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From local to global processing: The development of illusory contour perception

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ABSTRACT

Global visual processing is important for segmenting scenes, extracting form from background, and recognizing objects. Local processing involves attention to the local elements, contrast, and boundaries of an image at the expense of extracting a global percept. Previous work is inconclusive regarding the relative development of local and global processing. Some studies suggest that global perception is already present by 8 months of age, whereas others suggest that the ability arises during childhood and continues to develop during adolescence. We used a novel method to assess the development of global processing in 3- to 10-year-old children and an adult comparison group. We used Kanizsa illusory contours as an assay of global perception and measured responses on a touch-sensitive screen while monitoring eye position with a head-mounted eye tracker. Participants were tested using a similarity match-to-sample paradigm. Using converging measures, we found a clear developmental progression with age such that the youngest children performed near chance on the illusory contour discrimination, whereas 7- and 8-year-olds performed nearly perfectly, as did adults. There was clear evidence of a gradual shift from a local processing strategy to a global one; young children looked predominantly at and touched the "pacman" inducers of the illusory form, whereas older children and adults looked predominantly at and touched the middle of the form. These data

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show a prolonged developmental trajectory in appreciation of global form, with a transition from local to global visual processing between 4 and 7 years of age.

Introduction

Visual information about objects is often incomplete. Parts of objects can be occluded or missing or can blend seamlessly into the background, yet adults perceive the objects as complete global forms rather than a collection of disconnected local elements. In the laboratory, adults perceive holistic contours of shapes based on illusory edges that have no physical luminance, color, or texture boundary. How does this global perceptual ability come about? Although some researchers have found evidence for perception of illusory figures in young infants (e.g., Bertenthal, Campos, & Haith, 1980; Bulf, Johnson, & Valenza, 2011; Kavsek, 2002; Otsuka & Yamaguchi, 2003), others have reported that global form perception and discrimination of illusory shapes do not reach maturity until late childhood (Abravanel, 1982; Hadad, Maurer, & Lewis, 2010; Kimchi, Hadad, Behrmann, & Palmer, 2005; Sherf, Behrmann, Kimchi, & Luna, 2009). Here, we used a novel approach—accuracy on a match-to-sample (MTS) task paired with several measures of spontaneous manual and visual behaviors—to investigate the development of illusory contour perception as an assay of global form perception in children from 3 to 10 years of age. Our objective methods and converging behavioral evidence show a clear protracted developmental program for global visual processing that begins during the preschool years and reaches adult levels by 7 or 8 years of age.

Local to global processing

The development of object recognition is widely believed to be a hierarchical process, progressing from elemental perceptual function to more complex sophisticated integrative processing with age (e.g., Johnson, Davidow, Hall-Haro, & Frank, 2008; Kimchi, 1992; Kimchi et al., 2005). A critical aspect of this process is the development of global processing—the ability to appreciate coherent global structure over the local elements that make up an entire image (Kimchi, 1992; Navon, 1977). Operationally, local processing is based on selective attention to individual elements of an object or scene, whereas global processing involves establishing spatial relationships among discrete local elements and linking them together to form a coherent global structure (e.g., Kimchi, 1992; Kovács, 1996; Lewis et al., 2004; Neiworth, Gleichman, Olinick, & Lamp, 2006). These two types of processing are thought to rely on different underlying neural substrates (e.g., Conci, Tollner, Leszczynski, & Muller, 2011; Ringach & Shapley, 1996; Spillmann & Dresp, 1995; Wu et al., 2012).

A logical corollary of a hierarchical developmental process is that global perception develops at a later age than local processing, such that infants and young children rely on local perceptual strategies and attend to individual features of an object, whereas older children and adults appreciate global object structure (Dukette & Stiles, 1996; Kimchi et al., 2005; Kovács, Kozma, Feher, & Benedek, 1999; Lewis et al., 2004; Neiworth et al., 2006; Sherf et al., 2009). However, this profile for the later development of global perceptual abilities is a matter of some debate. A number of researchers report that young infants show evidence of global processing by distinguishing global forms such as Gabor contours in noise, Navon letters, and illusory shapes (Bertenthal et al., 1980; Bremner, Slater, Johnson, Mason, & Spring, 2012; Bulf, Valenza, & Simion, 2009; Csibra, 2001; Gerhardstein, Kovács, Ditre, & Feher, 2004; Ghim & Eimas, 1988; Kavsek, 2002; Otsuka, Kanazawa, & Yamaguchi, 2004). Indeed, Freeseman, Colombo, and Coldren (1993), studying 4-month-olds, concluded that global processing is evident *before* local processing. Other studies suggest that global processing and the ability to link discrete elements to extract coherent contours and shapes is weak or lacking in 3- to

5-year-olds (Abravanel, 1982; Kovács et al., 1999), although in some cases it may be demonstrated via manipulation of stimulus configuration (e.g., De Lillo, Spinozzi, Truppa, & Naylor, 2005; Dukette & Stiles, 1996; Neiworth et al., 2006). Compelling evidence suggests that adult-like global perceptual processing continues to mature up to the teenage years (Hadad et al., 2010; Kimchi et al., 2005; Sherf et al., 2009), so it is interesting that it is evident already at 4 to 8 months.

Global form perception and boundary completion in the service of visual object recognition have been extensively studied in adults using Kanizsa illusory contours (KICs) (Kanizsa, 1976). KIC perception involves the induction of contours in the absence of physical boundaries. In classic KICs, the percept of an illusory shape is induced by strategically placed ''pacman'' elements. Although most adults perceive an illusory shape—evidence of global processing—it is possible to see the image veridically as a collection of unassociated pacman elements, which reflects local processing (Guttman & Kellman, 2004; Ringach & Shapley, 1996).

A number of infant studies have used KIC stimuli to investigate the emergence of global form perception. Based on habituation and looking time methods, infants appear to perceive KIC figures, although researchers disagree as to the age at which this global perceptual ability is evident (range: 1–8 months; Bertenthal et al., 1980; Bremner et al., 2012; Bulf et al., 2009; Csibra, 2001; Otsuka et al., 2004; Treiber & Wilcox, 1980). Some researchers question whether the looking-time data actually indicate perception of the illusory shape or simply a novelty preference, a stimulus-related preference, or some other variable (Bulf et al., 2009; Colombo, Mitchell, & Horowitz, 1988; Freeseman et al., 1993; Kavsek & Yonas, 2006; Sato et al., 2013), but other researchers argue that appropriate control conditions explicitly address potential confounding variables in static (Otsuka et al., 2008) and dynamic illusory displays (Curran, Braddick, Atkinson, Wattam-Bell, & Andrew, 1999; Kavsek & Yonas, 2006; Sato et al., 2013). Using a visual search paradigm combined with eye tracking, Bulf et al. (2009) found that 6-month-olds did not attend to a KIC triangle when embedded in background noise yet looked significantly longer at a KIC image compared with a non-illusory image. In contrast, adults immediately segmented the KIC under all test conditions. The authors concluded that the binding processes involved in the perception of KICs in infants and adults demonstrate different perceptual abilities. Consistent with this view, a few prior illusory contour studies with children suggest that the ability to appreciate illusory forms emerges during early childhood, becoming ''adult-like'' beyond 5 to 7 years of age (Abravanel, 1982; Hadad et al., 2010; Happé, 1996; Milne & Scope, 2008).

Abravanel (1982) used two methods to assess KIC perception in children: a direct perception task and a recognition/matching task. In the direct perception case, the experimenter asked children to report whether they saw a shape they knew and then to trace the figure and label the shape verbally; in the recognition task, children were presented with a number of different solid shapes and, after being confronted with an illusory figure, were asked whether they saw any of the solid shapes in the center of the display. For the latter condition, the experimenter provided verbal prompting and guided attention to the center of the figures. Performance was less reliable for the direct perception task than for the recognition task at each age, but children under 5 years did not reliably show evidence of perception of the illusion in either case, whereas most 5- and 6-year-olds did. It is unclear whether successful recognition of the KIC forms, and therefore the appearance of global perception, by the older children was facilitated in this study by verbal prompting and guided attention to the figures or was hampered in the direct perception case by the need for verbal reporting. Happé (1996) studied typically developing children between 7 and 9 years of age with a variety of illusions. These children had difficulty in perceiving KIC triangles despite explicit verbal instructions, with only approximately 60% of the group showing evidence of the illusion (see also Milne & Scope, 2008). Hadad et al. (2010) found that 6- and 9-year-olds were able to perform a KIC ''fatness'' discrimination task (i.e., report whether an illusory contour was ''fat'' or ''thin'') but that children's performance was not adult-like until 12 years of age. Taken together, these studies suggest that global perceptual organization is at best inconsistently present in younger children, that it is qualitatively and quantitatively different in children compared with adults, and that KIC perception undergoes substantial development during childhood.

