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Object complexity modulates the association between action and perception in childhood

Erez Freud [a,b,c,*], Jody C. Culham [d,e,f], Gal Namdar [g], Marlene Behrmann [c]

[a] Department of Psychology, York University, Toronto, Ontario M3J 1P3, Canada
[b] Vision: Science to Applications (VISTA) Program, York University, Toronto, Ontario M3J 1P3, Canada
[c] Department of Psychology, Carnegie Mellon University, Pittsburgh, PA 15213, USA
[d] Department of Psychology, University of Western Ontario, London, Ontario N6A 3K7, Canada
[e] Brain and Mind Institute, University of Western Ontario, London, Ontario N6A 3K7, Canada
[f] Neuroscience Program, University of Western Ontario, London, Ontario N6A 3K7, Canada
[g] Department of Psychology, Ben-Gurion University of the Negev, Beersheba 8410501, Israel

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ABSTRACT

Vision for action and vision for perception both rely on shape representations derived within the visual system. Whether the same psychological and neural mechanisms underlie both forms of behavior remains hotly contested, and whether this arrangement is equivalent in adults and children is controversial as well. To address these outstanding questions, we used an established psychophysical heuristic, Weber's law, which, in adults, has typically been observed for perceptual judgment tasks but not for actions such as grasping. We examined whether this perception–action dissociation in Weber's law was present in childhood as it is in adulthood and whether it was modulated by stimulus complexity. Two major results emerged. First, although adults evinced visuomotor behavior that violated Weber's law, young children (4.5–6.5 years) adhered to Weber's law when they grasped complex objects ("Efron" blocks), which varied along both the graspable and non-graspable dimensions to maintain a constant surface area, but not when they grasped simple objects, which varied only along the graspable dimension. Second, adherence to Weber's law was found across all ages in the context of a

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* Corresponding author at: Department of Psychology, York University, Toronto, Ontario M3J 1P3, Canada.
E-mail address: efreud@yorku.ca (E. Freud).

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perceptual task. Together, these findings suggest that, in early childhood, visuomotor representations are modulated by perceptual representations, particularly when a refined description of object shape is needed.

Introduction

From birth, the developing visual system derives shape representations that come to support fundamentally different functions such as object perception (vision for perception) and visuomotor control (vision for action). Given the different functional demands associated with these two functions, differential shape representations are thought to mediate these behaviors. Indeed, many previous investigations have revealed a dissociation between the representations that underlie perception and those that underlie action. In particular, whereas perceptual representations are found to be sensitive to contextual cues, shape representations that subserve visuomotor control are considered to be veridical and analytical and, thus, immune to contextual cues (e.g., Aglioti, DeSouza, & Goodale, 1995; Chen, Sperandio, & Goodale, 2015; Ganel, Chajut, & Algom, 2008; Ganel & Goodale, 2003; Ganel, Tanzer, & Goodale, 2008; but see Franz, Fahle, Bülthoff, & Gegenfurtner, 2001, for a different view). A key question concerns the developmental origins of these dissociable representations and whether, over the course of development, representations engaged in action and perception are initially governed by similar principles and then become increasingly dissociated or whether these differential representations are present even from early childhood.

Previous developmental investigations have provided evidence for a rapid emergence of visual representations that support perceptual behaviors (e.g., face perception: de Heering et al., 2008; depth perception: Soska & Johnson, 2008). However, these representations are coarse in nature and are then increasingly refined in the context of a protracted developmental trajectory (e.g., Freud & Behrmann, 2017; Hadad, Maurer, & Lewis, 2011; Kovacs, Kozma, Feher, & Benedek, 1999; Nishimura, Scherf, Zachariou, Tarr, & Behrmann, 2015).

Similarly, visuomotor behaviors develop early in life, and, by the age of 12 months, infants can reach to objects quite accurately (Street, James, Jones, & Smith, 2011). Moreover, the underlying neural network that is engaged in adulthood in visuomotor control has also been observed in 4-year-old children (James & Kersey, 2018). However, as in the case of perception, detailed investigations of grasping behavior in children reveal developmental differences between adults and school-age children (e.g., Kuhtz-Buschbeck, Boczek-Funcke, Illert, Joehnk, & Stolze, 1999; Kuhtz-Buschbeck, Stolze, Jöhnk, Boczek-Funcke, & Illert, 1998).

The focus of the current study was on deriving a more detailed characterization of perceptual and visuomotor representations and their developmental trajectory. To this end, we measured the absolute accuracy of the perceptual or visuomotor behaviors and characterized and compared the representations that underlie perception and action. One dimension of the representations underlying perception and action that lends itself to examination is the variability of behavior. The variability can be well captured by Weber's law, a fundamental psychophysical law according to which an individual's ability to detect changes within a given physical dimension decreases linearly with the magnitude of this task-relevant dimension (Baird & Noma, 1978). Although historically Weber's law was studied with purely perceptual tasks, more recently it has been applied to contrast action with perception by examining whether trial-by-trial variability in perceptual judgments or grasping performance remains constant or is affected by context, namely object size. These investigations revealed that perception and action appeared to rely on differential processing mechanisms. In particular, whereas the perception of object size was relative and adhered to Weber's law, grasping movements violated this fundamental law, suggesting an absolute processing of the graspable relevant dimension (Ganel, Chajut, et al., 2008; Ganel, Freud, & Meiran, 2014; Manzone, Jazi, Whitwell, & Heath, 2017; for an alter-

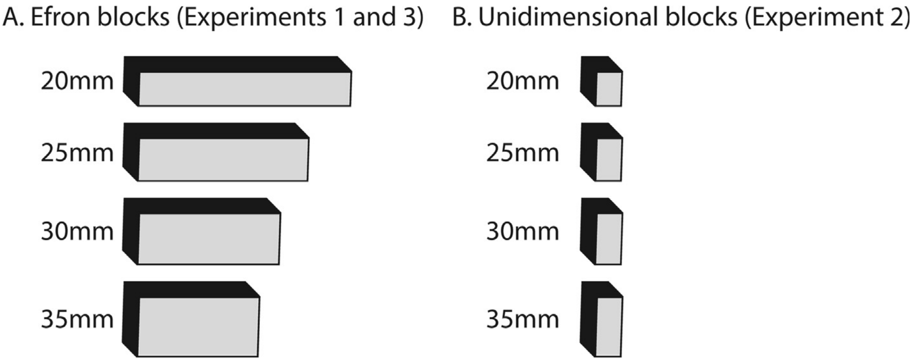


Fig. 1. Experimental stimuli. (A) A schematic illustration of the Efron blocks used as the experimental stimuli in Experiments 1 and 3. Stimuli varied along two dimensions while maintaining a constant surface area. The width (i.e., the task's relevant dimension) of each stimulus is indicated next to it. (B) Unidimensional blocks, used as the experimental stimuli in Experiment 2, vary only along the task-relevant dimension while the other dimension, length, is held constant.

