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Double dissociation between perception and action in children

Erez Freud [a,*], Nahal Binur [b], Ashish Srikanth [a], Emily Davidson [a], Tzvi Ganel [c], Bat-Sheva Hadad [b]

[a] Department of Psychology and Centre for Vision Research, York University, Toronto, Ontario M3J 1P3, Canada
[b] Department of Special Education and The Edmond J. Safra Brain Research Center, University of Haifa, Haifa 3498838, Israel
[c] Department of Psychology, Ben-Gurion University of the Negev, Beer Sheva 8410501, Israel

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ABSTRACT

Previous research has demonstrated a functional dissociation between vision for perception and vision for action. However, the developmental trajectory of this functional dissociation is not well understood. We directly compared the sensitivity of grasping and perceptual estimations within the same experimental design to the real and illusory sizes of objects positioned in the Ponzo illusion display. Two different-sized objects were placed such that the differences between their real sizes and their perceived sizes were pitted against each other. Children aged 5–8 years and adults made perceptual size discriminations and then grasped (action) or estimated (perception) one of the objects based on its perceived size. Consistent with previous results, for the action task, grasping apertures of adults were scaled with the physical differences in the objects' sizes, even in trials where their overt perceptual decisions were deceived by the illusion. In contrast, perceptual estimations were robustly modulated by the illusion. Interestingly, children outperformed adults in their perceptual discriminations but exhibited adult-like behavior in grasping and in perceptual estimations of the objects, demonstrating a dissociation between perception and action. These results suggest that although the two visual functions are not operating at fully mature levels during childhood, some key mechanisms that support a dissociation between these functions are already in place.

* Corresponding author.
E-mail address: efreud@yorku.ca (E. Freud).

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Introduction

According to the two visual pathways account, the neuronal mechanisms mediating the perception of objects are considered to be dissociable from those mediating the immediate control of actions directed at those objects (Goodale & Milner, 1992). The ventral "what" pathway, which projects from V1 (primary visual cortex) through the ventral temporal and occipital structures to the anterior temporal cortex, provides detailed representations of the world required for cognitive operations such as recognition and identification. In contrast, the dorsal "how" pathway, which extends from V1 to the posterior parietal structures, promotes visuomotor control.

Although representations mediating these functions may overlap and interact (for a review, see Freud, Plaut, & Behrmann, 2016), research has documented several instances of a functional dissociation between the two visual pathways, suggesting that action and perception rely on qualitatively different sets of representations. Initial support for this model was based on neuropsychological cases such as a patient, D.F., who suffered from a remarkable impairment in object recognition but nevertheless exhibited preserved visuomotor control of the same objects (Goodale, Milner, Jakobson, & Carey, 1991). Later studies demonstrated a corresponding pattern of dissociation in healthy observers. For example, psychophysical evidence shows that when observers are asked to grasp an object, their grasping apertures violate Weber's law, but when they are asked to perceptually estimate the size of the same object, their manual estimations obey this fundamental law of psychophysics (Ganel, Chajut, & Algom, 2008).

Understanding of the functional dissociation of action and perception was greatly informed by studies examining the effect of visual illusions on these two functions. Although some studies found that grasping movements escape the influence of visual illusion (Aglioti, DeSouza, & Goodale, 1995; Ganel & Goodale, 2003; Haffenden & Goodale, 1998), others indicated that grasping, just like perception, is sensitive to visual illusions (Franz, Fahle, Bülthoff, & Gegenfurtner, 2001; Franz, Gegenfurtner, Bülthoff, & Fahle, 2000). This disagreement on whether illusions affect the control of grasping is largely associated with a specific size-contrast illusion, the Ebbinghaus illusion (Kopiske, Bruno, Hesse, Schenk, & Franz, 2016). Findings on other illusions, such as the Ponzo illusion (Ganel, Tanzer, & Goodale, 2008; Gonzalez, Ganel, Whitwell, Morrissey, & Goodale, 2008; Whitwell, Buckingham, Enns, Chouinard, & Goodale, 2016) and the diagonal illusion (Smeets, Kleijn, van der Meijden, & Brenner, 2020), consistently show that whereas perceptual estimations are heavily influenced by the illusions, grasping trajectories can escape illusory effects.

