Developmental trends in susceptibility to perceptual illusions: Not all illusions are created equal

Bat Sheva Hadad [1]

Abstract

This study examined the development of the utilization of contextual information in visuospatial integration during childhood. We examined four contextual size illusions in children and adults asking whether young children's sensitivity to context is reduced or varies with the perceptual mechanisms or the levels of integration involved. We tested susceptibility to contextual illusions in four-year-olds, seven-year-olds, and adults, employing two psychophysical paradigms, perceptual estimation and a 2AFC discrimination task. We tested susceptibility to Ebbinghaus and Ponzo illusions to estimate the effect of the interaction of object size with its contextual background on the rescaling of its perceived size; we also tested susceptibility to the rectangle and 3D-cube illusions to estimate the effect of the interaction of two dimensions of the target object on the rescaling of its perceived size. While four-year-olds were affected by the Ebbinghaus and Ponzo illusions, they showed no susceptibility to the rectangle or 3D-cube illusion. The results show that, overall, sensitivity to context is not reduced in early childhood; rather, it varies with the perceptual mechanisms or the levels of integration involved. In particular, development is protracted for size illusions in which contextual effects entail the extraction of the relations of dimensions within an object.

Keywords Ponzo illusion · Ebbinghaus illusion · Integral-separable dimensions · 3D-cube illusion · Context · Visual illusions

Introduction

Protracted development of spatial integration skills has been demonstrated for several basic visual skills, including contour interpolation (e.g., Hadad, Maurer, & Lewis, 2010a), contour integration (Hadad & Kimchi, 2006; Hadad, Maurer, & Lewis, 2010b; Kovacs, 2000), shape formation of line configuration (e.g., Hadad & Kimchi, 2006), and hierarchical stimuli (e.g., Mondloch, Geldart, Maurer, & de Schonen, 2003; Kimchi, Hadad, Behrman, & Palmer, 2005). Integration over a larger scale of contextual effects on perception is also claimed to be weaker in children (e.g., Kaldy & Kovacs, 2003). Researchers have mainly used contextual visual illusions to demonstrate the implicit integration of visuospatial information, in which the neighboring context is automatically integrated into the perception of individual elements; however, developmental findings are mixed and hard to interpret. In a bid to clarify the mixed picture, we tested developmental trends in the susceptibility to contextual illusions of size perception, with each illusion reflecting a different constraint developed by the visual system to support the efficient formation of visual representations.

Susceptibility to perceptual illusions is often taken to reflect the constraints developed by the perceptual system to support the efficient formation of the representations required to adequately describe the external environment (see Eagleman, 2001 for a review). Although perceptual illusions reflect misrepresentations of the physical world, they may be consequences of a perceptual bias to integrate visual information based on statistically optimal computations underlying a coherent perception of objects and scenes (Weiss, Simoncelli, & Adelson, 2002). They have been extensively investigated in both the mature and the developing brain, as well as in atypical development. Although the underlying mechanisms of perceptual illusions remain unclear, researchers have used illusory stimuli to study perceptual development.

Susceptibility to contextual illusion is shown to be modulated by age (e.g., Billino et al., 2009). Some authors have suggested that susceptibility to visual illusion reaches an adult level between the ages of 6 (e.g., Weintraub, 1979; Zanuttini, 1996) and 15 years (e.g., Bondarko & Semenov, 2004;

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Brosvic et al., 2002), while developmental rates vary with the specific pattern employed (e.g., Billino et al., 2009; Coren & Girgus, 1978). The variability in the developmental results may be attributed to the diversity of the stimuli traditionally considered illusory. Illusions vary greatly in terms of: (a) the perceptual mechanisms or physiological pathways involved; (b) the levels of integration required; (c) the type of subjective impression they induce; and (d) the complexity of the display and the final appearance. Developmental trajectories also vary across paradigms employed – with some, the simple "yes/no" paradigms in particular, predisposed to criterion changes across trials, conditions, or subjects (e.g., Hanisch et al., 2001). Modulations in the magnitude of illusions have therefore been suggested, for example, to reflect age changes in perceptual strategies rather than age changes in the perceptual processes themselves (e.g., Girgus, Coren, & Fraenkel, 1975).

To cite one example, in the case of the Ebbinghaus illusion (or Titchener circles; Ebbinghaus, 1902; see Fig. 1a), a geometric illusion demonstrating contextual modulation in the perception of a local target, developmental studies have had inconsistent results. Some show that seven- to eight-year-olds (Happe, 1999), even children as young as five years old, are deceived by the illusion to the same extent as adults (Duemmler et al., 2008; Hanisch, Konzak, & Dohle, 2001). Others suggest that the effect of the illusion might be weaker in children (Kaldy & Kovacs, 2003; Weintraub, 1979; Zanuttini, 1996) or absent in children younger than seven years old (Doherty, Campbell, Tsuji, & Phillips, 2010). Still others have found varying age trends for different components of the same illusion configuration (Porac & Coren, 1981).

Developmental studies are equally inconsistent in the case of the Ponzo illusion (Ponzo, 1911; see Fig. 1b), a geometrical illusion wherein a pair of converging lines distorts the perception of two identically sized lines. The illusion effect has been to shown to increase with age (Hanley & Zerbolio, 1965). When tracked throughout the lifespan in participants aged 3.5–88 years, it increased rapidly up to about age 13 years, after which it remained stable through to age 50 years and then decreased markedly (Leibowitz & Judisch, 1967). Age-related changes in the utilization of pictorial depth cues are likely to account for the increased susceptibility to the illusory settings, such as the Ponzo, in which contextual information with a static depth leads to size rescaling. Sensitivity to static pictorial information for depth emerges between 22 and 26 weeks (Yonas, Cleaves, & Petterson, 1978), is present at age three (Benson & Yonas, 1973), but gradually develops over time. Three-year-olds lack the ability to process size-distance information presented by perspective, interposition, and texture; nine-year-olds make a better adjustment, while adults make consistent and ecological use of the information in the stimulus array (e.g., Wilcox & Teghtsoonian, 1971).