native view, see Smeets & Brenner, 2008). Interestingly, like adults, even at 5 years of age, children's grasping performance violated Weber's law, revealing that the graspable dimension of the object is processed in an absolute (rather than relative) manner even in early childhood (Hadad, Avidan, & Ganel, 2012). Based on these findings, the conclusion reached was that visuomotor representations in childhood are not qualitatively different from those derived by the mature system.

Before we conclude that the grasping behavior of children is comparable to that of adults, closer scrutiny of the previous studies is warranted. An important limitation of the previous studies is that the adherence to Weber's law was examined using objects whose size was manipulated only along the task-relevant dimension (e.g., Ganel, Chajut, et al., 2008; Ganel et al., 2014; Hadad et al., 2012; Heath, Mulla, Holmes, & Smuskowitz, 2011). It remains possible, therefore, that visuomotor representations of these objects might rely on simple, low-level visual cues (e.g., retinal size) that emerge early in the course of development (for a similar argument in the case of susceptibility to visual illusions across development, see Hadad, 2018). In natural environments, however, individuals are required to interact with more elaborate objects that may vary along multiple different dimensions. Interactions with such objects might require a more refined representation of object shape, which might not be available for the developing visuomotor system. This idea of refined sequential, staged development is also consistent with the initial failure on conservation tasks in young children and the subsequent change in behavior, as famously noted by Piaget (Piaget & Inhelder, 1941).

To assess the developmental sequence of shape representations for action and for visuomotor behavior, in Experiment 1 we characterized the movement kinematics of children and adults whose task was to grasp different objects. Importantly, the stimuli could be changed along the graspable and non-graspable dimensions, thereby increasing object complexity (Fig. 1A). Our analyses were designed to assess size sensitivity and to characterize the nature of visuomotor representations (i.e., adherence to Weber's law) as a function of age. In Experiment 2, children grasped objects of different size, but now the difference was restricted to the graspable dimension, rendering them as "simple" objects. Finally, Experiment 3 examined the perceptual aspect by comparing the judgments about object width in the context of a perceptual estimation task.

Experiment 1

Method

Participants

Data were acquired from 15 children aged 5.3 to 6.5 years (*M* = 5.8 years, *SD* = 0.46; 8 girls; 12 Caucasian, 2 Hispanic, and 1 Asian) and 13 adults aged 20 to 27 years (*M* = 22.4 years, *SD* = 2.97; 8 women). The data from 6 additional participants (5 children and 1 adult) were not analyzed because the participants either did not follow the experimental instructions or did not complete the experiment. The data from 1 additional child were excluded because this participant did not exhibit any sensitivity to object size even at the end point of the grasping movement.

All participants were right-handed and possessed normal or corrected-to-normal visual acuity. Adults provided informed consent and received course credit for their participation. Children were recruited from the children's school at the university, and informed consent was provided by their parents or legal guardians. All experimental procedures complied with the protocol approved by the Carnegie Mellon University internal review board.

The sample sizes used in all three experiments were based on two factors. First, previous studies that examined the effect of Weber's law on a range of perceptual and visuomotor tasks included similar numbers of participants (i.e., 6–24 participants; e.g., Ganel, Chajut, et al., 2008; Ganel et al., 2014; Hadad et al., 2012; Heath et al., 2011; Holmes & Heath, 2013; Holmes, Mulla, Binsted, & Heath, 2011; Utz, Hesse, Aschenneller, & Schenk, 2015). Second, a power analysis (Faul, Erdfelder, Buchner, & Lang, 2009; Faul, Erdfelder, Lang, & Buchner, 2007) on the results obtained from a previous developmental study that examined the adherence to Weber's law in childhood (Hadad et al., 2012) showed that the adherence to Weber's law (as demonstrated in the perceptual estimation task) was robust and could be identified based on a total sample size of 10 participants. Importantly, in our study, each group included a minimum of 13 participants.

Apparatus and stimuli

Participants sat in front of a table on which the target objects were presented at a viewing distance of approximately 40 cm. Target objects were four wooden "Efron" blocks (Efron, 1969) that were matched for surface area (25 cm^2), texture, mass, depth, and color but varied in width and length (see Fig. 1). The width of each block was the relevant dimension for the grasping task and ranged from 20 to 35 mm in gaps of 5 mm (Fig. 1A). To account for the larger maximal aperture of adult participants compared with that of children (a result of difference in hand size, ~1.5 times larger maximal aperture in adulthood), all adults completed an additional experimental block in which larger objects, ranging in size from 35 to 50 mm in gaps of 5 mm, were presented.

Motion capture used an Optotrak 3010 device (Northern Digital, Waterloo, Ontario, Canada) to track the three-dimensional (3D) position of three active infrared light-emitting diodes (IREDs) that were connected to the participant's index finger, thumb, and wrist. IREDs were placed in such a way as to allow for complete unrestricted movement of the hand and fingers. The apparatus tracked with a sampling rate of 200 Hz, providing 0.1-mm positional accuracy under the specified experimental conditions. During the grasping task, grip aperture was computed as the distance between the index finger and thumb.

Procedure

The child group completed one block of the grasping task, which began with 5 practice trials that were excluded from the analysis. The adult group completed this same task and, in addition, completed a block of trials that included only bigger objects in order to control for the given group differences in maximal hand aperture. In each block, each of the four objects was presented 12 times in a pseudorandomized order, resulting in a total of 48 trials. On each trial, participants placed their right index finger and thumb on a start button before the beginning of the trial. In the grasping task, following an auditory cue, they were instructed to reach out directly in front of them and pick up the Efron block across its width using a natural grasping movement with their index finger and thumb. Visual feedback was fully available during each grasp. To maintain children's attention, a star sticker was placed under the object in 6 of the 48 trials and they were asked to collect these stickers. Thus, after grasping the block, the children lifted the block and looked for the star sticker; this did not interfere with any measurements of the grasping behavior itself.