For example, a double dissociation between action and perception was observed in a study that pitted real and illusory sizes against each other in the context of the Ponzo illusion (Ganel, Tanzer, et al., 2008). In this research, which employed a similar design to the one used in the current study, participants completed a forced-choice perceptual judgment that was followed by a grasping movement. Importantly, in the same trials where perceptual estimates were deceived by the illusion, the grasping apertures between the fingers were scaled to the real size differences between the two objects. Hence, the physical differences in size affected grasping apertures in one direction, whereas illusory differences in size affected perceptual judgments in the opposite direction, demonstrating double dissociation between these two visual functions.

Importantly, however, these functional dissociations have typically been described in the context of the mature brain while their developmental trajectory is less clear. It has been argued that neither perception nor action qualifies as an ontogenetically privileged system because both develop from birth as a function of intrinsic processing constraints and experience (Bertenthal, 1996). Studies directly comparing the relative developmental rates of the two visual systems show inconsistent results. Whereas some studies suggest earlier maturation of the functions mediated by the ventral pathway than those mediated by the dorsal pathway (Dannemiller, 2001), other studies suggest otherwise (Ciesielski et al., 2019; Kovács, 2000). In addition, the extent to which the visual processing mediating perception and action is coordinated during development is not clear. Although newborns seem to be capable of performing many actions regulated by perceptual information (Bloch & Carchon, 1992; Kremenitzer, Vaughan, Kurtzberg, & Dowling, 1979), interactions between perception and action become better tuned as a function of neural development and experience (DeLoache, Uttal, & Rosengren, 2004; Nardini et al., 2008).

Only few studies directly investigated the developmental stage at which the dissociation between the two systems becomes adult-like. Qualitative differences in computations carried out for perception and on-line action have been observed in children as young as 5 years (Hadad, Avidan, & Ganel, 2012). In Hadad et al.'s study, children's pattern of results resembled that of adults, showing that whereas variability of perceptual estimates increased as a function of object size, variability of grasping did not scale with object size. However, this violation of Weber's law in grasping in young children was observed for simple objects where the perceived magnitude is based on a single dimension (i.e., diameter of a disk), not for more complex objects where the perceived magnitude is modulated by the relations between two different dimensions (i.e., width and length of a rectangle) (Freud, Culham, Namdar, & Behrmann, 2019). Notably, for adults, grasping violated Weber's law even for the complex objects. These results suggest that although the two visual pathways become increasingly specialized in their ability to compute different aspects of the visual environment, such computations may overlap to a larger extent during development.

The differential effects of visual illusions on perception and action in children are yet to be determined. There is ample evidence that perception is less susceptible to visual illusions during early childhood. However, this reduced susceptibility is not an all-or-nothing phenomenon (Hadad, 2018). For example, although 4-year-old children are affected (even if to a lesser degree) by illusions such as the Ebbinghaus illusion (Doherty, Campbell, Tsuji, & Phillips, 2010; Kaldy & Kovács, 2003) and the Ponzo illusion (Hadad, 2018; Leibowitz & Judisch, 1967), they do not exhibit susceptibility to other illusions such as the rectangle and three-dimensional (3D) cube illusions (Hadad, 2018).

To date, studies that used visual illusions to investigate the developmental trajectory of the relation between perception and action focused on the effect of the Ebbinghaus illusion. These studies yielded inconsistent results. In particular, it was found that both perception and action are influenced by the illusion in children (Duemmler, Franz, Jovanovic, & Schwarzer, 2008; Hanisch, Konczak, & Dohle, 2001). However, there is disagreement as to the nature of the effect; whereas Hanisch et al. (2001) demonstrated opposite directions of illusory effects on perception and action, Duemmler et al. (2008) found effects in the same directions in children. Notably, in both studies participants grasped an inner target surrounded by a set of small or large objects. Grasping the central target may be restricted by the contextual objects surrounding the target and thus may be modulated by adaptations to the spatial arrangements of the stimulus configuration. Therefore, grasping responses in such a case do not necessarily reflect illusory effects.