The current study

The developmental trajectory of global processing in general, and of KIC perception in particular, is an important but unresolved question. Adults can perceive KICs with greater than 90% accuracy (Fagot & Tomonaga, 2001; Ringach & Shapley, 1996), but apparently most children under 5 years of age do not. Given the conflicting data regarding the age at perception of global form in infants and the disparate results in the literature for children, it remains unclear at what age global processing ability is consistently present. The goal of the current study was to investigate age-related changes in global form perception across the span of ages covered in previous work with children. Toward this end, we developed a novel paradigm and converging measures to evaluate the performance of individual children on an objective task for which we preestablished the children's cognitive capability. We used quantitative psychophysical measures that could be applied to children across the age range of 3 to 10 years, avoiding confounds created by explicit practice, verbal prompting, and/or verbal report. We used an MTS paradigm with the addition of eye tracking and reaching movements to assess this developmental process and to identify perceptual differences between children of different ages. Our paradigm ensured that the children understood the task without the necessity of explicit training, verbal prompting, or contingent feedback on the illusory contour discrimination. Our results revealed a clear developmental trajectory for the emergence of reliable KIC discrimination, with a shift from initially local to later global perceptual processing.

Method

Participants

The participants were 75 children (44 girls and 31 boys) between 3.0 and 9.7 years of age and 23 adults (17 women and 6 men) between 18.2 and 40.0 years of age. All had normal or optically corrected-to-normal vision. Participants who wore glasses did not wear the eye tracker. Children were recruited from the New York City area via maternity wards in local hospitals, internet sites, and commercially available mailing lists. Adults were fellow students or friends who were naive to the hypotheses of the study. Data from an additional 20 children and 4 adults were not analyzed due to their failing to reach criterion during the training phases of the experiment (11 children between 3.0 and 4.1 years of age), being diagnosed with autism spectrum disorder (3 children), having strabismus (1 child), or having unusable data because of technical problems in video capture or malfunctions in the computer display (5 children and 4 adults). Children were compensated with age-appropriate toys; adults received no compensation.

Head-mounted eye tracker

We monitored participants' looking and manual behaviors with a Positive Science head-mounted eye tracker (http://www.positivescience.com). In contrast to remote eye trackers, which record only looking behavior, the head-mounted eye tracker also revealed participants' arm movements in the scene camera view. However, whereas remote trackers can calculate looking to regions of interest automatically, the head-mounted tracker required coding of both looking and manual behaviors (see below).

The headgear consisted of three components: an infrared light-emitting diode at the bottom of the visual field that illuminated participants' right eye for dark pupil and corneal reflection tracking; an eye camera, also at the bottom of the visual field, which recorded the eye's movements; and a scene camera attached to the glasses slightly above the eye that recorded the field of view (54.4° horizontal by 42.2° vertical). The field of view was filled with the display on the computer monitor and participants' arm movements (see Fig. 1). Yarbus software (Positive Science) superimposed a cross-hair indicating gaze location onto the field of view video (see Franchak & Adolph, 2010, and Franchak, Kretch, Soska, & Adolph, 2011, for details). The spatial accuracy of the eye tracker was 1.5° (maximum radius of error in any direction), and the sampling frequency was 30 Hz (video capture rate).

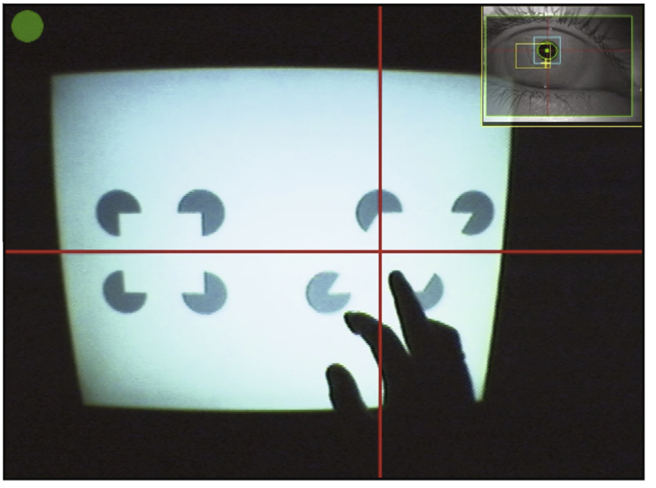

Fig. 1. Participants' view of the display while reaching toward the touch screen. The image recorded by the scene camera shows a pair of comparison forms with a child's hand in the field of view. The red cross-hair shows the child's point of gaze as calculated by the eye movements relative to calibrated points in the field of view. The small inset at the upper right shows an image of the eye recorded from the eye camera. (For interpretation of the reference to color in this figure legend, the reader is referred to the Web version of this article.)

To calibrate the eye tracker (i.e., link eye movements with known locations in the field of view video), we used the procedure described previously (Franchak & Adolph, 2010). Participants fixated each of nine targets presented across the entire region of the monitor while keeping their heads stationary (if needed, parents helped to steady children's heads); the experimenter registered each point in the software. Then, to verify the calibration, the experimenter called participants' attention to several points on the grid. If the cross-hair was off by more than 2°, the procedure was repeated until the calibration was acceptable.

Stimuli

Participants sat on an adjustable chair in a visually neutral room with a touch screen monitor (Planar capacitive 27 cm high × 33.5 cm wide LCD touch screen, model no. PT1701MX-BK) in the center of their field of view and located an arm's distance away (40–60 cm). Display stimuli were grayscale and matched in overall luminance. The luminance for each solid shape (real forms and inducers) was 30 cd/m^2, and the background luminance averaged 130 cd/m^2. The physical size of the KIC forms was fixed, such that at a 60-cm distance (where 1 cm = 1° of visual angle) the radius of the pacman inducer was 2° and the illusory edge length of the square was 3°, yielding a total edge length of 7° (see Fig. 2A for geometry of example shape). This geometry yields a support ratio (the relative length of the inducing/induced contour; Shipley & Kellman, 1992) of 57%; note that the support ratio necessarily varied slightly across the different KIC shapes. We used six illusory shapes: triangle, square, diamond, rectangle, trapezoid, and parallelogram (Fig. 2B). In areal measurement, the illusory triangle was the smallest (28.3 cm^2) and the parallelogram was the largest (56.6 cm^2). Based on previous studies of KIC discrimination as a function of support ratio in infants (see Otsuka et al., 2004), we used a fixed intermediate support ratio for all forms, which was 57% for the KIC square as illustrated in Fig. 2B. Note that the size of the display in visual angle was slightly larger for the children with the shortest arms—generally the youngest children, who were positioned closer to the screen. In no case did the size of the display pose a limit to the visibility of the stimuli.

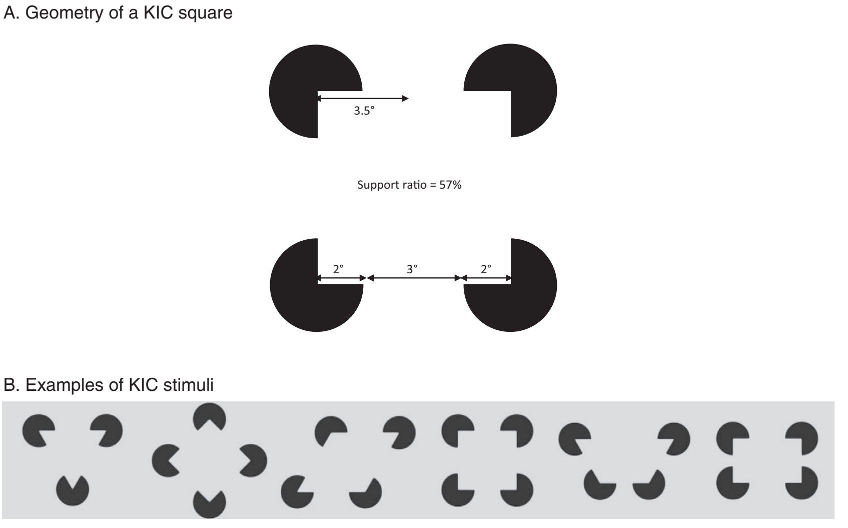

Fig. 2. (A) Geometry of an example KIC square. The pacman inducers give rise to the percept of an illusory square. The support ratio, in this case 57%, is the relative length of the real (inducing) portion of the contour to the total length of the perceived contour (real + illusory portions). (B) Examples of KICs for the six illusory shapes used as comparisons in Phase 3. The inducers give rise to the percept of an illusory triangle, diamond, parallelogram, square, trapezoid, and rectangle.