Data analysis

The 3D trajectories of the index finger and thumb were recorded. Movement onset was determined as the point in time when the aperture between the index finger and thumb increased by more than 0.1 mm for at least 10 successive frames (50 ms). Movement offset was determined as the point in time when the aperture between the index finger and thumb changed by no more than 0.1 mm for at least 10 successive frames (50 ms).

The maximum grip aperture (MGA) was extracted from each trial by measuring the largest distance between the index finger and thumb. Size sensitivity was assessed by calculating the linear slope between the MGA values observed for the different objects. To assess the adherence to Weber's law, we computed the just noticeable difference (JND) score for each participant. The JND measures the minimum detectable increment in stimulus magnitude and so reflects the sensitivity—which is the size resolution in this case—of the behavior under examination. Similar to previous studies, the JNDs were calculated based on the within-participant standard deviation of the responses at the point of the MGA (Freud & Ganel, 2015; Ganel, Chajut, et al., 2008; Ganel et al., 2014; Hadad et al., 2012; Heath et al., 2011). Finally, for each participant, the linear slope between the JND values was calculated to evaluate the adherence to Weber's law, where a significant positive linear slope reflects adherence to Weber's law (i.e., greater within-participant variability for bigger objects). In addition to the linear component, we conducted a trend analysis to explore whether a quadratic component could describe the data (Hadad et al., 2012). Because no quadratic component was present in any group or task, we focused our analysis on the linear component.

Results and discussion

The analysis was focused on the mean apertures and the within-participant variability (JND scores) of the grasping apertures at the MGA, the time point that best reflects the nature of the visuomotor representation (Ganel et al., 2014).

Aperture analysis

Fig. 2 depicts the MGA as a function of the graspable dimension size and group. Size sensitivity was observed for children as well as for adults, as is evident from the significant positive slopes [children: $t(14) = 4.96$, $p < .001$, Cohen's $d = 1.28$; adults–small objects: $t(12) = 11.70$, $p < .001$, Cohen's $d = 3.34$; adults–big objects: $t(12) = 14.00$, $p < .001$, Cohen's $d = 4.07$].

Interestingly, adults had a steeper MGA slope than children, as is evident by a robust main effect of group, $F(2, 38) = 13.40$, $p < .001$, $\eta_p^2 = .41$, and the results of planned comparisons demonstrated that the slope of the child group differed from that of the adult group, $F(1, 38) = 26.60$, $p < .001$. Moreover, there was no difference between the two size ranges tested in the adult group ($F < 1$), indicating that the age difference in slopes could not be explained based on differences in hand size between children and adults. That children show shallower slopes than adults is consistent with previous investigations (1999; Kuhtz-Buschbeck et al., 1998) and suggests that the precision of size resolution is greater in adulthood. However, this difference is quantitative in nature and might reflect the immaturity of motor processes rather than visuomotor processes per se.

JND analysis (adherence to Weber's law)

Fig. 3 depicts the JNDs (i.e., the within-participant variability) as a function of group and the graspable dimension size. Interestingly, and in contrast to previous findings, adherence to Weber's law is observed for children's grasping movements; the JNDs increased as a function of the size of the graspable dimension. For the adults' grasping movements, we replicated the violation of Weber's law as found in previous studies (Ganel, Chajut, et al., 2008; Ganel et al., 2014) (see Table 1).

Statistically, a one-way analysis of variance (ANOVA) with group (children, adults–small objects, or adults–big objects) as the independent variable and the linear slope between the JND scores as the dependent variable revealed a main effect of group, $F(2, 38) = 4.98$, $p < .01$, $\eta_p^2 = .20$. Planned comparisons confirmed that the linear slope, which reflects the adherence to Weber's law, was greater in the children compared with the adults, $F(1, 40) = 9.96$, $p < .01$, whereas for adult participants no slope differences were observed for action directed to the big versus small objects ($F < 1$). Furthermore, one-sample t-tests confirmed that the linear slope of the JND scores was greater than zero (i.e., adherence to Weber's law) for the child group, $t(14) = 2.32$, $p < .05$, Cohen's $d = 0.60$, but not for the adult group [small objects: $t(13) = -1.08$, $p > .29$; big objects: $t(13) = -1.82$, $p > .09$] (note the comment above that a linear fit was better than a quadratic fit).

