than by factors such as strength and balance (e.g., walking) (Cole et al., 2013; Day et al., 2015). For instance, errors in estimating whether you would fit through a doorway are made mostly when doorways are only a few centimeters smaller or wider than what you would actually fit through (Franchak, van der Zalm, & Adolph, 2010). In adults, these kinds of affordance estimations are directly influenced by changing online feedback to the body schema (Creem-Regehr, Payne, Rand, & Hansen, 2014). For instance, wearing weights on the wrists influences reachability estimations (Rochat & Wraga, 1997).

Research on the development of affordance perceptions and acting on them shows that when encountering a new affordance situation, infants' behavior reflects their experience with a certain skill such as walking (Adolph, 1995; Adolph, Bertenthal, Boker, Goldfield, & Gibson, 1997; Kretch & Adolph, 2013). Very young children, therefore, may attempt clearly impossible actions because they have had little experience with their own body in interaction with the environment. For instance, just after learning to walk, infants will try to descend impossibly steep slopes. After having some weeks or months of experience with walking, their actions will start reflecting their skill level. (Adolph, 1995; Kretch & Adolph, 2013). Interestingly, infants may also show a different strategy concerning error prevention than adults. For instance, whereas adults will want to avoid getting their hand stuck in an aperture, infants might not consider the penalty of getting stuck as severe (Ishak et al., 2014). The current study did not include children that young, and we did not see more liberal response criteria in our younger participants. But risk assessment, or more specifically the amount of safety margin participants take, may have played a role in our study.

#### *The safety margin in reaching movements*

In our body schema task, children from 6 years of age changed their reach movements to fit through the apertures and so adapted their movements to the affordances given in the task. There was some indication that children in the growth spurt may have higher compensation thresholds (i.e., start reducing their hand width at larger apertures) than people after the growth spurt. Because compensation thresholds were not clear in the pre-growth spurt group, we cannot be sure whether compensation threshold decreases with age or is larger during the pubertal growth spurt. Both

options, however, could have to do with the safety margin you incorporate when moving around (or between) obstacles in your environment. The extent of this safety margin could depend on the years of experience you have had with avoiding obstacles. It has been shown before that children under 12 years old make grasping movements with a larger safety margin (open their hand wider) than 12-year-olds (Kutzt-Buschbeck, Stolze, Jöhnk, Boczek-Funcke, & Illert, 1998). In addition, children under 8 years old used larger safety margins when crawling under or stepping over obstacles (Pryde, Roy, & Patla, 1997), and there is a correlation between safety margin when stepping over obstacles and age until at least 18 years (Corporaal, Swinnen, Duysens, & Bruijn, 2016). The current results show some indication that this effect may extend into the teenage years for manual obstacle avoidance as well.

Visual information may have influenced this safety margin. Berard and Vallis (2006) found that children show more cautious strategies in particular under dimmed lighting when less visual information is available. Because the participants needed to keep an eye on the monitor in the current experiment, this could also have led to more careful strategies in younger participants. Whereas participants typically looked at the monitor to check their next target, then looked at the setup while moving, and redirected their gaze to the monitor once they had reached their destination, this limits the amount of viewing time of the aperture. Alternatively, children in the pubertal growth spurt could temporarily adopt a larger safety margin, for instance, because they are less certain about their movements. Or, in fact, they could adopt a larger safety margin because they experience a temporary drop in motor competence. The cause and reliability of our possible finding of possibly higher compensation thresholds during the growth spurt range remains to be investigated given that we show only anecdotal evidence. However, our results in any case show no clear support for the hypothesis that clumsiness during the pubertal growth spurt is related to children underestimating how much space they need for their hand.

#### *Variability in perceiving affordances in children*

Previous studies have shown that young children scale motor behavior to changes in aperture (i.e., affordances) when reaching (Ishak et al., 2014) or walking (Franchak & Adolph, 2014; van der Meer, 1997; Wilmut & Barnett, 2011) through openings. Ishak et al. (2014) showed that children up to 5 years of age will already show sensitivity and consistency in their attempts similar to young adults when asked to reach through apertures of varying sizes, including ones that are too small. This means that they scale their behavior to the changing affordances (sensitivity), and trial-to-trial variability in participants' decisions (consistency) was comparable among young children and adults. However, children up to 5 years were less accurate; they were quite consistent in underestimating the aperture that they could fit their hand through. Accuracy improved in 7-year-olds and adults. Unfortunately, the study by Ishak et al. (2014) did not include older children and teenagers in their experiment.