Testing procedure

We used a similarity MTS paradigm throughout the study. On each trial, an initial "sample" shape appeared in the middle of the screen, followed by two simultaneously presented "comparison" shapes on the right and left sides of the screen; one shape (the target) was the same shape as the sample, and one shape (the distractor) differed from the sample. Each trial began with the sample displayed for 1 s, followed by the comparison shapes that appeared for an unlimited duration. Once the computer registered a touch anywhere on the screen, the trial ended and the screen blanked; on some trials, a looming smiley face appeared for positive reinforcement (see below) after the comparison stimuli disappeared. The first trial of a sequence began automatically when participants touched a point in the middle of the screen. The experimenter controlled the start of each subsequent trial. To ensure that children did not miss the presentation of a sample form, the experimenter started each trial when children were looking at the screen.

The study had three phases: two training phases with real forms to ensure that children understood the MTS concept and one test phase in which the two comparison stimuli were illusory. In Training Phases 1 and 2, sample shapes and comparison pairs were selected by the computer from among all possible pairs in the stimulus set and were presented in a randomized order. In Test Phase 3, the possible illusory shape pairs were preselected but were presented in a randomized order. Preselection was necessary to ensure that the comparisons were not dramatically different; for example, a triangle with three pacman inducers was paired with an inverted triangle but not with a KIC that had four inducers. Within each phase, the right–left location of targets and distractors was randomized except for a set limit of 4 consecutive trials with the correct choice on the same side.

At the beginning of the experimental session, the experimenter instructed participants that they would be playing a game in which they should select the form that best matched the sample: "You must pay attention to the screen. A picture will show up but then disappear very quickly, and then two more pictures will show up. You have to choose the one that looks the same as the first picture you saw. Touch the picture on the screen with your finger." The experimenter reminded children about matching one comparison form to the sample at the beginning of Phases 2 and 3 but otherwise provided no instruction.

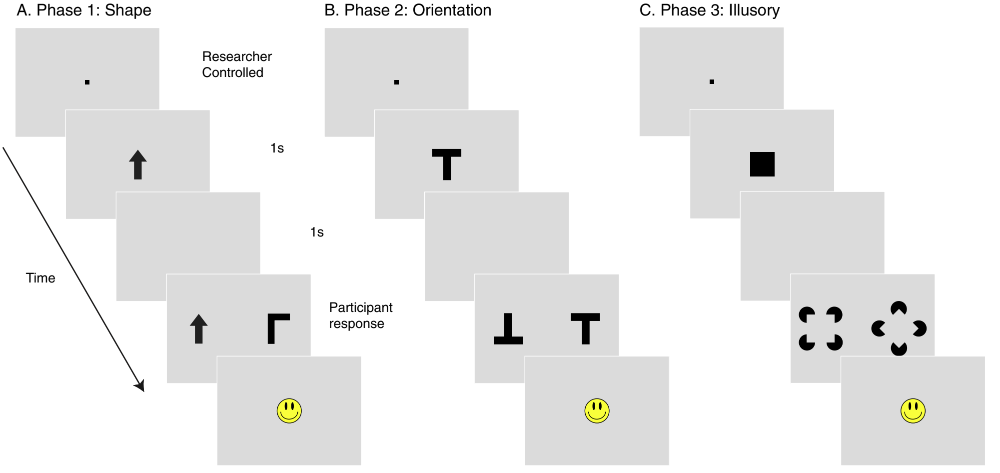

Fig. 3. Phases of the experiment. The trial sequence is illustrated for each phase (A–C). The sequence begins a participant touching the central point on an otherwise blank screen. A sample stimulus then appears for 1 s, followed by presentation of two comparison shapes. The location of the correct target shape varied in right–left position. A smiley face appeared following the response on some trials (see Method). Subsequent trials within a phase were researcher initiated. (A) Phase 1: Training on match-to-sample task—Shape discrimination with complete forms. (B) Phase 2: Orientation discrimination with complete forms. (C) Phase 3: Test phase with KIC comparisons.

Training Phase 1 involved simple shape discrimination among eight complete shapes (cross, arrow, horseshoe, oval, L-shape, X-shape, T-shape, and E-shape). Participants' task was to select the comparison shape that matched the sample, as illustrated in Fig. 3A. Training Phase 2 involved orientation discrimination among the same eight complete shapes pointing up, down, left, or right. Participants' task was to select the matching comparison shape that was positioned in the same orientation as the sample, as illustrated in Fig. 3B. Each training phase contained a maximum of three blocks of 11 trials. The experimenter noted the outcome of each trial and determined after each trial block whether participants had selected at least 9 of the 11 shapes correctly (82% correct criterion). If the criterion was reached, participants progressed to the next phase; if not, participants received the next trial block in the same phase; if participants failed to reach criterion on three consecutive trial blocks, the experiment ended without proceeding to KIC Test Phase 3.

Test Phase 3 was the actual test of global form perception using KICs. Note that Test Phase 3 was the first exposure participants had to the KICs. In this phase, the sample form was one of six complete shapes (square, rectangle, triangle, trapezoid, parallelogram, or diamond). The comparison forms were both KICs, as illustrated in Fig. 3C; Fig. 2B shows the complete set of KICs. The task was to select the comparison KIC that induced the same shape in the same orientation as the sample. Phase 3 consisted of 41 trials presented consecutively.

To maintain children's motivation throughout the two training phases (Phases 1 and 2), a smiley face was presented at the center of the monitor following correct responses. After every trial of KIC Test Phase 3, the smiley face appeared for positive reinforcement regardless of the accuracy of the response. In addition, a second monitor placed to the side of the touch screen displayed children's "personal score" (proportion of correct responses as determined by the experimenter's online coding) in an attractive animation at the end of each trial. Participants received an average of 65 trials in total across the three phases of the experiment. Complete test sessions, including all three phases, lasted approximately 20 min.

Data coding

A primary coder scored all outcome measures from the field of view video using Datavyu software (http://www.datavyu.org), which provides frame-by-frame analysis and calculates the frequency and duration of specified behaviors. For measures involving arm movements, the coder scored data from every participant. Because manual coding was so laborious for measures involving eye movements, the coder scored visual fixations only from a randomly selected subset of 18 children spread over the age range and 3 adults. To ensure inter-rater reliability, a second coder scored 25% of the trials from each participant scored by the primary coder. Coders agreed on more than 94% of trials for categorical measures (p values for all Cohen's kappa coefficients <.001). For latency, the correlation between coders' scores was $r(1375) = .986$, $p < .001$. For looking, coders agreed on $M = 93.8\%$ of frames. Discrepancies were resolved through discussion. The primary outcome measure was the *accuracy* of responses—whether participants touched the comparison shape that matched the sample. Accuracy was recorded for all three phases. The number of trial blocks to reach criterion in the training phases was in exact agreement with the experimenter's online codes. As expected, younger children required more trial blocks than older children to reach criterion in Phases 1 and 2, $t(73) = -0.315$, $p < .01$. Adults required only 1 trial block for each phase. Only data scored from the video were used in analyses of accuracy for Test Phase 3.

In addition to accuracy, coders scored a suite of manual and looking behaviors that were spontaneously produced by participants as they decided which illusory form matched the sample. Because our focus was on global form perception, coders scored additional measures only for Test Phase 3. *Latency* to touch, calculated from the time the two comparison forms appeared on the screen until participants touched the screen, reflected how long it took participants to make a decision about the correct shape. *Choice uncertainty,* moving the hand back and forth between shapes prior to touching, reflected uncertainty about which comparison shape was the correct target. *Touch location,* whether participants touched the pacman elements, an illusory "edge," the center of the shape, or elsewhere on the screen, was an indication of whether participants were attending to the constituent elements or the holistic form.

Coders scored visual fixations starting with the first gaze shift following the disappearance of the sample form. Thereafter, coders scored gaze location when the cross-hair rested at a particular location for at least three video frames (~100 ms). *Overall looking time* was the proportion of time during each trial that participants looked at the correct target form, the incorrect distractor form, and neither form (looks to blank parts of the screen and looks away from the screen). *Look location* was the proportion of time during each trial that participants looked at particular parts of the comparison forms (pacman elements, illusory edges, center of the forms, and elsewhere on the screen).

Results

Four outcome measures concern selecting the target form: accuracy, latency, duration of looking to the correct and incorrect forms, and whether the first fixation was to the correct or incorrect form. Two outcome measures indicated local versus global processing: the part of the comparison shape participants touched to register their choice and the proportion of time they directed their visual attention to particular components of the comparison forms. We operationally defined attention to—that is, touching or looking at—the inducer elements as indicative of local processing and defined attention to the middle or illusory edge as indicative of global form perception (see Gregory, 1972; Guttman & Kellman, 2004; Kimchi, 1992; Ringach & Shapley, 1996; Spillmann & Dresp, 1995). We assessed changes across age for each outcome measure using correlational analyses and analyses of covariance (ANCOVAs) with age as a covariate. We conducted statistical analyses only on the children's performance but show the adults' data in the figures as a comparison.