The reduced contextual modulations of perception during development have been attributed to the limited distances over which long-range interactions extend during development (Káldy & Kovács, 2003; Kovács, 2000; Kovács et al., 1999; Kozma et al., 1997). Visuospatial integration skills, as measured in contour integration tasks (Hadad, Maurer, & Lewis, 2010; Kovács, 2000) or shape formation tasks (Hadad & Kimchi, 2006; Kimchi et al., 2005), demonstrate protracted development, particularly when the perception of inter-relations of within-object dimensions is required (Hadad & Kimchi, 2006, 2017; Stiles, 2001). In geometric illusions, however, the effect of context has mostly been tested using the Ponzo and Ebbinghaus displays, demonstrating between-object context modulation of the perception of a local target. These particular developmental studies have focused on age-related changes in the magnitude of the illusions, however, not on the perceptual mechanisms or the levels of integration involved.

Susceptibility to contextual illusions may develop at different rates depending on the visuospatial integration levels required. For example, in contextual illusions involving the processing of within-object relations, it is the integral processing of the specific dimensions of the target stimulus (e.g., width and length of a shape), not its interaction with a contextual background that leads to perceptual rescaling. This is demonstrated in settings such as the rectangle illusion (Ganel & Goodale, 2003; see Fig. 1c), in which short rectangles are often perceived as being wider than longer ones with equal width, and in the 3D-cube illusion (Ben-Shalom & Ganel, 2012; see Fig. 1d), in which the horizontal side of a cube with increased depth is perceived as being shorter. Contextual effects, which, in such displays, entail the extraction of the relations within an object, have been considered a relatively late processing stage that demands the higher-level processing abilities of adults (Ben-Shalom & Ganel, 2012).

We examined developmental trends in the susceptibility to contextual illusions of size perception, with each illusion reflecting a different constraint developed by the visual system to support the efficient formation of visual representations. In all cases, illusion arises from the implicit integration of visuospatial information, whereby the neighboring context is automatically integrated into the perception of individual elements in a mandatory manner, with little or no dependence on higher cognition (e.g., Doherty et al., 2010). We ran within-subject comparisons of the different contextual illusions of size perception, asking whether young children's sensitivity to context is reduced overall or if it varies with the perceptual mechanisms or the levels of integration involved.

We employed two robust psychophysical paradigms, perceptual estimation and a 2AFC discrimination task, to estimate a group of illusions reliably at age as young as four years. We tested susceptibility to the Ebbinghaus and Ponzo illusions to estimate the effect of the interaction of an object's size with its contextual background (i.e., between-object) on the rescaling of its perceived size, and we tested susceptibility to the rectangle and the 3D-cube illusion to estimate the effect of
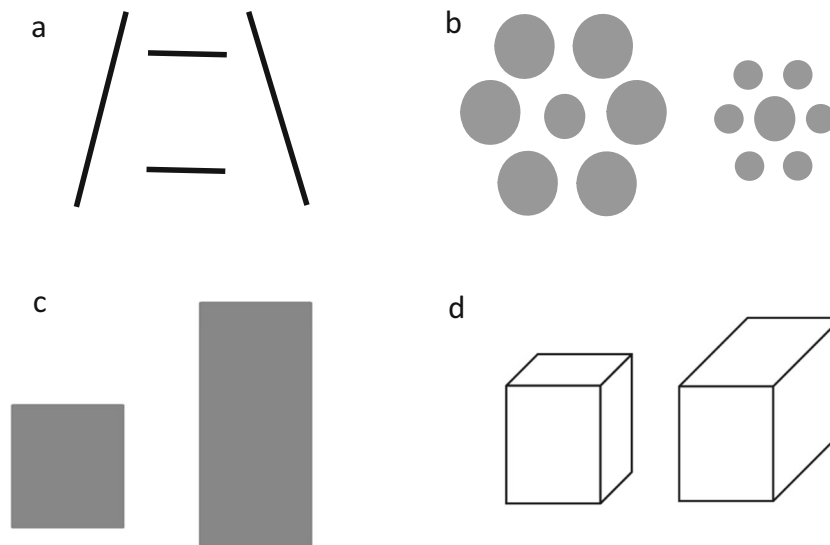
Fig. 1 Examples of the (**a**) Ponzo, (**b**) Ebbinghaus, (**c**) rectangle, and (**d**) 3-D cube illusions

the interaction of two dimensions of the same object (i.e., within-object) on the rescaling of the perceived size. Different developmental trends for the different contextual size illusions would indicate that the development of the ability to utilize context varies with the perceptual mechanisms or the levels of integration involved.

Experiment 1: Size adjustment tasks

Participants Sixty participants in three age groups participated in the experiment: 20 aged four to five years (mean age = 4.79; range = 4.08–5.37 years; 11 females), 20 aged seven to eight years (mean age = 7.72; range = 7.06–8.72 years; eight females), and 20 adults (mean age = 26.5; range = 24–30 years, 12 females). Participants had normal or corrected-to-normal vision. Adults, who were students at the University of Haifa, received course credit, and children received a gift card at the end of the experiment as a reward for their participation.

The experimental protocol was approved by the Research Ethics Committee of the University of Haifa (approval number 016/15). The procedures were explained, and informed consent was obtained from the adult participants and from the parents of the children. Each participant completed a perceptual adjustment task for the four illusions, presented in random order across participants in each age group. For the four-year-olds, the experiment was divided into two sessions (each containing two of the four illusions), carried out on different days.