To overcome these drawbacks, we tested the specialization of the two visual systems using the Ponzo illusion for which visual computations for perception are shown to exhibit susceptibility (albeit to a reduced degree) during early childhood (Hadad, 2018; Leibowitz & Judisch, 1967). Sensitivity to the size of objects positioned on a background containing texture gradient and linear perspective, giving rise to the Ponzo illusion, was measured in participants' grasping responses. Grasping responses immediately followed the participants' perceptual decision on the difference between the objects' sizes. This paradigm allowed a direct comparison of the sensitivity of grasping and perceptual estimations to real and to illusory size differences within the same experimental design. Therefore, it offered a clearer definition of the developmental trajectory of the specialization of the visual systems mediating perception and action.

Method

Participants

Sample size for each group was based on previous studies comparing visuomotor and perceptual behaviors in children and adults (Freud et al., 2019; Ganel, Tanzer, et al., 2008; Hadad et al., 2012). Grasping data were analyzed for 17 children (5.5–8.5 years of age, M = 6.44, SD = 0.89; 10 female) and 18 adults (18–33 years of age, M = 20.1, SD = 3.65; 13 female). The data for 3 children were excluded because the participants did not exhibit sensitivity to object size at the end point of the grasping. The data of 1 adult and 3 children were excluded because there were not enough incorrect trials (≤5 trials) in at least one of the experimental conditions. Perceptual (estimation) data were analyzed for 17 children (5.5–8.7 years of age, M = 7.37, SD = 1.07; 10 female) and 16 adults (18–33 years of age, M = 20.4, SD = 3.11; 11 female).

All participants were right-handed with normal or corrected-to-normal visual acuity. Adults were tested at York University and provided informed consent and received course credit for their participation. Children were recruited from the community (City of Haifa, Israel), and informed consent was provided by their legal guardians. The same setup (i.e., cameras, markers, and stimuli) was used in both testing sites. All experimental procedures complied with the protocol approved by the internal review board for York University and the ethical committee of the Faculty of Education for the University of Haifa.

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. Two of three objects were presented in each trial. For the critical incongruent trials (32 of 40), the length of the larger object was 42 mm and the length of the smaller object was 40 mm. These objects were placed on a linear perspective background, giving rise to the Ponzo illusion (see Fig. 1A), such that the smaller object was perceived as spatially distant and thus was perceptually enlarged compared with the physically bigger "closer" object. The illusionary background was flipped every 10 trials to balance right and left movements directed to the bigger and smaller objects. A total of 8 congruent trials in which a 47-mm object was presented in the "close" location were used as "catch" trials. Given the large difference between the physical lengths of the objects (40 and 47 mm), participants were expected to perceive the physically long object as bigger despite the illusory background. The kinematic data from the catch trials were not analyzed given the small number of trials in this condition.

Motion capture used an OptiTrack system (NaturalPoint Inc. DBA OptiTrack, Corvallis, OR, USA) with four 13-W prime cameras to track the 3D position of three active infrared-light-emitting diodes attached to the participant's index finger, thumb, and wrist (Fig. 1B). Markers were placed in such a way as to allow complete and unrestricted movements of the hand and fingers. The apparatus used a 100-Hz sampling rate. During the grasping task, grip aperture was computed as the distance between the index finger and thumb. Perceptual estimation data were collected using in-house software installed on a Samsung Galaxy Tab tablet (screen size = 8 inches).

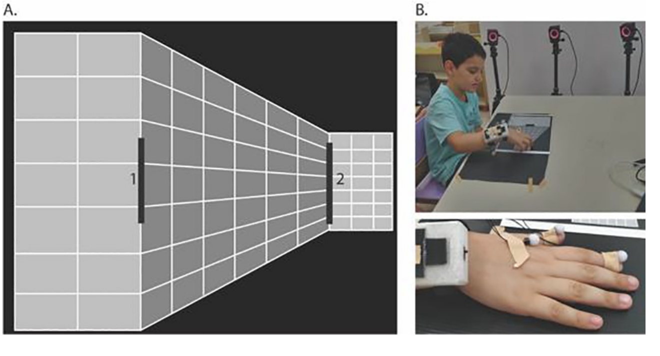

Fig. 1. (A) Experimental setup. The figure illustrates the arrangement of the objects in critical incongruent trials pitting the physical and illusory sizes against each other. In this example, Object 1 is typically perceived as shorter than Object 2, although it is actually longer. (B) Marker setup. Motion capture was based on the OptiTrack system. Three infrared markers were attached separately to each participant's index finger, thumb, and wrist with small pieces of surgical tape. The picture was taken and published with permission.