Selecting the target form

All four measures concerned with selecting the correct target form showed significant improvement with age. The primary measure of global perception of illusory contours was accuracy—the proportion of correct responses in Test Phase 3. As shown in Fig. 4A, many of the youngest children performed at chance (~.50) despite demonstrating understanding of the MTS task by passing the 82% correct criterion on the first two phases (based on real forms), and some of the older children

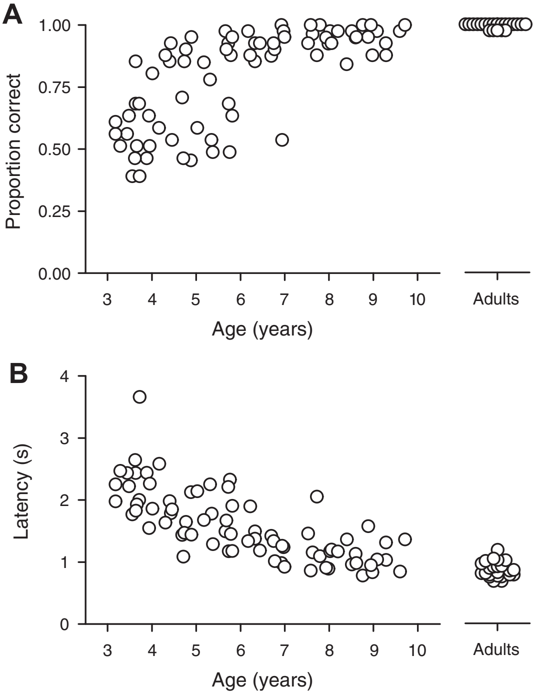

Fig. 4. Performance on KIC discrimination (Phase 3) as a function of age. (A) Accuracy, measured as the proportion of correct responses, for each participant plotted by age. (B) Latency, in seconds, to select a form plotted by age. Each symbol represents data from 1 participant averaged across the 41 test trials.

performed perfectly. On the other hand, a few of the youngest children performed above 82% accuracy even on Test Phase 3, which highlights the wide range of variation across the younger children. Accuracy increased with age from 3 to 10 years, $r(73) = .70$, $p < .01$; adults were at ceiling. In total, 24 participants never made an error: 18 adults and 6 children between 6.9 and 9.7 years of age. Adults' accuracy ($M = 99.5\%$) far outstripped the accuracy of 3- and 4-year-olds ($M = 64.4\%$), $t(48) = -9.53$, $p < .001$. Across children, boys ($M = .84$, $SD = .17$) and girls ($M = .84$, $SD = .20$) were equally accurate.

Latency to select a shape by touching the screen decreased with age. As shown in Fig. 4B, the youngest children averaged 2 to 3 s to touch a shape, whereas the oldest children and adults selected a comparison form within approximately 1 s. Latency decreased significantly from 3 to 10 years of age, $r(73) = -.73$, $p < .01$. Developmental changes in response speed appeared to be driven by faster choices on correct trials but not on incorrect ones, ruling out a simple difference in motor performance between younger and older children. On correct trials latency decreased with age, $r(73) = -.71$, $p < .01$, but on incorrect trials latency and age were not significantly correlated, $r(67) = -.21$, $p = .09$. Note that children who never erred did not contribute data to analyses of incorrect trials. We found no reliable differences in accuracy or latency among the illusory shapes.

Overall looking times provided converging evidence that older children directed more of their visual attention to the correct comparison forms, whereas younger children directed more of their attention to the incorrect forms. As shown in Figs. 5A and 5B, looking to the correct target form increased with age, $r(16) = .52$, $p = .03$; conversely, looking to the incorrect distractor form decreased with age, $r(16) = -.74$, $p < .01$. Note that we converted accumulated duration of looking per trial to a proportion of each trial to take younger children's longer latencies into account. On average, the youngest children spent less than half of each trial looking at the correct form, whereas children older than approximately 6 years and adults spent more than half of each trial looking at the correct form. For example, the 3- and 4-year-olds spent $M = .41$ ($SD = .12$) of the trial looking at the correct shape,

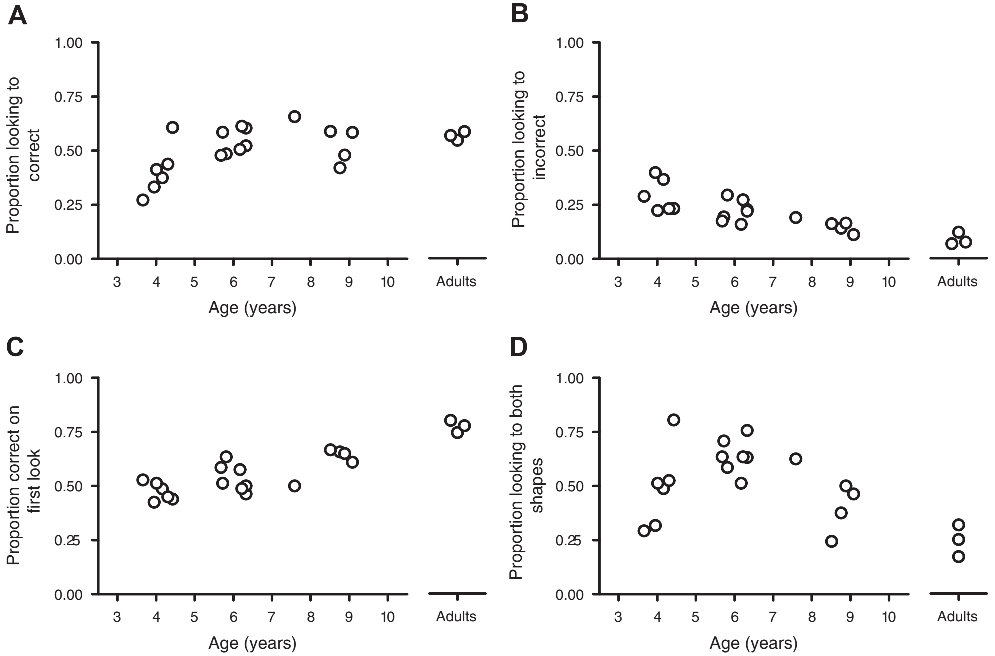

Fig. 5. Gaze patterns to the comparison shapes plotted as a function of age. (A,B) Average proportion of time spent looking to the correct (A) and incorrect (B) comparison shapes. (C) Proportion of trials on which the first fixation was directed to the correct shape. (D) Proportion of trials on which participants looked at both the correct and incorrect forms at least once. Each symbol represents data from 1 participant averaged across trials.

and the adults spent *M* = .57 (*SD* = .02) of the trial looking at the correct shape. Reciprocally, the 3- and 4-year-olds spent approximately one third of each trial looking at the incorrect form (*M* = .29, *SD* = .08) compared with less than 10% by the adults (*M* = .09, *SD* = .03) (see below; Table 2). Looking time to “neither” shape did not change with age, *r*(16) = .01, *p* = .98, accounting for *M* = .29 (*SD* = .09) of the trial across age groups.

The first shape fixated would provide further evidence of global form perception, that is, whether children looked first to the correct target form and not the distractor. As shown in Fig. 5C, the youngest children performed at chance (.50) in terms of fixating the correct shape first, but the oldest children fixated the correct shape first on a greater proportion of trials (*M* = .62, *SD* = .16). Across the age range, the proportion of trials on which the correct target was fixated first increased, *r*(16) = .72, *p* = .01. For adults, a large proportion (*M* = .77, *SD* = .03) of first looks were directed toward the correct shape.

Looking at both the correct and incorrect forms in the same trial (at least one fixation to each form) indicates that children engaged in a comparison process to select the target form. As shown in Fig. 5D, looking at both shapes follows an inverted U-shaped trajectory from 3 to 10 years. Fitting a quadratic model, age accounted for R^2 = .47 of the variance in proportion of looking to both shapes, *F*(2, 15) = 6.54, *p* = .01. Adults looked at both shapes on only *M* = .25 (*SD* = .07) of trials, less than children at any age. These gaze patterns show clear evidence of rapid global adult-like perception of the illusory shapes in the older children. The younger children showed greater uncertainty in their looking patterns. Moreover, we observed manual choice uncertainty—where children moved their hand back and forth between comparison shapes prior to touching the screen—in 15.2% of the trials; adults showed manual uncertainty on only 3.1% of trials, *t*(82) = 4.20, *p* < .001. In addition to more manual choice uncertainty between comparisons in children relative to adults, we noted that some children also demonstrated a wider variety of touching strategies: young children sometimes used both hands with open palms or fists, to select both illusory comparison forms simultaneously, and used multiple fingers to simultaneously touch several inducers. These behaviors suggest that young children were unable to readily appreciate the illusory form and, hence, were unsure how to respond.