Stimuli and procedure For each trial, participants used the "up" and "down" arrow keys to adjust a comparison stimulus to appear the same along a physical dimension as a standard stimulus (or a particular part of the optical illusion display

designated as the comparison feature). Participants were given as much time as they needed to complete each trial and pressed a "done" button displayed on the bottom-left of the computer screen when they felt they had matched the comparison stimulus to the standard. The participant's final adjustment was measured in pixels.

The Ebbinghaus display was composed of a central circle surrounded by relatively big circles, 55 mm in diameter (big context condition), or relatively small ones, 15 mm in diameter (small context condition). The diameter of the central circle was 25, 35, or 45 mm. The initial diameter of the comparison discs varied randomly from 15 to 55 mm across trials. Participants were asked to use the mouse to adjust the comparison circle presented at one side of the screen to match the central circle.

In the Ponzo illusion, the display contained a pair of converging lines with two horizontal lines, one above the other, embedded between them. In each trial, either the "far" or the "near" bar appeared as the standard at possible lengths of 20, 30, and 40 mm. Participants were asked to use the mouse to adjust the comparison bar presented at one side of the screen to match the bar presented at the Ponzo display. The initial length of the comparison bars varied randomly from 10 to 50 mm across trials.

In the rectangle illusion, the standard rectangle's width was 27, 30, or 33 mm, and the length was either 40 or 80 mm. The participant's task was to adjust the width of the comparison bar to match the standard's width. The initial width of the bar varied randomly from 20 to 40 mm across trials.

In the 3D-cube illusion, the standard was a filled three-dimensional cube with black contour lines that were either 27, 30, or 33 mm in length and width. The cube depth dimension was either 20 mm or 50 mm. The participant's task was to adjust the width of the comparison bar to match the standard's

width. The initial width of the bar varied randomly from 20 to 40 mm across trials.

Results

To examine illusion size across the different physical sizes of the estimated feature, we computed the dependent variable in each of the illusions as the standardized difference between the perceived and the real size ((perceived-real)/real), for each participant, in each of the conditions. We examined age-related changes in the illusion size in terms of the differences between the estimated sizes in the two context conditions (e.g., big and small context in the Ebbinghaus).

Ebbinghaus illusion Figure 2a depicts the mean estimated sizes for the "big" and the "small" contexts for the different age groups. When the illusion is effective, a targer disc surrounded by small circles is perceived as larger than an identical disc surronded by large circles. We carried out a mixed-design ANOVA on the illusion size, with age as between-subject factor and context (big or small) as within-subject factor. The analysis revealed a significant effect of context, $F(1,45)=92.55$, $p<0.0001$, $\eta_p^2=0.67$, demonstrating that the central circle was perceived bigger when it appeared in the smaller context (.36, .42, and .37, for four-year-olds,

seven-year-olds, and adults, respectively) than when it appeared in the bigger context (-.25. -.16, and -13 for four-year-olds, seven-year-olds, and adults, respectively). Although the illusion was observed at as early as four years of age, $t(15)=9.14$, $p<0.0001$, there was also a significant effect of age, $F(2,45)=3.66$, $p<0.03$, $\eta_p^2=0.14$, and an interaction between age and context, $F(2,45)=4.34$, $p<0.02$, $\eta_p^2=0.16$. Further inspection of the interaction revealed a decrease in illusion size with age for the bigger context, $F(2,45)=7.92$, $p<0.0001$, $\eta_p^2=0.26$, but not for the smaller one, $F(2,45)=1.46$, $p>.24$. Because no condition of size estimation of a circle free of context was manipulated, we can only speculate that this may be a result of an overall bias towards underestimation of size at young ages, particularly in the case of the smaller circle (diameter 25 mm).

Consistent with this pattern, correlations computed between age and illusion size revealed a reduced illusion size with age, $r(48)=-.294$, $p<.05$ (Fig. 2b), specifically, more extreme size estimations in the bigger context at early ages, $r(48)=.415$, $p<.0003$. Despite these age-related changes, the results suggest that children as young as four are affected by the context in the Ebbinghaus displays.

Ponzo illusion Figure 3a depicts the mean estimated lengths of the "far" and the "near" contexts for the different age groups. When the illusion is effective, a pair of converging lines
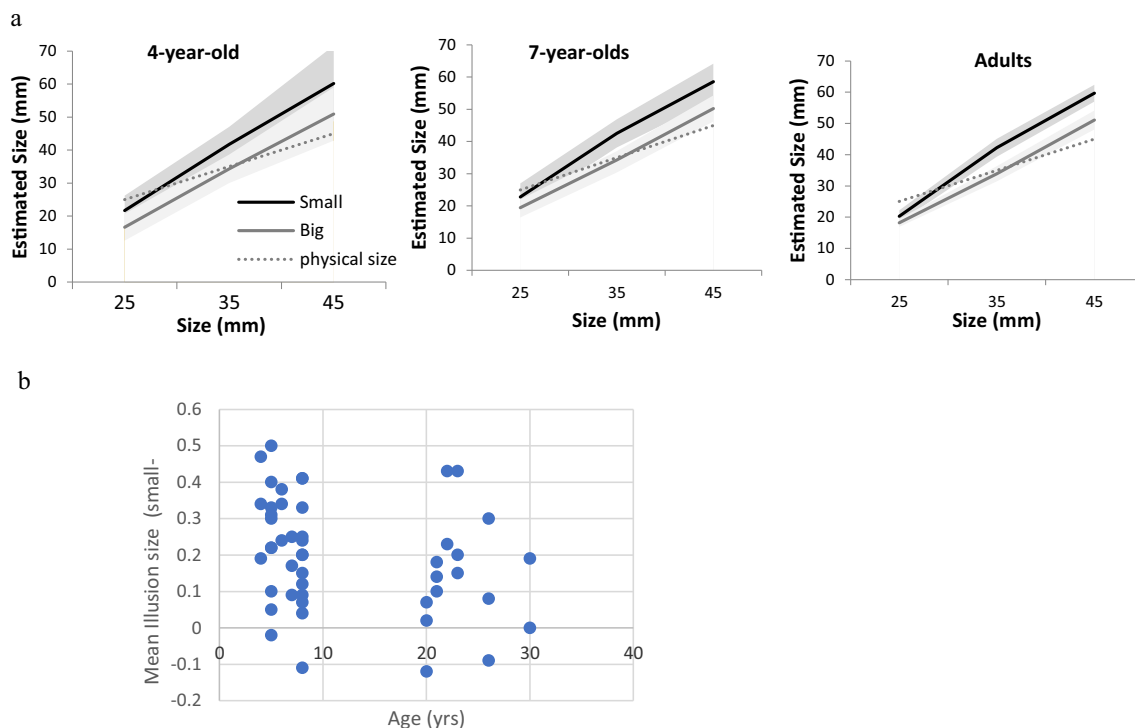