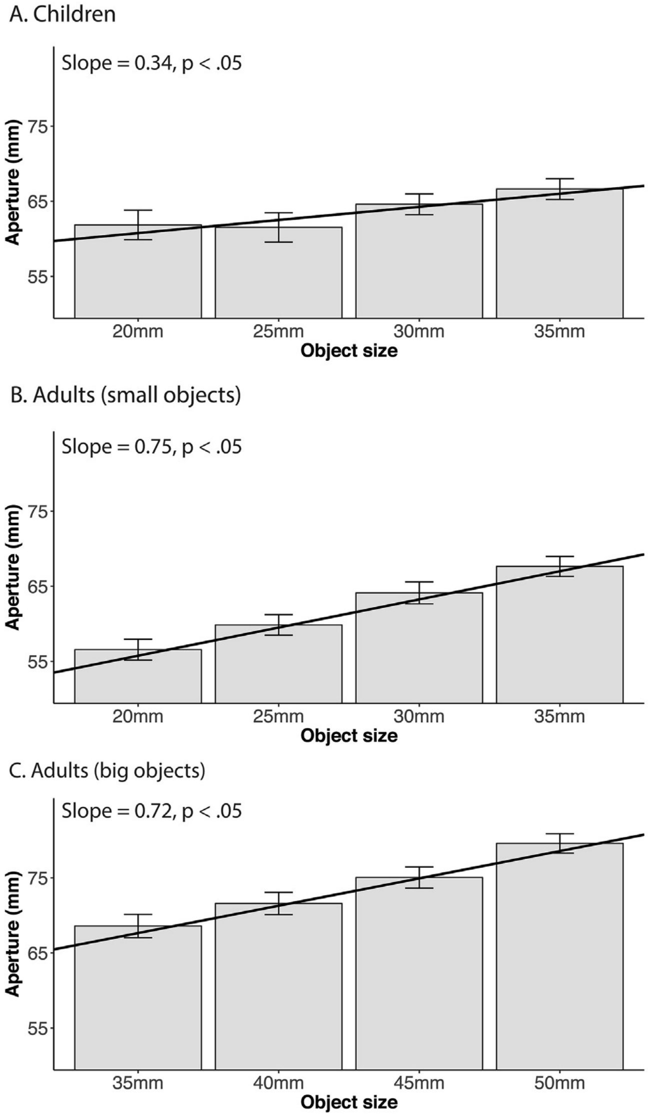


Fig. 2. Experiment 1 results. Grip aperture as a function of object width along the graspable dimension is shown for children (A), adults (B), and adults who grasped bigger objects (C). Size sensitivity was evident as the aperture increased linearly with object width for all groups; however, a steeper slope was found for the adult group. In all panels, the black line represents the linear slope. Error bars represent the standard errors of the mean.

Finally, to further establish the linear component in the JND size function, we calculated Weber's fraction by dividing the JNDs by the intensities (corrected for the response precision; see Smeets & Brenner, 2008). This procedure was applied only on the data from the children because they exhibited adherence to Weber's law. The Weber's fraction values were then subjected to a repeated-measures ANOVA in which no effect of size ($F < 1$) was observed, reflecting the consistency of Weber's fraction across intensities. This finding confirms our observation that children obey the constraints of Weber's law in their visuomotor behavior.

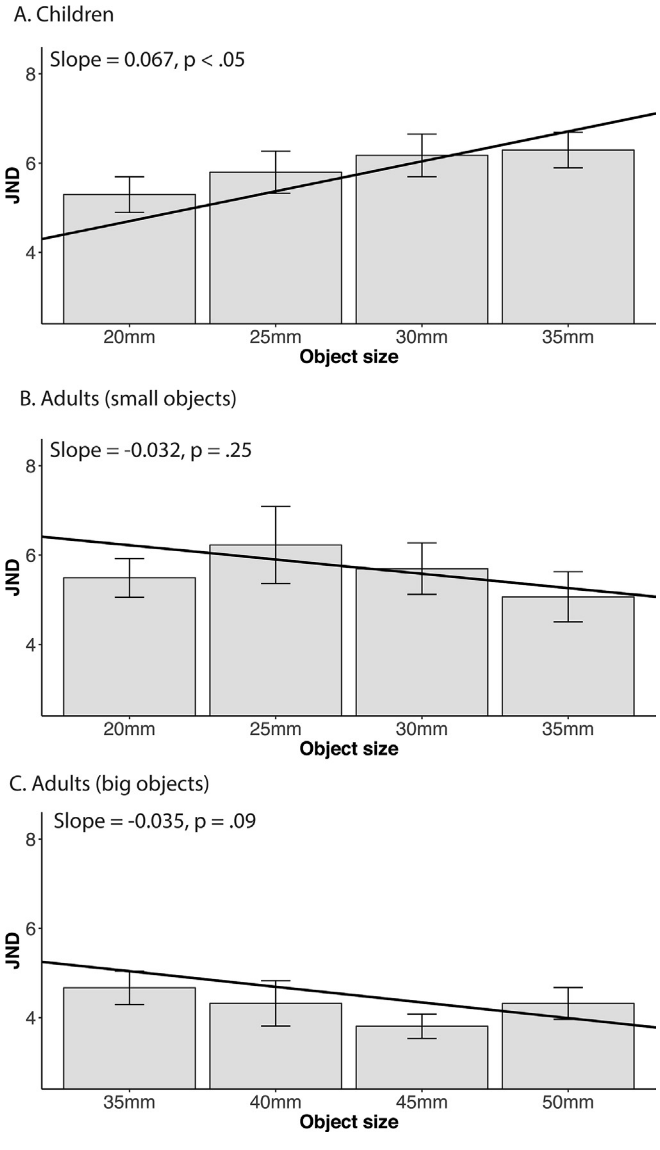


Fig. 3. Experiment 1 results. Aperture variability as a function of object width along the graspable dimension is shown for children (A), adults (B), and adults who grasped bigger objects (C). Variability increased linearly with object width only for the children, reflecting the adherence to Weber's law. JND, just noticeable difference.

Table 1
Effect of Weber's law on perception and action in adulthood and childhood.

Experiment	Children	Adults
Experiment 1: Grasping complex objects	Yes	No
Experiment 2: Grasping simple objects	No	No[a]
Experiment 3: Estimating complex objects	Yes	Yes

[a] Not tested here (see Ganel, Chajut, et al., 2008).

The results of Experiment 1 showed that although children scaled their grip aperture in accordance with object size, they were less sensitive to object size compared with adults. Moreover, children's grasping adhered to Weber's law in that the JNDs increased as the magnitude of the graspable dimension increased. In contrast, in adulthood, grasping behaviors violated Weber's law, reflecting the veridical processing of the graspable dimension even for complex objects.

Experiment 2

The results of Experiment 1 are inconsistent with a previous investigation in which children's grasping movements violated Weber's law when the movements were directed toward discs that varied in size along their diameter (i.e., the graspable dimension) (Hadad et al., 2012). In contrast to Hadad et al. (2012), our Experiment 1 used Efron shapes in which the surface area of differentially sized objects remained constant. That is, as the graspable dimension increased, the non-graspable dimension decreased concomitantly. Given that children may fail to gauge holistic size or volume perceptually, as in the Piagetian concept of conservation (Piaget & Inhelder, 1941), they may also fail to do so during actions.

To test this account of the discrepant results, in Experiment 2 children were required to grasp rectangular ‘‘simple" objects whose size varied only along the graspable dimension, whereas the length of the non-graspable dimension was kept constant.

Method

Participants

Data were analyzed from 13 children aged 4.5 to 6.5 years ($M = 5.8$ years, $SD = 0.6$; 6 girls; 13 Caucasian). The data from 2 children were not analyzed because the participants did not follow experimental instructions or did not complete the experiment. A subset of 7 children participated in both Experiments 1 and 2, albeit with a gap of 2–3 months between the experiments. Because only a subset of the participants completed the two experiments, we adopted a conservative approach and applied only between-participants analyses. Notably, a preliminary analysis confirmed that there were no differences in grasping parameters between the participants who completed both experiments and those who completed only Experiment 2 ($F < 1$).