Within trials, looking and manual behaviors were related; the proportion of looking to the correct target form was related to whether children's response was correct or incorrect. We calculated the proportion of looking to the correct shape for correct and incorrect trials for each child (2 children who never erred were not included in these analyses). An ANCOVA on proportion of looking at the correct shape with the two response types (correct/incorrect) as a factor and age as a covariate confirmed an overall effect for age, as expected, $F(1, 13) = 24.86$, $p < .001$. Moreover, the ANCOVA revealed a main effect of response; across ages, children spent a greater proportion of time looking at the correct shape on trials when they correctly chose it, $F(1, 13) = 47.37$, $p < .01$. However, the effect of response type was mediated by age, as evidenced by a Response × Age interaction, $F(1, 13) = 18.14$, $p < .01$. On incorrect trials, looking at the correct shape increased with age, $r(13) = .87$, $p < .01$, despite not choosing it. But for correct trials, time spent looking at the correct shape did not differ by age, $r(16) = .06$, $p = .80$.

Attention to the holistic form

The location on the comparison forms where participants touched and looked provides evidence of attention to elementary parts (touching or directing gaze to the pacman inducers) or to holistic form (touching or directing gaze to the middle of the illusory shapes). Touches to illusory edges were rare, accounting for only $M = .03$ proportion of trials overall; edge touches did not vary by children's age, $r(73) = .01$, $p = .92$. However, as shown in Fig. 6, touches to the pacman inducers (Fig. 6A) and the middle of the illusory shapes (Fig. 6B) differed by age; the youngest children most often touched the inducers, whereas older children and adults primarily touched the middle of the shape. Indeed, the

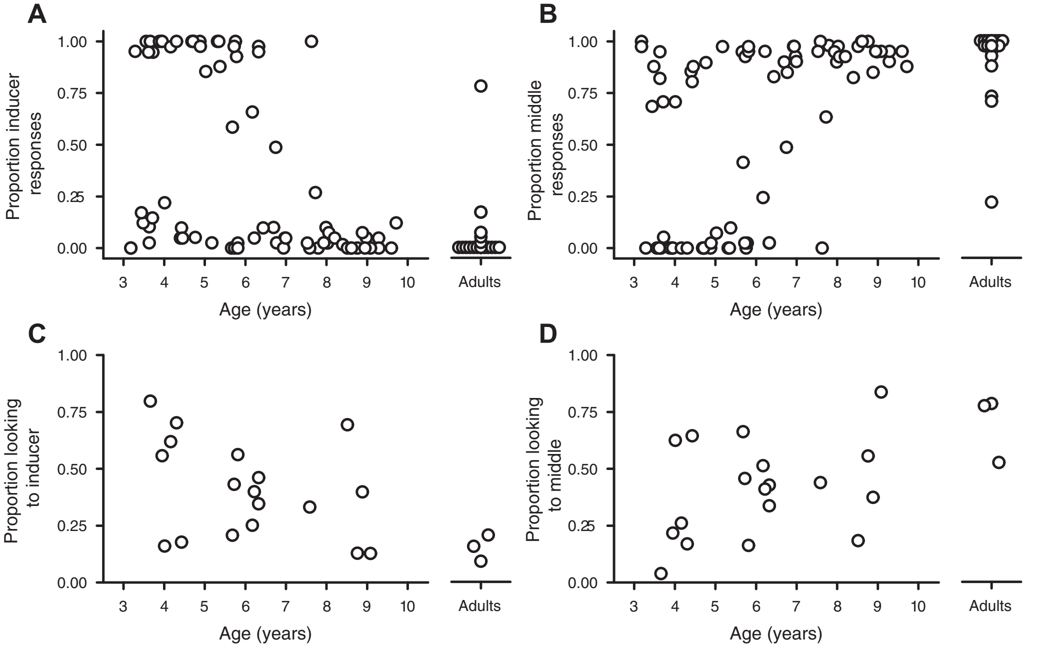

Fig. 6. Patterns of touching and looking at components of the comparison shapes plotted as a function of age. (A) Proportion of trials on which participants touched the pacman inducers. (B) Proportion of trials on which participants touched the middle of the illusory shape. (C) Average proportion of each trial spent looking at the pacman inducers. (D) Average proportion of each trial spent looking at the middle of the illusory shape. Each symbol represents data from 1 participant averaged across trials.

proportion of touches on the inducers decreased with age, $r(73) = -.48$, $p < .01$, and touches on the middle of the illusory shapes increased with age, $r(73) = .50$, $p < .01$.

Figs. 6A and 6B also show that most children and adults consistently touched either the middle of the shape or the inducers; that is, most data points are clustered near 0 and 1, not spread throughout the .30 to .70 range that would indicate mixed response patterns. The oldest children (>8 years) showed no evidence of mixed responses; they touched the middle of the shape on 100% of trials. Likewise, all but 3 adults consistently touched the middle of the shape; the overall average of middle touches across adults was 92.2% of trials. Thus, to examine the relation between touch location and response accuracy—a sort of behavioral link between attention to the holistic form and KIC perception—we separately analyzed data only from the children under 8 years of age. We categorized children into two groups: those who touched the middle on more than 50% of trials ("middle touchers," $n = 31$) and those who touched the inducers on more than 50% of trials ("inducer touchers," $n = 28$). An ANCOVA on the proportion of accurate responses with group (middle/inducer touchers) as a factor and age as a covariate revealed an effect of age, $F(1, 56) = 31.11$, $p < .01$, and an effect of group, $F(1, 56) = 5.32$, $p = .025$. Children who registered their shape selection by touching the middle of the shape were more accurate ($M = .83$ of trials, $SD = .15$) than those who touched the inducers ($M = .69$ of trials, $SD = .20$).

To establish where on the shapes children directed their gaze, we calculated the proportion of time that they directed their gaze to the illusory edges, inducers, or middle of the shape (time looking at neither shape was excluded) out of the total time the children spent looking at the shapes. As with touch responses, children looked least to the illusory edges ($M = .18$, $SD = .07$), more to the pacman inducers ($M = .37$, $SD = .22$), and even more to the middle of the shapes ($M = .46$, $SD = .23$). Looking to illusory edges did not vary with children's age, $r(16) = .06$, $p = .83$. Fig. 6C shows that looks to the inducers tended to decrease with age, $r(16) = -.35$, $p = .15$, and Fig. 6D shows that looks to the middle of the shapes tended to increase with age, $r(16) = .34$, $p = .17$, but neither correlation was strong enough to reach significance with the sample size we scored. This trend appears to continue to adulthood: Adults spent the majority of their time looking at the middle of the shape ($M = .70$, $SD = .15$).

To learn what aspects of the display children sampled prior to making their choice, we also calculated the proportion of trials that a feature was fixated at least once. As age increased, children were marginally less likely to sample the inducers, $r(16) = -.46$, $p = .05$, and illusory edges, $r(16) = -.43$, $p = .07$. However, the proportion of trials on which children looked to the middle of the shape at least once did not vary by age, $r(16) = -.003$, $p = .99$. Moreover, from 3 to 10 years of age, children became less likely to fixate more than one feature within the same form in a single trial, $r(16) = -39$, $p = .04$.

Post hoc analysis by group

To more readily compare our results with those of prior studies, we separated the participants into convenient age groups. We compiled four age groups: 3- and 4-year-olds, 5- and 6-year-olds, 7- to 10-year-olds, and adults (see Table 1 for actual ages for each group). We addressed two questions with the grouped data:

1. What was the average percentage correct by group?
2. What was the average proportion of time that each group spent looking at the correct versus incorrect form out of the overall time spent viewing the comparison stimuli?

Table 1
Accuracy data from post hoc group analysis.

Age group (years)	*n*	Minimum	Maximum	M	SD	*t*
3–4 (3.18–4.89)	27	.39	.95	.644	.176	4.244
5–6 (5.02–6.99)	25	.49	1.0	.816	.171	9.251
7–10 (7.53–9.71)	23	.84	1.0	.949	.045	47.415
Adult (18.18–39.98)	23	.98	1.0	.995	.010	229.469

Note. Inclusive age is listed for each of the four age groups. Average accuracy is listed for each group along with the maximum and minimum score achieved by any participant within that group. The *t* values against chance performance (.50) appear in the last column; all tests were significant at the .001 level.

Table 2
Average looking time from post hoc group analysis.

Age group (years)		*n*	Minimum	Maximum	M	SD
3–4	Correct form	6	.27	.61	.406	.115
	Incorrect form	6	.22	.40	.290	.076
5–6	Correct form	7	.48	.61	.542	.057
	Incorrect form	7	.16	.29	.220	.050
7–10	Correct form	5	.42	.66	.546	.095
	Incorrect form	5	.11	.19	.154	.030
Adult	Correct form	3	.54	.58	.566	.020
	Incorrect form	3	.07	.12	.087	.029

Note. Mean looking time to the correct and incorrect target is presented for each age group along with the maximum and minimum times shown by any participant within that group. The *n* per group was not sufficient to support statistical tests for these comparisons.