Fig. 2 (a) Mean estimated sizes for the "big" and the "small" contexts in the different age groups. The shaded error bands indicate standard deviations demonstrating scalar variability – a proportional increase in SDs with the mean of the reproduced sizes (25, 35, and 45 mm circles) at all ages. SDs also increase with the illusory perceived size (larger SDs for the small context condition), providing further indication of the illusory effect at all ages. (b) Mean illusion size as a function of age
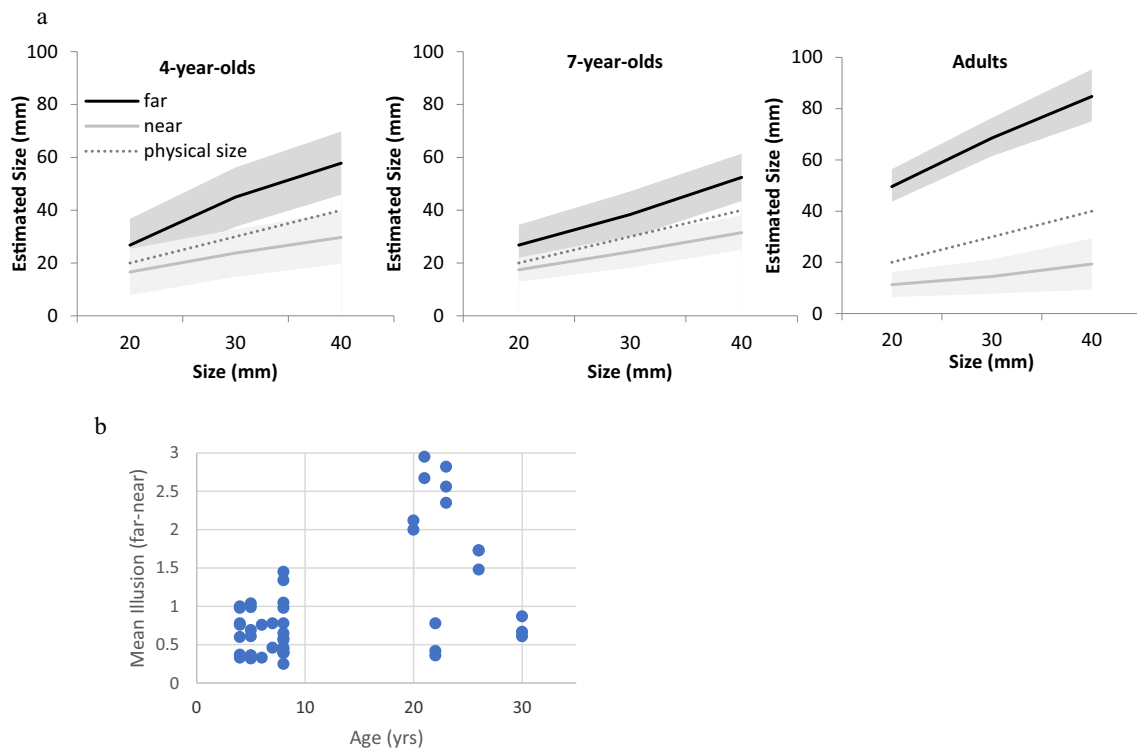
a

b

Fig. 3 (**a**) Mean estimated sizes for the "far" and the "near" contexts in the different age groups. The shaded error bands indicate that the variability of estimations scale with the mean of the reproduced sizes

(20, 30, and 40 mm) at all ages. SDs also increase with the illusory perceived size (larger SDs for the near context condition); (**b**) Mean illusion size as a function of age

distorts the perception of two identically sized lines, with the upper line appearing illusorily longer than the lower line. A mixed-designed ANOVA was carried out on the illusion size, with age as a between-subject factor and context ("farther" or "closer" in depth) as a within-subject factor. The analysis revealed a significant effect of context, $F(1,45)=98.01, p<0.000, \eta_p^2=0.68$, demonstrating that the length of the upper, "far" bar (.43, .28, and 1.18, for four-year-olds, seven-year-olds, and adults, respectively) was percieved as substantially longer than the lower, "near" one (-.19, -.15, and -.45, for four-year-olds, seven-year-olds, and adults, respectively). Importantly, this difference between size estimation of the "far" and the "near" bar was already observed at age four, $t(15)=9.41, p<.0001$. The analysis also revealed a significant effect of age, $F(2,45)=11.68, p<0.0001, \eta_p^2=0.34$, and an interaction between age and context, $F(2,45)=16.60, p<0.0001, \eta_p^2=0.42$, indicating that although they were observed for both the "far" and the "near" bar, $F(2,45)=14.84, p<0.0001, \eta_p^2=0.40$, $F(2,45)=21.30, p<0.0001, \eta_p^2=0.48$, respectively, age-related changes in the differences between real and estimated length were more pronounced for the "far" bar.