Procedure

Following a short practice and an equipment calibration block, 40 experimental trials were completed. For each of the two tasks (grasping and perceptual estimation), a single trial was composed of two parts. First, participants performed a two-alternative forced-choice task in which a verbal command (‘‘big” or ‘‘small”) was presented and they were asked to differentiate objects’ sizes. Then, in the grasping task, participants grasped the object, based on their forced-choice perceptual decision, using the thumb and index finger; and in the perceptual estimation task, they matched the size of the chosen object on a tablet. The initial size of the on-screen object randomly ranged between 38 and 43.25 mm, and each button press added or omitted 0.15 mm to or from object length.

Data analysis

For both tasks, accuracy was calculated based on the forced-choice task completed in the first part of each trial. For the grasping experiment, the 3D trajectories of the index finger and thumb were analyzed manually (on a trial-by-trial basis) using MATLAB (MathWorks Inc., Natick, MA, USA) based on the following parameters. Movement onset was set as the point in time when the aperture between the index finger and thumb increased sharply for five successive frames. Movement offset was set as the point in time when the location of the index finger (z coordinate) was at a minimum and the gap between the fingers was stable for five successive frames. The maximum grip aperture (MGA) was automatically extracted for each trial by measuring the largest distance between the index finger and the thumb. For the estimation task, the final size of the object presented on the tablet was recorded.

Statistical analysis

Statistical analyses were conducted using JASP (JASP Team, 2018). We employed analysis of variance (ANOVA) and Bayesian ANOVA on the grasping and estimation data. For all Bayesian analyses, we used the null model as the reference model, and priors were set as equal across all experimental conditions. Notably, in contrast to the null hypothesis significance testing, the Bayesian approach allowed us to look for supportive evidence for either the alternative hypothesis (H1) or the null hypothesis (H0) (van den Bergh et al., 2019; Wagenmakers et al., 2018).

Results

Accuracy rates

First, we analyzed the accuracy rates of participants’ forced-choice perceptual decisions. Consistent with previous studies (Ganel, Tanzer, et al., 2008), adults exhibited low accuracy rates (~20%), reflecting the robustness of the Ponzo illusion, and this was true for both the grasping and estimation tasks (Fig. 2). Children’s accuracy rates were robustly higher (~50%) than those of adults, and this was evident across the two experiments.

Consistent with these observations, an ANOVA with accuracy as the dependent variable revealed a significant effect of age, $F(1, 64) = 43.90$, $p < .001$, $\eta_p^2 = .40$, with no effect of task and no interaction between task and age (Fs < 1). These results were corroborated by a Bayesian ANOVA that revealed decisive support for the effect of age ($BF_{10} = 1.78 \times 10^6$). We also found evidence of the lack of task effect (perception or action) ($BF_{10} = 0.263$) and the lack of interaction between the two factors ($BF_{10} = 0.47$). The results demonstrate susceptibility to the illusion at all ages but point to a significant difference between children and adults. These age-related changes have been observed in previous perceptual tasks (Hadad, 2018; Leibowitz & Judisch, 1967). We discuss these developmental changes below in the context of the grasping and perceptual estimation tasks.

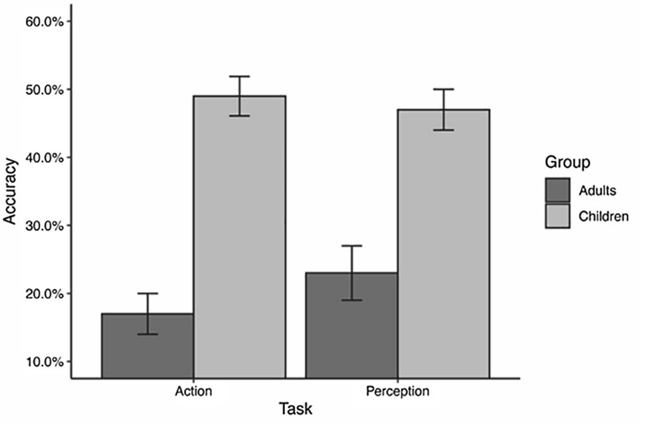

Fig. 2. Accuracy results. Both children and adults exhibited clear susceptibility to the Ponzo illusion, although children were overall more accurate (less susceptible to the illusion). Error bars represent the standard error of the mean for each condition.