The accuracy data are presented in Table 1. Bonferonni-corrected *t* tests comparing age groups revealed significant differences in accuracy among all combinations of age groups ($ps < .003$) with one exception: No difference was found between adults and 7- to 10-year-olds ($p = 1.00$). Although accuracy was lower for the two youngest age groups, and the variance across children within these groups was higher (see Fig. 4A; Table 1, maximum and minimum scores), group means show $M = .64$ ($SD = .18$) and $M = .82$ ($SD = .17$) proportion correct for the 3- and 4-year-olds and 5- and 6-year-olds, respectively.

Although the criterion for mastery on our MTS task was 82% correct, we conducted *t* tests against chance (.50) for each age group to compare our data with infant studies. We confirmed that accuracy in every age group was significantly above chance level ($ps < .001$, alpha level of .0125 to correct for multiple comparisons). For the 3- and 4-year-olds, the high accuracy of a few children raised the mean level above chance for the group (1 3-year-old and 5 4-year-olds scored above 82%). To more finely evaluate whether there was a consistent change in accuracy with age, we computed the proportion of children performing above chance (.50 ± .1025, binomial variance for a two-choice task with 41 trials) by year: .33 of 3-year-olds, .66 of 4-year-olds, .69 of 5-year-olds, and .92 of 6-year-olds. All children age 7 years or over performed above chance. This steady improvement in accuracy across age parallels the developmental trajectory from local to global strategy found in our analysis of the manual and looking behaviors.

The looking data, sorted by age group and by correct versus incorrect response, show a distinct difference between the youngest age group and the older children (see Table 2). The 3- and 4-year-olds inspected the correct shape only ($M = .41$, $SD = .12$) of each trial; the older children and adults directed their gaze to the correct shape more than $M = .54$ of each trial. In addition, the 3- and 4-year-olds spent $M = .29$ ($SD = .08$) of each trial looking at the incorrect form; that proportion dropped dramatically across the older groups. It is important to note that the range of variance of these metrics is also much larger in the younger children than in the older age groups.

Discussion

Both global and local processing are essential for visual perception. Global perceptual abilities allow linking together different features of an object to create a coherent holistic percept, whereas local attention directs focus to individual features or a subset of the object parts. In the current study, we employed an objective similarity MTS behavioral paradigm coupled with eye tracking and reaching movements to assess the development of global processing, as indexed by KIC perception, in typically developing children. Our data are consistent with the view that the ability to appreciate global form in KIC images matures during childhood, and our children's response patterns demonstrate a smooth transition from local to global processing with age.

The current study is unique in that we tested children over a broad range of ages (3–10 years) as well as adults, we used an active and objective similarity MTS task, and we obtained converging behavioral measures of accuracy and processing strategies. In two initial phases, children demonstrated understanding of the MTS concept using real complete forms. In the third phase, children were confronted for the first time with the illusory comparison stimuli and, therefore, received no explicit training with the KICs. Moreover, we obtained converging evidence from response selection and eye-tracking data to demonstrate a shift in strategy as well as improved accuracy with age. Using a head-mounted eye tracker, manual video coding of reaching movements, and a touch-sensitive screen, we obtained measures of performance accuracy for all participants and documented where on the display they touched and looked. This approach enabled us to gather converging evidence about the visual processing strategy that participants used to solve the task.

Developmental changes in global processing

Our data show strong converging evidence for a developmental trajectory from a primarily local processing strategy to global perception. We found adult-like skills consistent with KIC perception by 7 or 8 years of age. Response accuracy increased steadily between 3 and 8 years of age. In addition, latency to touch the correct target decreased, proportion of looks to the correct target stimuli increased, and touches to the pacman inducer elements (prevalent in the youngest children) decreased, whereas touches to the center of the KIC increased. Our data are consistent with other studies on the development of global processing showing a transitional age between 4 and 8 years (Dukette & Stiles, 1996; Hadad et al., 2010; Kaldy & Kovács, 2003; Poirel, Mellet, Houdé, & Pineau, 2008; Poirel et al., 2011). Interestingly, we saw evidence from the transitional age range that children begin to look more at the correct target but may actually still select the *incorrect* one. Also during this period, children were more likely to visually sample both comparison stimuli before making a response. Unlike most studies of this kind, we sampled over a continuous age range as opposed to testing only one or a few discrete ages and analyzed individual data. It is clear from Figs. 4 to 6 that children of a similar age show considerable inter-individual variability in both perceptual ability and strategy, and variability is greater in the younger transitional age ranges; this variation is not unexpected but is often not acknowledged. Nonetheless, we found a relatively smooth transition across age from the youngest children employing a predominantly local strategy, by looking at and touching the pacman elements, to a global adult-like strategy of predominantly looking at and touching the center of the illusory form. In addition, the youngest children showed longer latency to touch and lower accuracy compared with the older children, which is typically indicative of a local strategy (Conci et al., 2011; Kimchi, 1992; Ringach & Shapley, 1996; Sherf et al., 2009). Older children and adults responded with faster latencies and higher accuracy, perhaps due to well-established global processing skills that allow the KIC figure to easily pop out. Indeed, those who touched the middle of the KIC to register their choice were more accurate than those who touched the inducers. Finally, our data also show that adults and older children looked at the correct target on their first looks more frequently than younger children. Adults and older children may use peripheral vision for quick global processing. As Kimchi (1992) demonstrated, global processing has precedence in the periphery, and perhaps older children are better at attending to peripheral stimuli than younger children.

Previous studies are inconclusive with respect to the development of global perception. A number of earlier studies concluded that young infants can appreciate the global form in KICs as well as other illusory constructs (e.g., Bertenthal et al., 1980; Bremner et al., 2012; Csibra, 2001; Kavsek, 2002; Otsuka & Yamaguchi, 2003; Otsuka et al., 2004, 2008), but other studies indicate that only older children reliably demonstrate the ability to extract global structure from illusory images (Abravanel, 1982; Hadad et al., 2010). Despite substantial methodological differences, our finding that young children do not reliably appreciate the global form in KICs, adopting a local strategy rather than a global one with overall poorer performance, is consistent with the few previous studies of school-age children. Abravanel (1982) reported poor performance of children under 5 years of age on illusory form recognition. This is despite the fact that children's attention was specifically guided to the illusory form and/or they were asked to trace and then verbally label the shape that was induced by the illusion. In that study, 90% to 100% of the 6-year-olds perceived the illusions with the instructional guidance, but only 50% of the youngest children did. Our children were uninstructed with the illusory stimuli; however, consistent with Abravanel's study, most of our older children demonstrated the ability to perceive the global forms. In contrast, Happé (1996) reported that only 57% of 8-year-olds were "fooled by" (i.e., appeared to perceive) the Kanizsa triangle illusion. She did not, however, test children of other ages. It is possible that her children may have been confused by the question "How many triangles can you see here?" which would account for their lower proportion of success.

Two prior studies employed a psychophysical-style task to assess whether children perceived Kanizsa shapes. Milne and Scope (2008) and Hadad et al. (2010) asked children to discriminate illusory figures as either "fat" or "thin" based on the angle of rotation of the pacman inducers. Milne and Scope (2008) reported overall average number of correct trials (~65%) and percentage of children performing the discrimination above chance levels (60% without explicit additional training) for children between 7 and 11 years of age (presented as grouped data), which is considerably poorer performance than our cohort that received no training. Hadad et al. (2010) tested children in four discrete age groups: 6-year-olds, 9-year-olds, 12-year-olds, and adults. They measured pacman rotation thresholds and found 6-year-olds to perform significantly worse than the older groups under all illusory test conditions; the range of variation across children in the youngest age group was also considerably larger than in the other groups, consistent with our data. Moreover, they found that under some conditions even 9-year-olds were not yet adult-like in their performance. It is clear that this task represents a challenging discrimination for children because explicit training with the illusory form discrimination substantially improved performance. Nevertheless, they demonstrated the relative immaturity of KIC perception in school-age children. These results are supported by studies of other types of global perceptual processing showing immaturity in young children and extended developmental trajectories (e.g., Dukette & Stiles, 1996; Kaldy & Kovács, 2003; Kovács et al., 1999; Lewis et al., 2004; Poirel et al., 2008, 2011; Sherf et al., 2009).

How is it, then, that young infants can be said to "perceive" Kanizsa forms, but many preschool and school-age children apparently either do not perceive them or perceive them sufficiently differently from adults that they perform poorly on objective tests? One explanation could be that the preschoolers perform poorly because they do not understand the task. We think that this is unlikely because in our study, and that of Hadad et al. (2010), the children were pretested to ensure that they understood the task. In addition, a few of the youngest children attained high accuracy despite the prevalence of a local processing strategy, suggesting that (a) they understood the task and (b) they solved it by either taking more time or using the elemental configuration of the display. Nonetheless, the presence of the real dark form as the sample in Test Phase 3, as in the earlier phases, but the absence of any "matching" dark forms as comparisons may have confused some young children, causing them to respond randomly. A control for that possibility might include using reversed-contrast versions of comparisons in Phase 2.