Consistent with this pattern, correlations computed between age and illusion size revealed an increased illusion size with age, $r(48)=.521, p<.000$ (Fig. 3b). Illusions size increased with age for both the "near" and the "far" bar ("far" bar, $r(48)=.496, p<.0001$; "near" bar, $r(48)=-.585, p<.0001$).

Rectangle illusion Figure 4a depicts the mean estimated sizes in the "short" and the "long" rectangles as a function of age. When this illusion is effective, short rectangles are perceived as being wider than longer ones with equal width. A mixed-designed ANOVA was carried out on the illusion size, with age as a between-subject factor and context (short or long) as a within-subject factor. The analysis revealed a significant effect of context, $F(1,45)=7.57, p<0.009, \eta_p^2=0.14$, demonstrating that the width of the rectngle was perceived as larger for shorter than for longer rectangles. This effect of context on width estimation was qualified by age, $F(2,45)=3.21, p<0.05, \eta_p^2=0.13$. Specific comparisons for each age group indicated that while seven-year-olds and adults' perception of one dimension of the rectangle (i.e., width) was affected by the other dimension (i.e., length), $t(15)=3.42, p<.004$; $t(15)=4.00, p<.001$, respectively, the four-year-olds did not show such an effect, $t(15)=.12, p>.90$.

Consistent with this pattern, correlations computed between age and illusion size revealed an increased illusion size with age, $r(48)=.305, p<.04$ (Fig. 4b). Contrary to our findings for the Ebbinghaus and the Ponzo illusions, in this case, the four-year-olds did not demonstrate the contextual effects of the varying length on the estimated width.
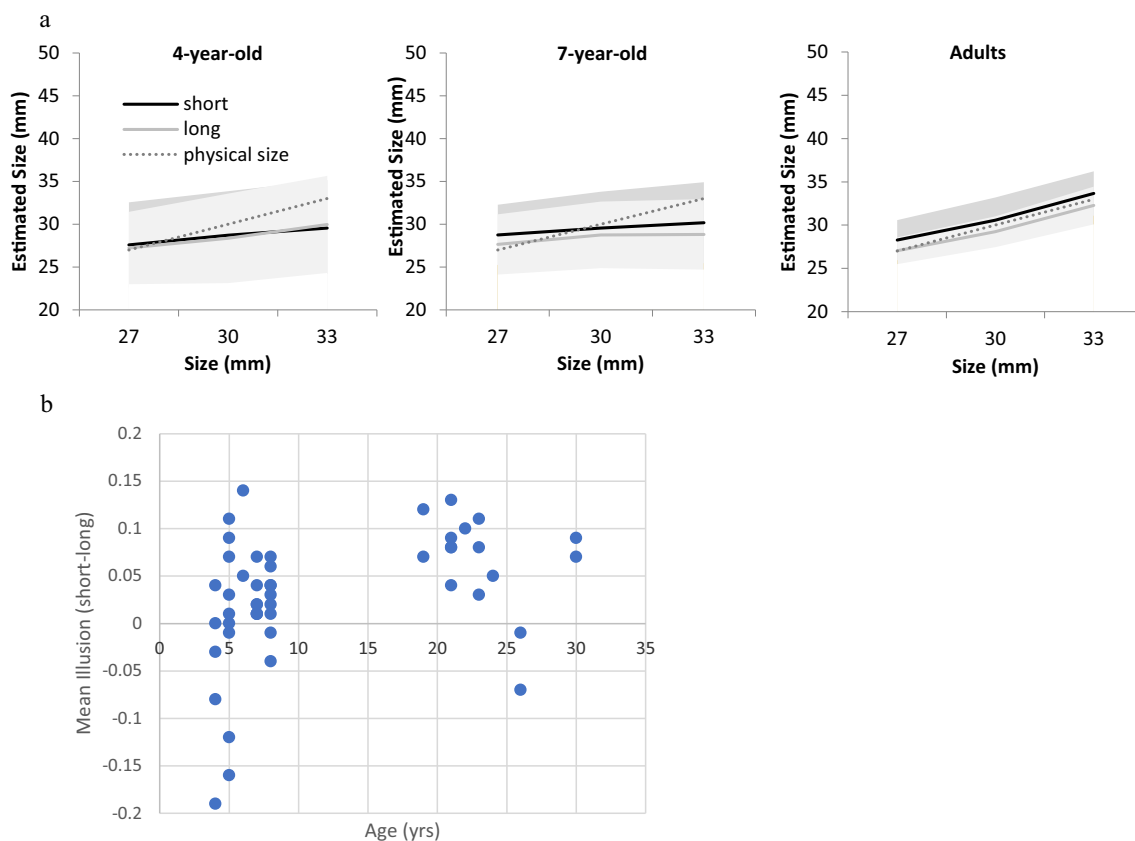
a

b

Fig. 4 (a) Mean estimated sizes for the "long" and the "short" rectangles in the different age groups. The shaded error bands indicate that the variability of estimations scale with the mean of the reproduced sizes (27, 30, and 33 mm) at all ages, even for the four-year-olds who do not show the illusion. (b) Mean illusion size as a function of age

3D-cube illusion Figure 5a depicts the mean estimated widths in the 20-mm and 50-mm depth cubes as a function of age. When this illusion is effective, the horizontal side of a cube with increased depth is perceived as shorter. A mixed-designed ANOVA was carried out on the illusion size, with age as a between-subject factor and context (20 mm or 50 mm depth) as a within-subject factor. The analysis revealed a significant effect of context, $F(1,45)=8.36$, $p<0.006$, $\eta_p^2=0.16$, demonstrating that the width of the cube with greater depth was perceived as smaller. This effect of context on width estimation was qualified by age, $F(2,45)=6.67$, $p<0.003$, $\eta_p^2=0.23$. Specific comparisons for each age group indicated that while seven-year-olds and adults perceived the width of the cubes with greater depth as smaller, $t(15)=3.26$, $p<.005$; $t(15)=3.72$, $p<.02$, respectively, the four-year-olds did not show such an effect, $t(15)=.205$, $p>.84$.