Apparatus and stimuli

The apparatus and stimuli were the same as in Experiment 1 except for the following changes. The target stimuli were four blocks, all with a fixed length (15 mm). The width of the blocks was the relevant dimension for the grasping task and ranged from 20 to 35 mm in gaps of 5 mm (Fig. 1B).

Procedure

The procedure was identical to that adopted in Experiment 1.

Data analysis

Data analysis was conducted in the same way as in Experiment 1. To determine whether object complexity modulated the adherence to Weber's law, we also compared the JND scores when children grasped complex objects (Experiment 1) versus simple objects (Experiment 2) using an independent-samples *t*-test.

Results and discussion

Aperture analysis

Children grasped simple objects that varied only along the graspable object dimension, whereas all other dimensions were kept constant. As in Experiment 1, size sensitivity was observed in children (i.e., a positive slope of the MGA apertures; see Fig. 4), $t(14) = 8.66$, $p < .001$, Cohen's $d = 2.40$. Notably, despite a numeric trend, the aperture slope was similar for the children who grasped complex objects

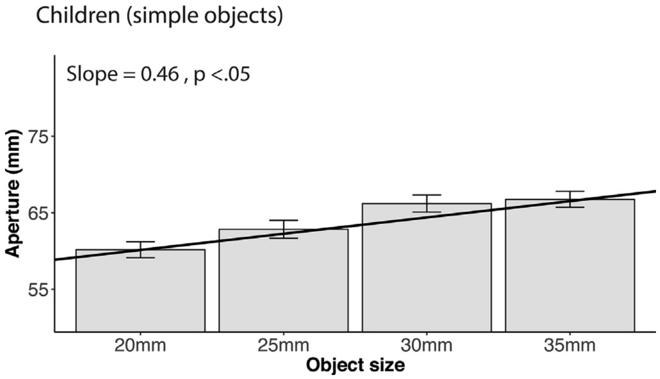


Fig. 4. Experiment 2 results. The aperture size between the fingers, as a function of object width, is shown for children who grasped objects that varied only along the graspable dimension. Size sensitivity was observed (i.e., a positive slope), and it was not statistically different from the sensitivity observed in Experiment 1.

(Experiment 1) and those who grasped simple objects (Experiment 2), $t(26) = 1.25$, $p > .22$, suggesting that the overall size sensitivity was similar between the two experiments.

JND analysis (adherence to Weber's law)

The adherence to Weber's law was assessed by calculating the linear slope of the JND scores. No linear slope was found between object size and the magnitude of the JNDs (Fig. 5), leading to the conclusion that grasping movements directed toward simple objects violated Weber's law (see Table 1). A one-sample *t*-test confirmed that the linear slope of the JND scores was not different from 0, $t(12) = -1.40$, $p > .17$. In addition, an independent-samples *t*-test revealed a greater slope (adherence to Weber's law) for the JND scores for the children in the complex object group (Experiment 1) versus the simple objects group (Experiment 2), $t(26) = 2.50$, $p < .05$, Cohen's $d = 0.94$. Note that because children violated Weber's law, it did not make sense to undertake further analysis such as dividing the JNDs by the intensities (corrected for the response precision; see Experiment 1).

The results of Experiment 2 showed that children's grasping can violate Weber's law, as was evident for the adults, but not for the children, in Experiment 1. This violation replicated previous findings (Hadad et al., 2012) and showed that children's grasping behavior adhered to Weber's law, but only for complex objects that demanded more fine-grained representations of object shape and

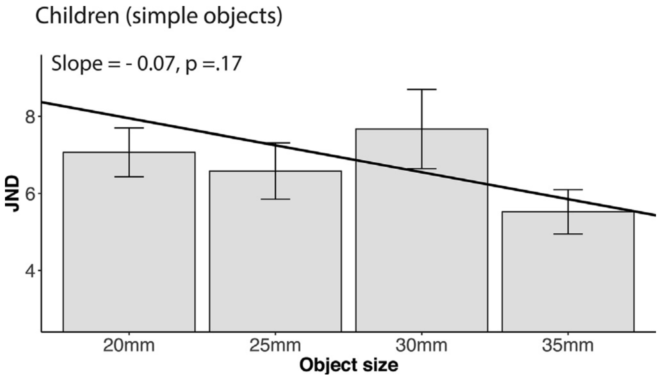


Fig. 5. Experiment 2 results. The just noticeable difference (JND) scores, as a function of object width, are shown for children who grasped objects that varied only along the graspable dimension. JND scores did not change as function of object size, violating Weber's law.

not for simpler objects in which the non-graspable dimension was held constant. These more precise representations required for grasping the more complex objects appear to emerge later and not to be mature by 6 years of age and, therefore, might still be influenced by contextual factors (i.e., the changeability of the non-graspable dimension modulates the processing of the graspable dimension) that are typically processed for perceptual tasks.

Experiment 3

So far, we have examined only the visuomotor representations in children versus adults when grasping is directed to the task-relevant dimension when accompanied by changes in the relevant dimension or not. To examine whether the apparent qualitative difference in the nature of visuomotor representations between adults and children is also observed in the context of a perceptual task, in Experiment 3 children and adults were instructed to make a perceptual judgment and estimate the width of complex (Efron) stimuli. The hypothesis was that in the context of a perceptual task, although children might be less accurate than adults, their perception would still be governed by Weber's law.

Method

Participants

Data were analyzed from 14 children aged 4.75 to 5.90 years (*M* = 5.15 years, *SD* = 0.38; 5 girls; 12 Caucasian, 1 Hispanic, and 1 Asian) and from 14 adults aged 18 to 28 years (*M* = 19.60 years, *SD* = 2.81; 7 women) who did not participate in Experiment 1 or 2. The data from 1 additional child was excluded because his JNDs deviated from the mean JNDs by more than 2.5 standard deviations.

Apparatus and stimuli

Participants sat in front of a table on which the target objects were presented at a viewing distance of approximately 40 cm. Target objects were the same as those used in Experiment 1 (i.e., Efron blocks; see Fig. 1A). In addition to the object, an Amazon Fire tablet (screen size of 7 inches) was placed in front of the participants. Using in-house software written in Python, perceptual estimations were recorded from the measurement of the finger pressure on the tablet.