A second explanation for infants' apparent success and preschoolers' apparent difficulty in perceiving KICs is that infants and young children process information in KICs similarly but that adult-like perception develops later—by approximately 7 years of age according to our analysis. Any discrepancy may be only methodological. Studies with young infants rely on looking time measures or similar indirect methods. What is driving the *preference* for illusory contour stimuli, therefore, is unknown. The preference may reflect infants' ability to extract a global form. But it is also plausible that the preference instead reflects a simple preference for the illusory stimulus configuration over the non-illusory one (Colombo et al., 1988; Freeseman et al., 1993; Kavsek & Yonas, 2006) or detection of local configural or brightness differences that attract infants' attention (Bertenthal et al., 1980). Bulf et al. (2009) demonstrated that a Kanizsa figure embedded in a background of non-illusion-inducing pacman elements did not guide the attention of 6-month-old infants, but infants nevertheless showed longer looking times for an isolated Kanizsa figure compared with a non-illusory organization of the same pacman elements. Sherf et al. (2009) suggested that infant perceptual organization may be based on element clustering because this skill shows earlier development than shape formation (see also Kimchi et al., 2005). In that case, perhaps inward pointing pacman elements draw the infants' attention more readily than outward or randomly oriented ones. Interestingly, our post hoc group analysis shows a performance level that is significantly different from chance even for the youngest children (3- and 4-year-olds) despite the overall poor accuracy of most children in this age group. Perhaps a parsimonious interpretation is that infants and young children are more similar, given the application of a similar criterion, than the different test methods would indicate.

A third possibility is that global form information is available in the infant visual system and is sufficient to drive basic attentional mechanisms that are reflected in stronger preference at a young age but is insufficient for, or unavailable to, the decision-making processes that are necessary to solve a psychophysical task, thereby reducing the accuracy of performance in preschoolers. We think that this is an unlikely explanation given that, again, the youngest children in the current study demonstrated mastery of the MTS task, which has the same cognitive and attentional constraints for the real forms as for the KIC discrimination. However, if the illusory shape signal is weaker than that evoked by real forms, it might not be reliably sufficient to guide behavior. Nonetheless, converging evidence based on lower accuracies, touches, and visual attention to the individual pacman elements, and longer latency to touch in the younger children in our sample, suggests the use of a different strategy compared with adults and implies weaker unreliable or absent ability to perceive illusory global forms.

Possible neural correlates

Our results showing younger children's weakness to appreciate the global form in KIC patterns may suggest immature neural correlates in higher order visual areas (Gregory, 1972; Imber, Shapley, & Rubin, 2005; Spillmann & Dresp, 1995) such as ventral stream visual areas involved in object processing (Mendola, Dale, Fischl, Liu, & Tootell, 1999; Sary et al., 2008) and the lateral occipital complex (Stanley & Rubin, 2003; Wu et al., 2012). Although higher visual areas and global perception may develop during later childhood, younger children's ability to process locally suggests intact and relatively early development of early visual areas, which are presumed to be involved in contour completion and may be used in focusing on the individual elements of an illusory contour (Lee & Nguyen, 2001; Maertens & Pollmann, 2005). In contrast, the lateral occipital complex has been strongly associated with perceptual completion and other higher level computations, such as object representation and completion, and may be necessary for integrating the local pacman features to perceive the illusory figure in KICs (Harris, Schwarzkopf, Song, Bahrami, & Rees, 2011; Ringach & Shapley, 1996; Stanley & Rubin, 2003). It is possible that higher order visual areas develop later over different time courses than early ones, and perhaps the later development of KIC perception during childhood reflects this extended maturation process. However, a number of recent studies suggest a requirement for recurrent interaction between higher and lower visual areas, demonstrating both feed-forward and feed-back mechanisms involved in perceptual completion of illusory figures (Murray et al., 2002; Scholte, Jolij, Fahrenfort, & Lamme, 2008; Wokke, Vandenbroucke, Scholte, & Lamme, 2013). The time course for maturation of this complex brain organization is unknown but may contribute to the age-related shift in processing strategy shown by the children in our study.

Understanding the mechanisms that underlie the development of global form perception is important for interpreting the perceptual world of typically developing infants and children and also for gaining deeper understanding of developmental disorders that affect global perceptual processing. In autism spectrum disorders, a prototypical developmental disorder, sensory perception is often reported to be atypical. In particular, autistic participants display poor global form processing in some studies (Happé, 1996; Happé & Frith, 2006; Plaisted, Swettenham, & Rees, 1999), although the existence of global perceptual deficits in autism is still open to debate (e.g., Bernardino et al., 2012; Gadgil, Peterson, Tregellas, Hepburn, & Rojas, 2013; Hayward et al., 2012; Milne & Scope, 2008; Rondan & Deruelle, 2007). Establishing a developmental profile for global form processing using an objective approach like ours may provide insights into differences between perceptual skills of developmentally challenged children and those of typically developing children as well as provide clues into the neural mechanisms involved in KIC perception.

Conclusions

Global form perception in KICs matures during childhood, with a transition in processing strategy between 4 and 7 years of age. Our objective response measures, eye-tracking data, and reaching data provide coherent convergent evidence for a gradual shift from a local perceptual strategy to a global one during this age period. Therefore, it is likely that global perception more generally follows an extended developmental trajectory during childhood.

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References

Abravanel, E. (1982). Perceiving subjective contours during early childhood. *Journal of Experimental Child Psychology, 33*, 280–287.
Bernardino, I., Mouga, S., Almeida, J., van Asselen, M., Oliveira, G., & Castelo-Branco, M. (2012). A direct comparison of local–global integration in autism and other developmental disorders: Implications for the central coherence hypothesis. *PLoS One, 7*, e39351.
Bertenthal, B. I., Campos, J. J., & Haith, M. M. (1980). Development of visual organization: The perception of subjective contours. *Child Development, 51*, 1072–1080.
Bremner, J. G., Slater, A. M., Johnson, S. P., Mason, U. C., & Spring, J. (2012). Illusory contour figures are perceived as occluding contours by 4-month-old infants. *Developmental Psychology, 48*, 398–405.
Bulf, H., Johnson, S. P., & Valenza, E. (2011). Visual statistical learning in the newborn infant. *Cognition, 121*, 127–132.
Bulf, H., Valenza, E., & Simion, F. (2009). The visual search of an illusory figure: A comparison between 6-month-old infants and adults. *Perception, 38*, 1313–1327.
Colombo, J., Mitchell, D. W., & Horowitz, F. D. (1988). Infant visual attention in the paired-comparison paradigm: Test–retest and attention–performance relations. *Child Development, 59*, 1198–1210.
Conci, M., Tollner, T., Leszczynski, M., & Muller, H. J. (2011). The time-course of global and local attentional guidance in Kanizsa-figure detection. *Neuropsychologia, 49*, 2456–2464.
Csibra, G. (2001). Illusory contour figures are perceived as occluding surfaces by 8-month-old infants. *Developmental Science, 4*, 7–11.
Curran, W., Braddick, O. J., Atkinson, J., Wattam-Bell, J., & Andrew, R. (1999). Development of Illusory contour perception in infants. *Perception, 28*, 527–538.
De Lillo, C., Spinozzi, G., Truppa, V., & Naylor, D. M. (2005). A comparative analysis of global and local processing of hierarchical visual stimuli in young children (*Homo sapiens*) and monkeys (*Cebus apella*). *Journal of Comparative Psychology, 119*, 155–165.
Dukette, D., & Stiles, J. (1996). Children's analysis of hierarchical patterns: Evidence from a similarity judgment task. *Journal of Experimental Child Psychology, 63*, 103–140.
Fagot, J., & Tomonaga, M. (2001). Effects of element separation on perceptual grouping by humans (*Homo sapiens*) and chimpanzees (*Pan troglodytes*): Perception of Kanizsa illusory figures. *Animal Cognition, 4*, 171–177.
Franchak, J. M., & Adolph, K. E. (2010). Visually guided navigation: Head-mounted eye-tracking of natural locomotion in children and adults. *Vision Research, 50*, 2766–2774.
Franchak, J. M., Kretch, K. S., Soska, K. C., & Adolph, K. E. (2011). Head-mounted eye tracking: A new method to describe infant looking. *Child Development, 82*, 1738–1750.
Freeseman, L. J., Colombo, J., & Coldren, J. T. (1993). Individual differences in infant visual attention: Four-month-olds' discrimination and generalization of global and local stimulus properties. *Child Development, 64*, 1191–1203.
Gadgil, M., Peterson, E., Tregellas, J., Hepburn, S., & Rojas, D. C. (2013). Differences in global and local level information processing in autism: An fMRI investigation. *Psychiatry Research, 213*, 115–121.
Gerhardstein, P., Kovács, I., Ditre, J., & Feher, A. (2004). Detection of contour continuity and closure in three-month-olds. *Vision Research, 44*, 2981–2988.
Ghim, H. R., & Eimas, P. D. (1988). Global and local processing by 3- and 4-month-old infants. *Perception & Psychophysics, 43*, 165–171.
Gregory, R. L. (1972). Cognitive contours. *Nature, 238*, 51–52.
Guttman, S. E., & Kellman, P. J. (2004). Contour interpolation revealed by a dot localization paradigm. *Vision Research, 44*, 1799–1815.
Hadad, B. S., Maurer, D., & Lewis, T. L. (2010). The development of contour interpolation: Evidence from subjective contours. *Journal of Experimental Child Psychology, 106*, 163–176.
Happé, F. G. (1996). Studying weak central coherence at low levels: Children with autism do not succumb to visual illusions: A research note. *Journal of Child Psychology and Psychiatry, 37*, 873–877.
Happé, F., & Frith, U. (2006). The weak coherence account: Detail-focused cognitive style in autism spectrum disorders. *Journal of Autism and Developmental Disorders, 36*, 5–25.
Harris, J. J., Schwarzkopf, D. S., Song, C., Bahrami, B., & Rees, G. (2011). Contextual illusions reveal the limit of unconscious visual processing. *Psychological Science, 22*, 399–405.
Hayward, D. A., Shore, D. I., Ristic, J., Kovshoff, H., Iarocci, G., Mottron, L., et al (2012). Flexible visual processing in young adults with autism: The effects of implicit learning on a global–local task. *Journal of Autism and Developmental Disorders, 42*, 2383–2392.