Consistent with this pattern, correlation computed between age and illusion size revealed an increased illusion size with age, $r(48) =.347$, $p<.016$ (Fig. 5b). As in the case of the rectangle illusion, the four-year-olds did not respond to the contextual effects of the varying depths on the estimated width.

Experiment 2: Size discrimination task

To confirm the age trends for the two types of contextual modulations of perception, we used the classic psychophysical method of constant stimuli to a new group of participants, comparing susceptibility to illusions based on relational properties between objects (Ebbinghaus) to those based on within-object relational properties (rectangle).

Participants Twenty-four participants in two age groups participated in the experiment: Twelve four- to five-year-olds (mean age = 4.89; range = 4.18–5.17 years; eight females), and 12 adults (mean age = 22.5; range = 19–30 years, six females). Participants had normal or corrected to normal vision.

Stimuli and procedure Participants performed a 2AFC discrimination task indicating on each trial which looked bigger, a physical dimension used as a standard stimulus (or a particular part of the optical illusion display designated as the standard feature) or a comparison stimulus.
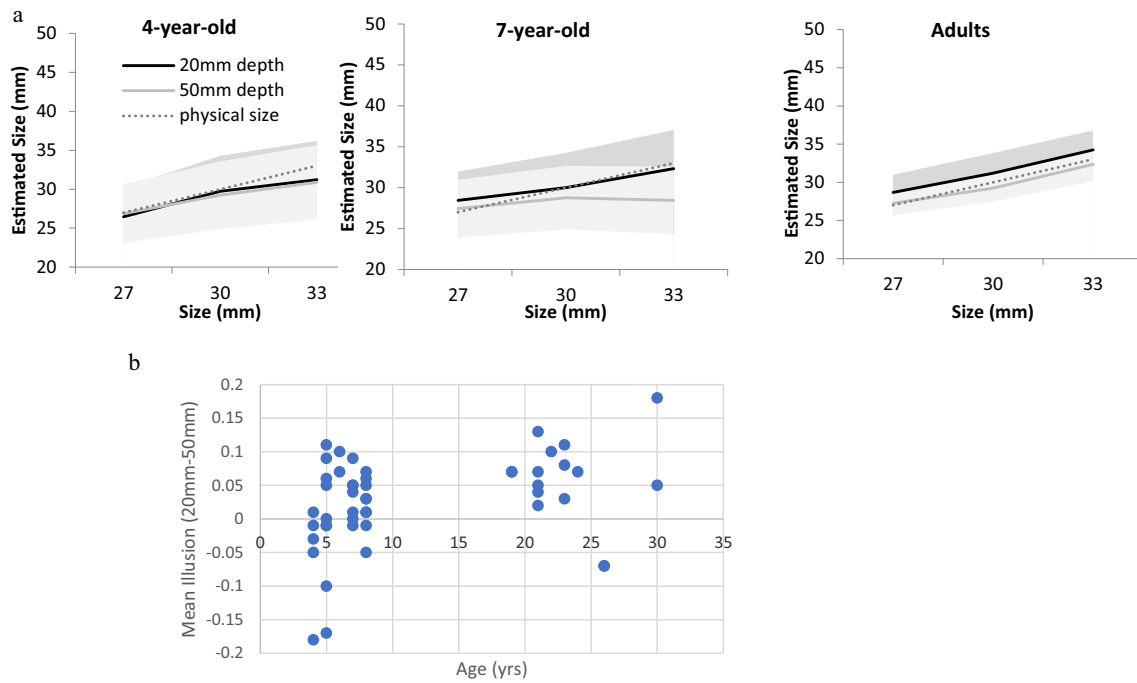
Fig. 5 (**a**) Mean estimated sizes for the 20-mm and 50-mm cubes in the different age groups. The shaded error bands indicate that the variability of estimations scales with the mean of the reproduced sizes (27, 30, and 33 mm) at all ages, even for the four-year-olds who do not show the illusion. (**b**) Mean illusion size as a function of age

For the Ebbinghaus displays, the standard stimulus was held constant at 35-mm diameter, while the comparison stimulus had one of eight different sizes (31, 32, 33, 34, 36, 37, 38, and 39 mm). Each comparison size was presented ten times. For half of the trials, the neighboring context was composed of relatively big circles of 50 mm in diameter (big context condition), while for the other half, the neighboring context was composed of relatively small circles of 10 mm in diameter (small context condition). Participants were asked to refer to the central circle and to compare it with the other circles. The order of trials and the side on which the comparison disk was presented were randomized for each block of trials. Short blocks of 20 trials were used to help the children remain on task.

For the rectangle displays, the standard stimulus was held constant at a length of 30 mm, while the comparison stimulus was one of eight different lengths (26, 27, 28, 29, 31, 32, 33, and 34 mm). Each comparison length was presented ten times. For half of the trials, the rectangle was relatively short (10 mm), while for the other half, it was relatively long (50 mm). Participants were asked to refer to the lower horizontal side of the rectangle and to compare it with the comparison rectangle.

Participants were told that the comparison was always either larger or smaller than the standard and asked to guess if they could not decide. Twelve practice trials, for which feedback was given, were carried out before the presentation of the experimental trials.