In line with this finding, the current study shows similar accuracy in children aged 6 years and up and adults. However, we show less sensitivity in children aged 6–9 years (girls) and 6–11 years (boys) than in the older participants; the hand compensation in the Pre growth participants did not follow a sigmoidal pattern as clearly as the older two groups. It is possible that previous studies had less time pressure on the movements than the current experiment. Moreover, in the current study, participants needed to keep track of the visual stimuli on the monitor as well, directing attention and vision away from the apertures. This could have been harder for younger participants, causing responses to be less influenced by affordances. Distracting situations are actually more common in daily life than an experimental setup in which all you need to focus on is reaching through an aperture. You would, for instance, try to grab a glass of milk amid a cluttered breakfast table while discussing the day ahead with your partner (or sister, mother, etc.). Still, even in many controlled experimental body schema tasks, highly variable performance is seen more often in younger children. Huang, Ellis, Wagenaar, and Fetters (2013) showed that children aged 3–5 years start picking up an object with two hands instead of one hand at the same object size (in ratios of hand size) as adults but that children are more variable; they switched between using one and two hands before the critical ratio, whereas adults did not. Similar to our findings, Hackney and Cinelli (2013) could not estimate an affordance threshold for children aged 7 and 8 years walking through apertures due to high variability in strategy between participants but also between trials. They suggested that this indicates that children may be more



affected by dynamic factors (e.g., movement control) than by geometric measures (Hackney & Cinelli, 2013). In line with this idea, van der Meer (1997) found that when asked to walk under a barrier, children aged 4 and 5 years were more variable than adults and, for instance, changed how much they ducked or whether they were running or walking. Our findings indeed show quite variable hand compensation in particular in the youngest participants in response to the affordances presented by the different apertures.

### *Is there an increase in clumsiness during the growth spurt?*

To summarize, our results show no evidence for the claim that clumsiness during the pubertal growth spurt may be due to the body representations lagging behind the fast physical growth rate. Future studies could aim at investigating more dynamic factors such as muscle control during the growth spurt but perhaps could also reconsider whether, and in what domains, teenagers in the pubertal growth spurt are clumsy at all. The amount of literature investigating clumsiness when growing is small, and effects are quite variable between participants. Beunen and Malina (1988) already reported that a decline in motor competence is something seen in individual cases rather than being characteristic for all children going through puberty. They also suggested that this could be related to differences in motivation and changing attitudes rather than to growth rate. Similarly, it has been proposed that clumsiness during puberty could be mediated by poorer self-esteem and, as a consequence, less active play with peers (Schoemaker & Kalverboer, 1994). Reports on clumsiness during the growth spurt have not been that definite. The drop in performance related to the growth spurt reported by Hirtz and Starosta (2002) could be succeeding the onset of the growth spurt by as much as 1 year. The drop in motor competence in young participants in the experiment by Visser et al. (1998) was explained in relation to growth spurt onset, but as the authors themselves mentioned, this interpretation was based on the hypothesis that this would be an important predictor. It is difficult to separate time effects from growth speed effects, and their data were described as well by a model with linear, quadratic, and cubic time elements (and so no effects of growth spurt) as by the chosen linear effect of time with a negative influence of growth velocity. Finally, the current study found more variable movements during the growth spurt than after it, but even more in pre-growth spurt children. Perhaps it is our perception that changes when children reach puberty. Now that they are changing into adults, we increasingly notice and disapprove of clumsiness they had all along, and their increased limb size means that they do have a larger region of space in which they can knock into things.

## **Conclusion**

Our results show no evidence in favor of a delay in updating either the metric body image or the body schema during the pubertal growth spurt. Children from 6 years of age completed tactile distance estimations similar to adults, showing that this comparison between tactile input and the metric body image is well developed during early childhood. Moving through apertures did not show the pattern predicted by a negative influence of the growth spurt on body schema accuracy. Therefore, our results provide some evidence against the idea that children in the growth spurt perceive themselves as smaller than they actually are and even more convincing evidence against them moving as if their body representation is lagging behind their actual body size.

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