Imber, M. L., Shapley, R. M., & Rubin, N. (2005). Differences in real and illusory shape perception revealed by backward masking. *Vision Research, 45*, 91–102.
Johnson, S. P., Davidow, J., Hall-Haro, C., & Frank, M. C. (2008). Development of perceptual completion originates in information acquisition. *Developmental Psychology, 5*, 1214–1224.
Kaldy, Z., & Kovács, I. (2003). Visual context integration is not fully developed in 4-year-old children. *Perception, 32*, 657–666.
Kanizsa, G. (1976). Subjective contours. *Scientific American, 234*, 48–52.
Kavsek, M. J. (2002). The perception of static subjective contours in infancy. *Child Development, 73*, 331–344.
Kavsek, M. J., & Yonas, A. (2006). The perception of moving subjective contours by 4-month-old infants. *Perception, 35*, 215–227.
Kimchi, R. (1992). Primacy of wholistic processing and global/local paradigm: A critical review. *Psychological Bulletin, 112*, 24–38.
Kimchi, R., Hadad, B., Behrmann, M., & Palmer, S. E. (2005). Microgenesis and ontogenesis of perceptual organization: Evidence from global and local processing of hierarchical patterns. *Psychological Science, 16*, 282–290.
Kovács, I. (1996). Gestalten of today: Early processing of visual contours and surfaces. *Behavioural Brain Research, 82*, 1–11.
Kovács, I., Kozma, P., Feher, A., & Benedek, G. (1999). Late maturation of visual spatial integration in humans. *Proceedings of the National Academy of Sciences of the United States of America, 96*, 12204–12209.
Lee, T. S., & Nguyen, M. (2001). Dynamics of subjective contour formation in the early visual cortex. *Proceedings of the National Academy of Sciences of the United States of America, 98*, 1907–1911.
Lewis, T. L., Ellemberg, D., Maurer, D., Dirks, M., Wilkinson, F., & Wilson, H. R. (2004). A window on the normal development of sensitivity to global form in glass patterns. *Perception, 33*, 409–418.
Maertens, M., & Pollmann, S. (2005). FMRI reveals a common neural substrate of illusory and real contours in V1 after perceptual learning. *Journal of Cognitive Neuroscience, 17*, 1553–1564.
Mendola, J. D., Dale, A. M., Fischl, B., Liu, A. K., & Tootell, R. B. (1999). The representation of illusory and real contours in human cortical visual areas revealed by functional magnetic resonance imaging. *Journal of Neuroscience, 19*, 8560–8572.
Milne, E., & Scope, A. (2008). Are children with autistic spectrum disorders susceptible to contour illusions? *British Journal of Developmental Psychology, 26*, 91–102.
Murray, M. M., Wylie, G. R., Higgins, B. A., Javitt, D. C., Schroeder, C. E., & Foxe, J. J. (2002). The spatiotemporal dynamics of illusory contour processing: Combined high-density electrical mapping, source analysis, and functional magnetic resonance imaging. *Journal of Neuroscience, 22*, 5055–5073.
Navon, D. (1977). Forest before the tree: The precedence of global features in visual perception. *Cognitive Psychology, 9*, 353–383.
Neiworth, J. J., Gleichman, A. J., Olinick, A. S., & Lamp, K. E. (2006). Global and local processing in adult humans (*Homo sapiens*), 5-year-old children (*Homo sapiens*), and adult cotton-top tamarins (*Saguinus oedipus*). *Journal of Comparative Psychology, 120*, 323–330.
Otsuka, Y., Kanazawa, S., & Yamaguchi, M. K. (2004). The effect of support ratio on infants' perception of illusory contours. *Perception, 33*, 807–816.
Otsuka, Y., & Yamaguchi, M. K. (2003). Infants' perception of illusory contours in static and moving figures. *Journal of Experimental Child Psychology, 86*, 244–251.
Otsuka, Y., Yamazaki, Y., Konishi, Y., Kanazawa, S., Yamaguchi, M. K., & Spehar, B. (2008). The perception of illusory transparent surfaces in infancy: Early emergence of sensitivity to static pictorial cues. *Journal of Vision, 8*(16), 1–12. http://dx.doi.org/10.1167/8.16.6.
Plaisted, K., Swettenham, J., & Rees, L. (1999). Children with autism show local precedence in a divided attention task and global precedence in a selective attention task. *Journal of Child Psychology and Psychiatry, 40*, 733–742.
Poirel, N., Mellet, E., Houdé, O., & Pineau, A. (2008). First came the trees, then the forest: Developmental changes during childhood in the processing of visual local–global patterns according to the meaningfulness of the stimuli. *Developmental Psychology, 44*, 245–253.
Poirel, N., Simon, G., Cassotti, M., Leroux, G., Perchey, G., Lanoë, C., et al (2011). The shift from local to global processing in 6-year-old children is associated with grey matter loss. *PLoS One, 6*, e20879.
Ringach, D. L., & Shapley, R. (1996). Spatial and temporal properties of illusory contours and amodal boundary completion. *Vision Research, 36*, 3037–3050.
Rondan, C., & Deruelle, C. (2007). Global and configural visual processing in adults with autism and Asperger syndrome. *Research in Developmental Disabilities, 28*, 197–206.
Sary, G., Koteles, K., Kaposvari, P., Lenti, L., Csifcsak, G., Franko, E., et al (2008). The representation of Kanizsa illusory contours in the monkey inferior temporal cortex. *European Journal of Neuroscience, 28*, 2137–2146.
Sato, K., Masuda, T., Wada, Y., Shirai, N., Kanazawa, S., & Yamaguchi, M. K. (2013). Infants' perception of curved illusory contour with motion. *Infant Behavior and Development, 36*, 557–563.
Scholte, H. S., Jolij, J., Fahrenfort, J. J., & Lamme, V. A. (2008). Feedforward and recurrent processing in scene segmentation: Electroencephalography and functional magnetic resonance imaging. *Journal of Cognitive Neuroscience, 20*, 2097–2109.
Sherf, K. S., Behrmann, M., Kimchi, R., & Luna, B. (2009). Emergence of global shape processing continues through adolescence. *Child Development, 80*, 162–177.
Shipley, T. F., & Kellman, P. J. (1992). Strength of visual interpolation depends on the ratio of physically specified to total edge length. *Perception & Psychophysics, 52*, 97–106.
Spillmann, L., & Dresp, B. (1995). Phenomena of illusory form: Can we bridge the gap between levels of explanation? *Perception, 24*, 1333–1364.
Stanley, D. A., & Rubin, N. (2003). FMRI activation in response to illusory contours and salient regions in the human lateral occipital complex. *Neuron, 37*, 323–331.
Treiber, F., & Wilcox, S. (1980). Perception of a "subjective" contour by infants. *Child Development, 51*, 915–917.
Wokke, M. E., Vandenbroucke, A. R., Scholte, H. S., & Lamme, V. A. (2013). Confuse your illusion: Feedback to early visual cortex contributes to perceptual completion. *Psychological Science, 24*, 63–71.
Wu, X., He, S., Bushara, K., Zeng, F., Liu, Y., & Zhang, D. (2012). Dissociable neural correlates of contour completion and contour representation in illusory contour perception. *Human Brain Mapping, 33*, 2407–2414.