Results

A logistic function was fitted to the data, and the point of subjective equality (PSE), indicating the size value at the point of chance accuracy (50% correct), was computed for each participant, in each of the conditions. The goodness of fit of each participant to a logistic function was measured (mean R^2 =.96 for the Ebbinghaus and mean R^2 =.97 for the rectangle). For each of the illusions, the effect of context on size scaling was indicated by the shift of the PSEs of the curve (see Fig. 6). A mixed-design ANOVA on the PSEs, was carried out with age group (four-year-olds and adults) as the between-subject factor and context as the within-subject factor.

Ebbinghaus The analysis revealed a significant effect of context on the PSEs, $F(1,22)=58.28$, $p<0.0001$, $\eta_p^2=0.73$, with smaller PSEs indicating circles were perceived as smaller when surrounded by bigger circles (Fig. 7a). Overall, PSEs were lower at age four, $F(1,22)=6.87$, $p<0.02$, $\eta_p^2=0.24$, but the interaction between context and age did not reach significance, $F(1,22)=1.51$, $p>0.23$, indicating similar susceptibility to the Ebbinghaus displays in four-year-olds, $t(11)= 5.15$, $p<0.0001$, and adults, $t(11)= 6.27$, $p<0.0001$. Illusion size did not vary across age, $r(24) =-.282$, $p>.018$, and, if anything, the trend indicated a reduced illusion size with age.

Rectangle We observed a different pattern of results for the rectangle. The context affected PSEs, $F(1,22)=13.21$,
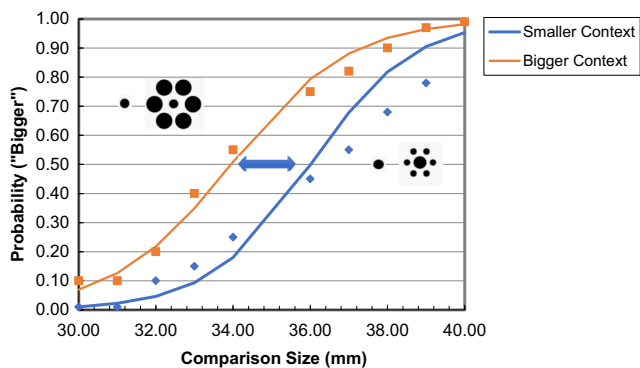
Fig. 6 Data for a representative adult participant: psychometric curves for "bigger" and "smaller" context conditions where the percentage of "larger" responses is plotted as a function of the difference between the comparison and the standard stimuli. An observer's susceptibility to the contextual modulations is inferred from the difference between the PSEs of the two functions (indicated by the arrow). The yellow curve shows a case where the point of subjective equivalence is shifted to the left, indicating that the size of the central circle was perceived as smaller when presented with bigger circles

$p<0.0001$, $\eta_p^2=0.38$, with smaller PSEs for longer rectangles indicating that width was perceived as smaller for longer ones (Fig. 7b). Once again, PSEs were lower at age four, $F(1,22)=6.53$, $p<0.018$, $\eta_p^2=0.23$; however, unlike the Ebbinghaus displays, the interaction between context and age was significant, $F(1,22)=5.93$, $p>0.023$, $\eta_p^2=0.21$, indicating susceptibility to the rectangle illusion in adulthood, $t(11)= 5.30$, $p<0.0001$, but not at four years of age, $t(11)=.732$, $p>0.48$. Illusion size increased significantly with age, $r (24) =.447$, $p<.03$.

Discussion

The results show that the developmental trends in susceptibility to perceptual illusions depend on the specific nature of the contextual illusions being viewed. We observed susceptibility to size illusions as early as four years of age for the Ebbinghaus and the Ponzo illusions, with age-related changes observed for both. However, while contextual modulations of

size scaling decreased with age for the Ebbinghaus illusion, they increased with age for the Ponzo illusion, presumably because of the immature utilization of pictorial depth cues underlying size rescaling in these displays. The most dramatic age-related changes were observed for the rectangle and the 3D cube illusory displays. In contrast to the early susceptibility to the Ebbinghaus and the Ponzo illusions, within-object illusory context biased the size scaling only at age seven. This pattern of results, suggesting different developmental rates for different illusions, was obtained for both the adjustment and the discrimination tasks.

Critically, scalar variability indicating a linear increase in standard deviation with the mean of reproduced magnitude (e.g., diameter of the central disc in Ebbinghaus), which is considered a strong form of Weber's law (e.g., Rakitin et al., 1998), was observed in all conditions, at all ages. This indicates that the perceived magnitude of the estimated dimension was similarly encoded across the different ages, and that the developmental changes observed cannot be attributed to differences in basic encoding or to misunderstandings of the task. Although, as expected, SDs for the youngest group were overall larger than those of adults, the ratio between SDs of adults and children remained constant across the illusions and thus cannot explain the dissociation found in age-related changes between the different illusions. Remarkably, scalar variability also scaled with the illusive values for all illusions for the seven-year-olds and adults, indicating that Weber's law holds for the perceived input, not just for the physical input (Ross & Gregory, 1961). Interestingly, for the four-year-olds, SDs scaled with the mean of the reproduced magnitudes only for the illusions for which this age group shows susceptibility (Ebbinghaus and Ponzo illusions). Consistent with our finding of four-year-olds' resistance to the rectangle and the cube illusions, SDs did not vary between the different context conditions for them, thus strongly supporting our conclusion that these two illusions have no influence on perception in early childhood.