Dissociation of action and perception in children and adults

To examine age-related changes in the degree of the dissociation between action and perception, we included age, task, and size as independent variables. Critically, the two-way interaction between task (grasping or estimation) and size (small or big) was significant, $F(1, 64) = 45.15$, $p < .001$, $\eta_p^2 = .41$, reflecting differential sensitivity to size for the two tasks. The three-way interaction was not significant ($F < 1$), suggesting that children and adults exhibited a similar dissociation. Notably, the results of a Bayesian ANOVA examining the probability of a three-way interaction supported the null hypothesis (i.e., no three-way interaction) ($BF_{10} = 0.37$), such that models that did not include the three-way interaction were 2.69 times more likely to occur.

A separate analysis conducted for each group (children or adults) revealed a two-way interaction between task and size in each age group [adults: $F(1, 32) = 20.40$, $p < .001$, $\eta_p^2 = .38$; children: $F(1, 32) = 24.80$, $p < .001$, $\eta_p^2 = .43$], indicating a dissociation between the sensitivity of perception and action to size in both children and adults. For the child group, the interactive effect of task and size demonstrating a dissociation held when we included age as a covariate, $F(1, 32) = 22.42$, $p < .001$, $\eta_p^2 = .42$, and also when the analysis of the child group was restricted to the younger participants (<7 years), $F(1, 20) = 21.757$, $p < .001$, $\eta_p^2 = .52$. An additional Bayesian ANOVA provided decisive evidence of a two-way interaction across the groups (adults: $BF_{10} = 174.829$; children: $BF_{10} = 557.8$). In the following sections, we analyze the tasks separately to provide a more comprehensive description of the nature of the dissociation in each group.

Grasping task

MGAs were used to estimate the sensitivity of vision for action to the physical size of the objects under the illusory influence. First, we analyzed sensitivity to real size within the child group. Importantly, because this group had a relatively high accuracy rate, we were able to analyze sensitivity to size across trials where the forced-choice perceptual decisions were either correct or incorrect. As depicted in Fig. 3, sensitivity to size was found regardless of the correctness of the decision. Accordingly, a repeated-measures ANOVA revealed a main effect of size, $F(1, 16) = 12.11$, $p < .005$, $\eta_p^2 = .43$, with no effect for correctness and no interaction between correctness and size (both Fs < 1). This effect of size held when children's age was added as a covariate to the model, $F(1, 16) = 10.05$, $p < .01$, $\eta_p^2 = .40$. An additional repeated-measures Bayesian ANOVA found substantial support for an effect of size on the grasping aperture ($BF_{10} = 6.83$), such that the model including the effect of size was 6.83 times more likely to occur than the null model. In addition, we found substantial evidence against

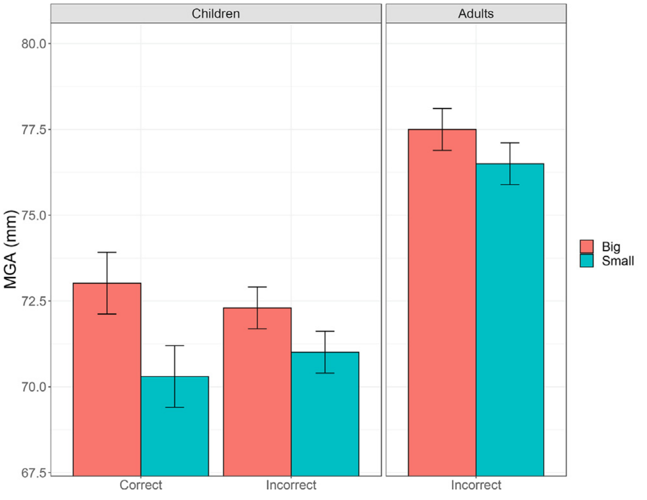

Fig. 3. Grasping experiment results. Size sensitivity was measured at the point in time when the maximum grip aperture (MGA) occurred by comparing the grasping apertures for big and small objects. Children and adults were sensitive to the real size differences between the objects even in trials where their perceptual decisions were deceived by the illusion. For adults, only trials in which erroneous decisions were made were included in the analysis. Error bars represent confidence intervals for the main effect of object size as calculated by repeated-measures analyses of variance (Jarmasz & Hollands, 2009).

the effect of correctness (BF_{10} = 0.24) and against an interaction between correctness and size (BF_{10} = 0.47). Our findings of the sensitivity of children to object size, irrespective of their perceptual decision, provides the first direct evidence of the resilience of grasping behaviors to the Ponzo illusion.