Procedure

All participants performed one block of the perceptual estimation task, which began with 5 practice trials that were excluded from the analysis. In the experiment, each object was presented 12 times in a pseudorandomized order, resulting in a total of 48 trials. Before the beginning of each trial, the participants placed their right index finger and thumb on a start button. Following an auditory cue, they were instructed to estimate the width of the displayed Efron block by bringing the tip of the index finger and thumb down on the tablet screen, with the distance between the fingers reproducing the perceived object's width. To ensure that participants received the same tactile feedback as in the grasping task, participants were asked to grasp the object following their manual estimation (this part of the movement did not form part of the analysis).

Data analysis

The final aperture between the index finger and thumb (i.e., manual estimation) of each trial was used as the dependent variable. As in Experiments 1 and 2, the slope of the apertures across object size was extracted and the JND scores were calculated based on the within-participant standard deviation of the responses. The linear slopes of the JND scores were used to estimate the adherence to Weber's law (a trend analysis ensured that the quadratic fit was not significant).

To compare directly between perception and action in the two age groups, an ANOVA was conducted with object size, task, and group as independent variables and JND scores as the dependent variable. However, because a preliminary analysis revealed that the assumption of equality of variances between the two groups was violated [Levene's test, $F(3, 53) = 8.02$, $p < .05$], we applied a log10 transformation to the JND scores [transformed data Levene's test, $F(3, 53) = 1.85$, $p = .15$]

(Howell, 2009; McDonald, 2014), and the slopes were recalculated. Establishing homogeneity of variance across groups is frequently done, especially in the context of comparing children with adults (Scherf, Luna, Avidan, & Behrmann, 2011; Scherf, Luna, Kimchi, Minshew, & Behrmann, 2008). The ANOVA was then conducted with the transformed data. Similar results were obtained when a different type of transformation (square root) was applied, and so the findings were not contingent on the type of transformation.

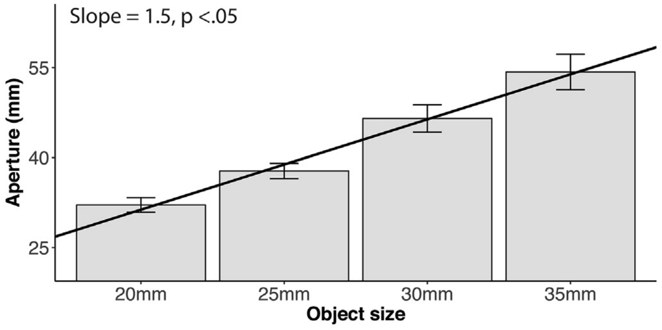
Results and discussion

Children and young adults estimated the width of "complex objects" (i.e., blocks that varied along two dimensions: width and length), and the size sensitivity and adherence to Weber's law of their perceptual estimations were assessed.

Estimation analysis

Size sensitivity was observed for children as well as for adults, as is evident from the significant positive slopes observed for both groups [children: $t(13) = 7.48$, $p < .001$, Cohen's $d = 1.99$; adults: $t(13) = 18.70$, $p < .001$, Cohen's $d = 5.07$] (Fig. 6). In contrast to the visuomotor domain (Experiment 1), children had a greater slope than adults, $t(1, 26) = 3.05$, $p < .01$, Cohen's $d = 1.15$. However, given that the ideal observer should have a slope of 1 (object size was changed linearly), the lower (and closer to 1) slope observed for the adults may reflect a more accurate representation of object size. In contrast to Experiment 1, however, we hypothesized that despite this quantitative difference between the groups, the perceptual behavior in both groups should still adhere to Weber's law.

A. Children



B. Adults

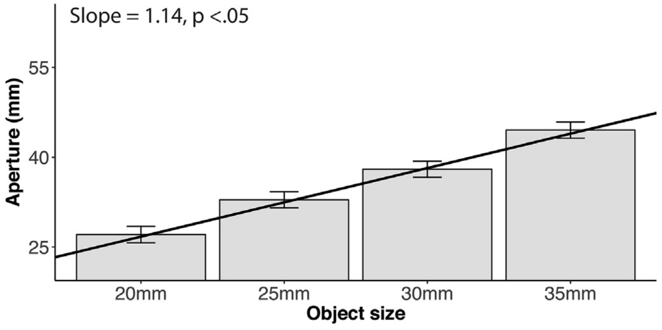


Fig. 6. Experiment 3 results. The aperture of the manual estimation as a function of object width is shown for children (A) and adults (B). Size sensitivity was evident because the manual estimations increased linearly with object width.

JND analysis (adherence to Weber's law)

Fig. 7 depicts the JND scores as a function of the estimated dimension size and group. For each participant, the linear slope between the JND values was calculated and served as the dependent variable. As predicted, and in contrast to the results observed for the grasping task (Experiment 1), adherence to Weber's law was found for both groups.

Two one-sample *t*-tests confirmed that the linear slope of the JND scores was greater than zero for the child group [$t(13) = 2.63$, $p < .05$, Cohen's $d = .70$] and for the adult group [$t(13) = 6.33$, $p < .001$, Cohen's $d = 1.69$]. Moreover, an independent-samples *t*-test revealed no differences between the groups' slopes, $t(26) < 1$, indicating that the adherence to Weber's law was similar between the two groups (see Table 1).