How might processing change during early childhood to produce this pattern of results? Although exhibiting a more veridical perception of the judged feature in the rectangle and the 3D cube illusory displays, the four-year-olds' performance
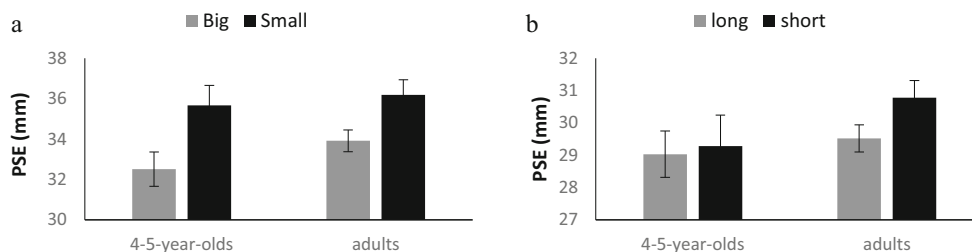

Fig. 7 Mean PSEs for the (a) Ebbinghaus and (b) rectangle illusions as a function of context for four-year-olds and adults. Error bars indicate within-subject 95% confidence intervals

suggests reduced visuospatial integration skills and shape formation. For adults, the susceptibility to such illusory settings has been taken to suggest integral processing of the dimensions composing an object, such that that the perception of one dimension of an object cannot be achieved independently from other dimensions of the same object (Felfoldy, 1974; Ganel & Goodale, 2003). In both the rectangle and the cube illusions used here, holistic processing of the object's shape is mandatory; single parts belonging to the same object cannot be represented in an isolated manner but must be perceived in relative terms. While this integrality of the two dimensions (i.e., length and width in the case of the rectangle) governs adults' perception even when the task entails independent processing, children show analytic processing, demonstrating a remarkable ability to ignore the other, irrelevant dimension. Clearly, enhanced selective attention skills at early ages is unlikely to account for this result (e.g., Plude, Enns, & Brodeur, 1994); performance at age four more likely reflects a weaker perceptual representation of the integrated dimensions. Although integration of the target with its nearby context underlies the illusory percept in all contextual illusions, integration levels may vary for the different types of size illusions. For the Ebbinghaus and the Ponzo, extracting the relations between the target and the context is based on the positions of the parts. Similar to the "place relationship" stimuli (Pomerantz, 1983), the global context can be extracted by the placement of the local elements, with little emphasis on their identity. In the 3-D cube and the rectangle illusion, in contrast, context is extracted by inter-element relational processing, determined by the nature of the individual elements, not just their spatial positions (Pomerantz, 1983). Spatial integration of the target with its associated context in such illusions has been considered a more advanced processing stage that demands the higher-level processing abilities of adults (Ben-Shalom & Ganel, 2012); accordingly, it may have a longer developmental trajectory. This interpretation of the results is consistent with former studies testing visuospatial integration skills more explicitly (e.g., Hadad & Kimchi, 2006, 2017; Hadad et al., 2010; Kovacs, 2000). Consistent with our findings, these studies specifically suggest that the spatial interrelations of elements composing the same object are particularly critical for spatial integration skills in young children and, in some cases, much more so than the spatial relations between an object and its neighboring context (Hadad & Kimchi, 2018; Hadad et al., 2010).

Another related explanation is that the developing perceptual system may progress from being broad and generalized to more tightly tuned activation (Simmering, Schutte, & Spencer, 2008; Ward, 1980). By this account, rather than reflecting weak integral representations of the dimensions composing an object, the analytic and the integrated representations may both be accessible in the immature system; the constraints governing the perceptual system supporting the efficient formation of representations lead to a dominant representation of the integrated shape in adults, but not in children. This broader tuning during early childhood may lead to more flexible representations that are less hardwired to process the most informative cues in the stimuli, resulting, in this case, in the analytic perception exhibited by the four-year-olds.

Interestingly, the results also show that the processes exhibiting longer developmental trajectories are identified as late, time-consuming, and requiring controlled processing. Studies of adults have found a dissociation of the susceptibility to within- and between-object contextual illusions for iconic and visual working memory: iconic memory is found to be immune to the effects of within-object contextual illusions, affected only by illusions driven by between-object contextual properties, while visual working memory is affected by both within- and between-object illusions (Ben Shalom & Ganel, 2012). Our findings point to a possible link between the microgenetic evolution of perceptual processes in adults and their ontogenesis over the years (Kimchi, Hadad, Behrman, & Palmer, 2005; Kimchi & Hadad, 2008). Resolving the interrelations of the within-object dimensions composing an object requires controlled resources and may not be accessible during the first few milliseconds of iconic memory. In our study, these relatively late processes in adult perception are the ones that show more protracted development in children.

The dissociation of the two types of illusions is also shown in individuals with autistic traits (Chouinard, Noulty, Sperandio, & Landty, 2013). Although tested in different exemplars of illusions than those used here, studies have demonstrated reduced susceptibility to within-object illusions in individuals with autistic traits compared to controls, and similar susceptibility to between-object illusions. Thus, the illusions that depend more strongly on within-object relational properties, presumably requiring more complex spatial processing, occur late in adults, are slower to develop in children, and are more affected by atypical neural development.

Methodologically, our data suggest illusions can be used to study perceptual development, but only if we take into account the level of the perceptual processing involved. Merely looking at the general susceptibility to perceptual illusions and more specifically to contextual illusions may lead to erroneous conclusions. Any attempts to investigate differences in typical developmental rates and in vulnerability to illusions in abnormal development must control for difficulty levels and, more critically, for the levels and types of processing involved. Considering these critical aspects will also reconcile mixed findings in neurodevelopmental disorders and in clinical populations (e.g., Gori, Molteni, & Facoetti, 2016; Mitchell, Mottron, Soulie`res, & Ropar, 2010), supporting the emerging claim that susceptibility to perceptual illusion is not an all or nothing phenomenon.

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