Next, we examined whether children were similar to adults in their sensitivity to object size. Given the low accuracy rates in the adult group, this analysis was restricted to incorrect trials (i.e., trials in which the forced-task perceptual decision was deceived by the illusion). Consistent with previous studies (Ganel, Tanzer, et al., 2008), adults' MGAs exhibited sensitivity to the real size of the objects even though their perceptual decisions were incorrect for the same trials (Fig. 3). Similar sensitivity to real size was observed for the child group, with children's MGAs reflecting the direction of the real size differences between the objects.

A repeated-measures ANOVA with MGA as the dependent variable and with group (children or adults) and size (small or big) as the independent variables revealed a main effect of size, $F(1, 16) = 7.397$, $p < .05$, $\eta_p^2 = .18$, reflecting the sensitivity of both groups to object size regardless of their perceptual decisions. We found an additional main effect of group, reflecting the expected overall greater grasping aperture in the adult group, $F(1, 16) = 6.01$, $p < .05$, $\eta_p^2 = .15$. Importantly, however, no interaction was found between group and size ($F < 1$), suggesting that sensitivity to real size was not modulated by age.

A Bayesian repeated-measures ANOVA revealed substantial support for a combination of two main effects of size and group (BF_{10} = 12.51), with a bigger aperture for adults than for children, alongside sensitivity to object size. This model was found to be 12.51 times more likely to occur than the null model. Notably, the isolated effect of size was substantiated (BF_{10} = 4.51). Finally, there was substantial evidence of a lack of interaction between size and group (BF_{10} = 0.26), supporting the null hypothesis, according to which size sensitivity is not modulated by age.

Estimation task

We examined performance in the vision-for-perception task by analyzing the perceptual estimates of the objects. In contrast to our findings for grasping, in the child group, we found a striking difference between correct and incorrect trials. In particular, size estimations mirrored the forced-choice percep-

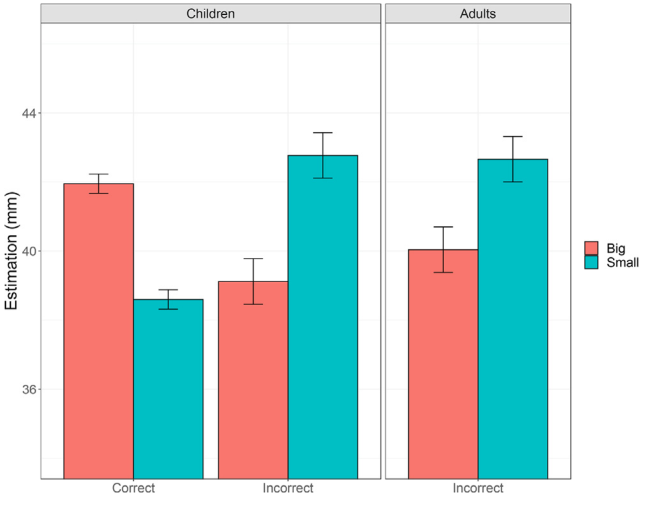

Fig. 4. Estimation experiment results. Size sensitivity was measured using a touchscreen app for big and small objects. Children were "sensitive" to size only when their perceptual decisions were in line with the actual size differences between the objects. In trials where erroneous decisions were made, the small object was estimated as bigger than the physically bigger object. For adults, only trials in which erroneous decisions were made were included in the analysis. Error bars represent confidence intervals for the main effect of object size as calculated by repeated-measures analyses of variance (Jarmasz & Hollands, 2009).