Together, the results of Experiment 3 demonstrated that during a perceptual task both children and adults adhered to Weber's law, such that object size was processed in a relative fashion rather than an absolute fashion. As reflected by the estimation analysis (see above), the equivalent adherence to Weber's law across the groups does not indicate that the perceptual representations of children are necessarily fully mature; it only indicates that the same set of cues were processed by both groups. This possibility is also supported by an analysis in which the values of the JND scores were subject to a mixed ANOVA with object size as a within-participant variable and group as a between-participants variable. This analysis revealed a main effect for object size (Weber's law), $F(3, 78) = 8.60$, $p < .001$, $\eta^2_p = .25$, but no interaction between size and group, $F(3, 78) = 1.48$, $p > .22$. In addition, a robust main effect for group was found, $F(1, 26) = 20.10$, $p < .001$, $\eta^2_p = .43$, with children having overall higher (noisier) JND scores compared with adults. These results were corroborated by the analysis

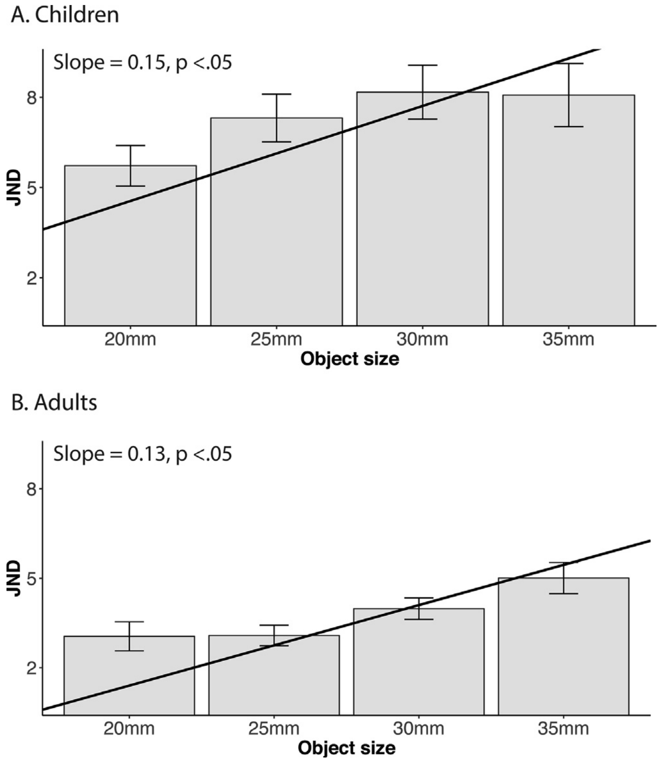


Fig. 7. Experiment 3 results. The just noticeable difference (JND) scores as a function of object width are shown for children (A) and adults (B). JND scores increased linearly with object width for both the child and adult groups, reflecting the adherence to Weber's law.

of Weber fractions. Similar to Experiment 1, Weber fractions were calculated for each group. In both groups, Weber fractions were not changed as a function of size (reinforcing the notion of a linear trend) [children: $F < 1$; adults: $F(3, 39) = 2.34$, $p > .087$]. However, a robust main effect of group was found, $F(1, 26) = 20.62$, $p < .001$, $\eta_p^2 = .44$, with a greater average Weber fraction for the children than for the adults, reflecting the poorer representation of object size for the children.

Finally, to compare directly between the effect of Weber's law on perception (Experiment 3) and its effect on action (Experiment 1) with the same complex objects across the groups, an ANOVA with three independent variables (age, modality, and size) was conducted on the JND data. This ANOVA revealed a trend for a three-way interaction, $F(3, 159) = 2.034$, $p = .11$, $\eta_p^2 = .037$. Given that the assumption of equality of variances between the two groups was violated, we repeated this analysis with the log-transformed data (see Method above). The ANOVA revealed a three-way interaction among age, modality, and size, $F(3, 159) = 4.579$, $p < .005$, $\eta_p^2 = .08$. This interaction revealed a distinction between action and perception in adulthood, with the former violating Weber's law and the latter adhering to Weber's law. In children, both perception and action followed the same profile, with an adherence to Weber's law in the context of complex object processing in both modalities.

General discussion

The current study was designed to elucidate the developmental trajectory of the relationship between the underlying shape representations that serve action, on the one hand, and those that shape perception, on the other. To this end, we measured size sensitivity and the adherence to Weber's law under corresponding visuomotor and perceptual tasks (see Table 1 for a summary of the results). Experiment 1 revealed quantitative and qualitative differences between children and adults when complex objects, varying along two dimensions, were employed as the stimuli. First, and consistent with previous investigations (Kuhtz-Buschbeck et al., 1998, 1999), children's grasping was less sensitive to object size than adults' grasping. The more novel finding, however, revealed a qualitatively different adherence to Weber's law; in contrast to the adult profile, children's grasping behaviors adhered to Weber's law when the target objects were changed along two dimensions. Thus, among children, the changeability of the irrelevant dimension influenced the processing of the graspable dimension, such that the resolution of the visuomotor representations was reduced for larger objects. Notably, the use of Efron blocks that are matched in surface area ensured that the adherence to Weber's law observed in the children truly reflected the processing of the graspable dimension rather than the processing of the overall surface area of the object.

Experiment 2 validated the claim that children's adherence to Weber's law in Experiment 1 is related to the complexity of the stimuli. Specifically, children who grasped simple objects, whose size was changed only along the graspable dimension, violated Weber's law. Interestingly, the overall size sensitivity was not modulated by this manipulation, and only the processing (i.e., the adherence to Weber's law) of the graspable dimension was changed.

Finally, Experiment 3 examined the perceptual representations of complex objects across ages. Similar to Experiment 1, reduced size sensitivity was observed for the children's group. However, in contrast to visuomotor control, the perception of complex objects was found to be governed by Weber's law in both children and adults.

Together, these findings shed new light on the developmental trajectory of the relationship between action and perception. In particular, the adherence of children's grasping to Weber's law indicates that, at least in early childhood (5–6 years), contextual cues such as shape-irrelevant dimensions, which typically modulate perceptual representations, also affected the nature of visuomotor representations. Based on the similar adherence to Weber's law for complex object reaching and for perception, we propose that there is a high degree of association between action and perception in early childhood but that this association changes over the course of development, with the mature system evincing a dissociation between the modalities.

These results are also consistent with a developmental study by Schum, Franz, Jovanovic, and Schwarzer (2012) that used the Garner paradigm to examine the nature of shape processing. Interestingly, these authors found that children processed object shape in a holistic fashion even when they performed a visuomotor task. Notably, similar to Experiment 1 in the current investigation, under the Garner paradigm multiple object dimensions were being varied, thereby increasing stimuli complexity. Thus, the results from developmental studies that used different psychophysics approaches (i.e., Garner paradigm and Weber's law) converge and suggest that children's visuomotor representations are sensitive to relative cues and are qualitatively different from those generated by the mature visuomotor system.