tual decision, with robust sensitivity to size in the correct trials, whereas a reversed pattern of results reflected a significant illusory effect in the incorrect trials (Fig. 4). A repeated-measures ANOVA with perceptual estimation as the dependent variable and with size (small or big) and correctness (correct or incorrect) as the independent variables revealed a main effect of correctness, $F(1, 16) = 9.86$, $p < .01$, $\eta_p^2 = .38$, qualified by size, $F(1, 16) = 42.80$, $p < .001$, $\eta_p^2 = .72$. This effect held when children's age was added as a covariate to the model, $F(1, 16) = 20.09$, $p < .001$, $\eta_p^2 = .57$. This was supported by a Bayesian repeated-measures ANOVA providing substantial evidence against isolated main effects (size: $BF_{10} = 0.26$; correctness: $BF_{10} = 0.36$) and decisive evidence of an interaction between the two factors ($BF_{10} = 5.186 \times 10^{10}$).

Next, we compared the child and adult groups based on the incorrect trials alone. As depicted in Fig. 4, both groups showed a pattern of reversed size sensitivity, with the small objects being illusively perceived as bigger than the physically bigger objects. The ANOVA revealed a robust effect for illusory size, $F(1, 31) = 44.08$, $p < .001$, $\eta_p^2 = .58$, with no interaction with group or a general difference between age groups (Fs < 1). A Bayesian repeated-measures ANOVA with perceptual estimations as the dependent variable and group (children or adults) and size (small or big) as independent variables revealed decisive evidence of the illusory effect of size ($BF_{10} = 1.11003 \times 10^5$). Importantly, there was anecdotal support for the lack of interaction between size and group ($BF_{10} = 0.454$).

When taken together with the results of the grasping experiment, the perceptual estimation data provide robust evidence of the sensitivity of vision for perception to visual illusions during childhood and adulthood. Children's data are of particular interest given the reversed pattern observed for correct and incorrect trials. These data strongly suggest that the higher accuracy rates of children could not be attributed to their misunderstanding of task instructions or to their shorter span of attention. We elaborate on this issue in the Discussion.

Discussion

The study was designed to tap age-related changes in the functional dissociation between perception and action during childhood. To this end, we measured whether sensitivity to physical size differences between objects was modulated by the Ponzo illusion for visuomotor control and for perceptual estimations in a group of adults and in children aged 5–8 years.

The results of the grasping task showed that children retained intact sensitivity to the physical size differences between objects not only in trials where they were deceived by the visual illusion but also in trials where their perceptual decisions were correct. In contrast, children's perceptual estimations in incorrect trials reflected the illusory effect rather than the physical size differences between the objects. These results replicate and extend the pattern of behavior observed in adults in this study and in a previous study that used a similar design (Ganel, Tanzer, et al., 2008), providing additional evidence of a double dissociation between perception and action in the context of illusory and real sizes. The similar pattern of results in the child group suggests that the functional dissociation of perception and action emerges, at least partially, during early childhood. This result is consistent with previous studies providing evidence of dissociation as early as 5 years of age (Hadad et al., 2012). Our results extend this research to demonstrate the early emergence of the specialization of the two visual functions in computing objects' size. Already at 5 years of age, visual representations for action are immune to contextual visual information, whereas those mediating the perception of objects are heavily affected by contextual information.

However, despite the apparently mature dissociation of action and perception in children, there are some indications, both in our data and in previous studies, of age-related changes in the pattern of the dissociation. In particular, perception and action have been shown to dissociate in their adherence to Weber's law in children as young as 5 years (Hadad et al., 2012); however, when more complex stimuli are presented, children's grasping trajectories adhere to Weber's law, in clear contrast to adults (Freud et al., 2019). This suggests that the representations mediating on-line grasping may become more refined and more sensitive to the absolute metrics of objects during childhood. The current data further suggest that the representations mediating perceptual processing may be refined with age and become more sensitive to contextual information. Altogether, the results suggest that although the two visual pathways are already specialized during early childhood at computing different aspects of the environment, the computations that mediate perception and action may overlap more closely during childhood. The refinement of this specialization therefore may take more than 5 years to become adult-like.

Reduced susceptibility to visual illusions during childhood

Previous research has shown that children are less susceptible to visual illusions compared with adults (Hadad, 2018; Happé, 1999; Kaldy & Kovács, 2003). It was recently suggested that this reduced susceptibility is not an all-or-nothing phenomenon (Hadad, 2018). Consistent with this conclusion, we found that children were affected by the Ponzo illusion; however, they were less susceptible to the illusion compared with adults. In particular, children were remarkably more accurate in deciding which object was smaller or bigger than adults (~50% vs. ~20%), and this pattern of results was consistent across the different groups of participants completing the grasping and manual estimation tasks.

Importantly, however, in the current study we evaluated perceptual performance based on a forced-choice task (a dichotomous measure) but also based on perceptual estimation (a continuous measure, more equivalent to the grasping task). Closer inspection of this latter measure reveals an interesting pattern. In particular, we found that in trials where children were affected by the illusion (i.e., incorrect decisions), the effect of the illusion was similar in magnitude to that observed in adults. These findings suggest that the nature of the task (adjustment vs. forced choice) might modulate the observed sensitivity to visual illusions during childhood and more broadly point to the need to control for task difficulty level, the types of processing involved, and the type of the task in future attempts to probe the developmental trajectory of susceptibility to illusions.

Finally, the accuracy scores of approximately 50% for the two-alternative forced-choice task of the child groups raise concerns that the children may have had difficulties in understanding or remaining on task. However, the data in the perceptual estimation task weaken such an alternative explanation. In particular, as described above, children's perceptual adjustments of perceived size closely matched their forced-choice perceptual decisions. This consistency suggests that the observed age-related changes reflected developmental changes in the susceptibility to illusions rather than other less relevant aspects of behavior.

The susceptibility of the perceptual system to contextual illusions has been shown to be modulated by age; however, the developmental trend of the susceptibility to illusions also depends on the specific nature of the contextual illusion. In the case of the Ebbinghaus illusion, for example, developmental studies have had inconsistent results. Some found that 7- and 8-year-olds (Happé, 1999), and even children as young as 5 years, are deceived by the illusion to the same extent as adults (Duemmler et al., 2008; Hadad, 2018; Hanisch et al., 2001). Others suggested that the effect of the illusion might be weaker in children (Kaldy & Kovács, 2003; Weintraub, 1979; Zanuttini, 1996) or even absent in children younger than 7 years (Doherty et al., 2010). Still others found varying age trends for different components of the same illusion configuration (Porac & Coren, 1981). The mixed pattern of results might be related to variations in the spatial arrangements of the stimulus configurations. The spatial distances between the elements composing the Ebbinghaus display varied across the different studies. Because the spatial interrelations of elements composing a scene are particularly critical for spatial integration skills in young children (Hadad & Kimchi, 2018), this uncontrolled parameter across studies may account for the inconsistencies.

Limitations

The study provides important insights into the development of a functional dissociation between perception and action. However, several limitations should be noted and perhaps addressed in future experiments.

First, we included data from children as young as 5.5 years. Importantly, by this age visuomotor control is already developed and children are engaged in various fine-grained visuomotor tasks such as tool use, writing, and manipulating small objects (e.g., blocks, toys, food) in their surroundings. Hence, future studies should probe the functional dissociation in younger children by adopting different experimental approaches to characterize visuomotor behavior. It is possible, for example, that our task and setup of kinematic data collection (i.e., active markers attached to the fingers) is not ideal for younger ages (for an adjusted task, see Street, James, Jones, & Smith, 2011). Note, however, that the data providing evidence of the perception–action dissociation in our age group are highly informative given that previous studies suggested that the dissociation between action and perception is not entirely mature in 5- to 7-year-old children (Doherty et al., 2010).

An additional limitation was the between-participants design. In particular, in many previous studies with adult populations, the same participants completed both perceptual and visuomotor tasks (Franz, Hesse, & Kollath, 2009; Ganel, Chajut, et al., 2008; Ganel, Tanzer, et al., 2008). For practical reasons (i.e., keeping the session duration as short as possible to allow children to complete the experiment without losing attention), we obtained data on perceptual and visuomotor tasks separately. This prevented us from looking at potential correlations between perceptual and visuomotor abilities.

Conclusions

Our goal was to explore the nature of the double dissociation between perception and action during childhood. We found that, similar to adults, children's grasping behavior can resist the effect of the Ponzo illusion, whereas their perceptual estimations are deceived by the illusion. These results suggest that the functional dissociation between perception and action emerges relatively early in life.

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