Functional role of the association between action and perception in childhood

Most obvious explanations of the greater similarity in representation of perception and visuomotor behavior in childhood but not in adulthood might appeal to the overall greater variability in children than in adults (Dinstein, Heeger, & Behrmann, 2015; Manoel & Connolly, 1995) or to the finding that children are more distractible than adults (Kannass, Colombo, & Wyss, 2010). Children also might not be as skilled as adults in representing volume, and then they go on to acquire this skill over time (Piaget & Inhelder, 1941). But these explanations do not do justice to the key finding, which is the *interaction* of age and modality (rather than a simple main effect of age). Therefore, the critical question that emerges from the current study is why, qualitatively, perceptual behavior mirrors that of adulthood but visuomotor behavior does not and that, in fact, these two behaviors evince the same profile in childhood but not in adulthood.

One possible explanation is that the elevated association between action and perception in childhood contributes to the development or bootstrapping of each of these two functions; that is, there is some reciprocity between the two modalities and, hence, their coupling promotes the sharing of representation. Such a mechanism predicts that information that is usually processed by one system (e.g., perception) will influence or "penetrate" the representations derived by the other system (e.g., action).

Evidence to support this claim comes from a number of sources. Previous research has indicated that the dorsal pathway is subject to a slower developmental trajectory than the ventral pathway (for a review, see Braddick & Atkinson, 2011). This hypothesis was further confirmed by findings that demonstrate the vulnerability of the dorsal pathway network in a wide range of both genetic and acquired developmental disorders (Atkinson et al., 1997; Braddick, Atkinson, & Wattam-Bell, 2003). In the case of the current investigation, it is plausible that the developing, immature visuomotor system is unable to derive a fine-grained description that suffices for generating precision grasping movements toward a complex object. Therefore, information from multiple sources, including from perceptual representations, might need to be aggregated to facilitate this behavior. This prediction was upheld here in that Weber's law, which is typically associated with perceptual processes, governed the visuomotor representations among children as well.

Notably, given that perceptual processes, mediated by the ventral pathway, also emerge over the course of development, it is plausible that the converse direction of modulation occurs as well. Namely, visuomotor abilities (albeit immature) might influence perceptual representations. This view is well articulated in an existing theoretical framework suggesting that the development of motor abilities shapes the knowledge and representations of objects and events (for a review, see Braddick & Atkinson, 2011), and this view has received empirical support. For example, infants who exhibited more developed motor skills (i.e., self-sitting experience, visual–manual exploratory skills) were found to be more sensitive to object 3D structure (Soska, Adolph, & Johnson, 2010). Hence, the ability to interact with objects provided the visual system with more samples of the objects, which in turn allowed the visual system to generate more elaborate representations.

Emergence of fine-grained visual representations over the course of development

The results of the current experiments are consistent with a growing body of literature suggesting that, despite the early sensitivity of the visual system to a variety of cues and stimuli, different types of visual representations are subject to differential developmental trajectories. For example, whereas sensitivity to faces is observed even in newborns (Mondloch et al., 1999), this perceptual ability has a prolonged developmental trajectory that lasts even into adulthood (Germine, Duchaine, & Nakayama, 2011). Another instance of a coarse to fine-grained development trajectory comes from the case of 3D perception; sensitivity to 3D information is evident even in infancy, as demonstrated by the seminal visual cliff experiment (Gibson & Walk, 1960), but more refined representations are subject to a protracted developmental trajectory (Freud & Behrmann, 2017; Nishimura et al., 2015).

The current study contributes further to the idea that visual representations follow a developmental trajectory in which early sensitivity is coarse, whereas fine-grained representations emerge slowly across development. In particular, visuomotor representations are essential for humans' ability to interact with their surroundings; accordingly, by 18 months of age toddlers can adjust their hand position based on the shape of the object and a corresponding slot (Street et al., 2011). Moreover, excluding some quantitative differences, the underlying neural network (i.e., the dorsal pathway) that supports visuomotor behaviors was found to be in place at 4 years of age (James & Kersey, 2018). Yet, despite this early sensitivity, the current findings suggest that visuomotor representations are not yet mature in 6-year-old children (see also Kuhtz-Buschbeck et al., 1998, 1999). This immaturity is particularly evident when more refined representations are needed (i.e., the Efron blocks in Experiment 1), but not when more simplified representations will suffice, to complete the task (i.e., the unidimensional objects in Experiment 2).

Weber's law as a tool to measure the dissociation between perception and action

During the last decade, Weber's law has been used extensively to measure the dissociation between action and perception under different conditions (e.g., Ganel, Chajut, et al., 2008; Ganel et al., 2014; Ganel, Namdar, & Mirsky, 2017; Heath, Holmes, Mulla, & Binsted, 2012; Holmes & Heath, 2013; Holmes et al., 2011; Ozana & Ganel, 2017). However, it has been argued that the violation of Weber's law by grasping movements reflects biomechanical constraints rather than the nature of visuomotor representations. According to this argument, the variability of the aperture (i.e., the JND scores) in the MGA is limited by the maximal aperture between the two fingers (i.e., the effective range of motion) (Utz et al., 2015). However, this concern was undermined in a recent study where stimulus sizes were adjusted to match each participant's effective range of motion. In contrast to the biomechanical account, under a perceptual condition of pantomimed grasping adherence to Weber's law was found (Manzone et al., 2017).

Consistent with Utz et al. (2015) findings, we found negative nonsignificant slopes for the adult group as well as for the children who grasped simple objects. However, the results observed for the children in Experiment 1 (adherence to Weber's law) are opposite to the main prediction made by the biomechanical constraint account. Moreover, for the adult group, we used two sets of stimuli that differed by size, and no difference in the slopes was observed. Hence, together with the findings reported by Manzone et al. (2017), the current results suggest that the measurement of Weber's law in a grasping task does not solely reflect the biomechanical constraints of the fingers but also reflects the nature of the visuomotor processing.

Conclusions

The current study was designed to uncover the developmental trajectory of the functional dissociation between action and perception. In a series of visuomotor and perceptual experiments, we provided novel evidence that the grasping behavior of young children, but not of adults, is constrained by Weber's law, which is typically associated with perceptual processes. These results suggest that, in childhood, perceptual representations modulate visuomotor representations, especially under conditions in which a refined or precise object description is required. Over the course of development, however, the dissociation between these two fundamental visual functions emerges.

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