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The development of contour interpolation: Evidence from subjective contours

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ABSTRACT

Adults are skilled at perceiving subjective contours in regions without any local image information (e.g., Ginsburg, 1975; Kanizsa, 1976). Here we examined the development of this skill and the effect thereon of the support ratio (i.e., the ratio of the physically specified contours to the total contour length). Children (6-, 9-, and 12-year-olds) and adults discriminated between fat and skinny shapes formed by subjective or luminance-defined contours. By 9 years of age, children were as sensitive as adults to small differences in luminance-defined contours, but not until 12 years of age were children as sensitive as adults in performing the same task with subjective contours. Remarkably, 6-year-olds' sensitivity to subjective contours was independent of the support ratio, unlike that of older children and adults. The results suggest that, during middle childhood, the interpolation of subjective contours becomes tied to the support ratio, so that contours that are more likely to reflect the contours of real objects (i.e., highly supported contours) are more easily interpolated.

Introduction

Organizing the retinal image into meaningful and coherent objects involves locating boundaries between objects and their surroundings. Boundaries or edges are often detected at the location where there is a large and abrupt change in luminance, color, or texture (e.g., Bennett, Sekuler, & Sekuler, 2007; Nothdurft, 1992, 1993). Adults, however, can perceive bounded objects even when local image information fails to provide cues to specify their edges (e.g., Ginsburg, 1975; Petry & Meyer, 1987). In

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the case of subjective contours, interpolation between isolated image parts leads to the perception of an object with edges where there is no physical change (e.g., Kanizsa, 1976, 1979). An example is the Kanizsa figure shown here in Fig. 1A. Luminance-defined edges of the square figure are present only at the positions of the four Pacman-shaped inducers. Yet a bright square figure is perceived in front of four disks. Although they are also known as "illusory contours," subjective contours often reflect real-world surface boundaries rather than illusions. In natural environments of dappled light and heterogeneous reflectance, subjective contours are often formed when luminance contours composing a real object are camouflaged by the luminance of the surrounding field (e.g., a bird with dark edges against a dark background). Interpolation of these contours allows edge detection and completion of boundaries between real objects and their background.

Perceptual interpolation of subjective contours appears to be instantaneous and effortless. However, time course studies in adults suggest that perceptual completion takes some measurable time (e.g., Guttman & Kellman, 2004; Imber, Shapley, & Rubin, 2005; Murray, Sekuler, & Bennett, 2001). Guttman and Kellman (2004), for example, found that it takes adults approximately 40 ms more to perceive subjective contours than to perceive luminance-defined contours. Furthermore, interpolation is constrained by spatial factors such as inducer size, inducer spacing, and overall size of the display. Adults report clearer perception of subjective contours when the overall retinal size (Dumais & Bradley, 1976) and the inducer separation (Watanabe & Oyama, 1988) are smaller. However, by systematically varying inducer size, inducer spacing, and overall stimulus size, Shipley and Kellman (1992) showed that although overall stimulus size has no effect on interpolation, both larger inducers and smaller spacing increase the clarity of the interpolated contours.

These effects of inducer size and spacing are not independent. In fact, interpolation strength is best predicted by the ratio of these two factors, defined as the support ratio—the ratio of the length of the specified contour (i.e., the contour specified by a luminance gradient) to the total length of the contour (i.e., physically specified plus interpolated) (see Fig. 1B). The length of the physically specified contour is $2r$, where r is the radius of the black Pacman, and the total length of the contour is l (the length of

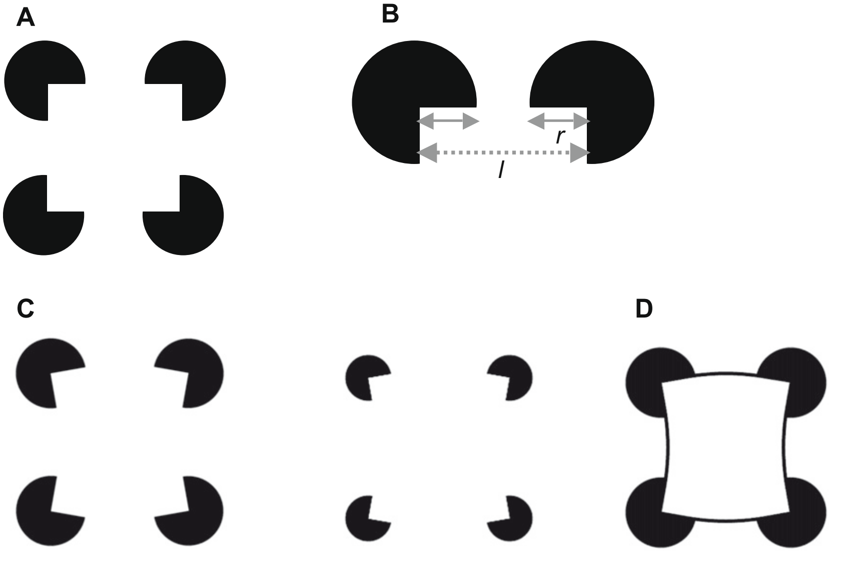

Fig. 1. Manipulation of the support ratio and its effect on the perception of subjective contours. (A) A Kanizsa subjective figure. (B) The support ratio denotes the ratio of the two radii of the Pacmen ($2r$) to the length of the side of the subjective square (l). (C) Examples of shapes with 50 and 30% contour support. The subjective square size (l) is constant across the two support ratios. When interpolation of contours between the inducers is over a small distance relative to the size of the inducers (i.e., high support ratio), a stronger representation of the interpolated contour is obtained. (D) An example of luminance-defined contours forming the same shape as in panel C.

one side of the square). The support ratio, therefore, is $2r/l$. The strength of interpolation increases with the support ratio ($2r/l$) but appears to be largely independent of absolute length of the contour (l) (Shipley & Kellman, 1992). Fig. 1 shows the computation of the support ratio (Fig. 1B) and its effect on interpolation strength (Fig. 1C).

Several studies using a variety of methods have established that the perception of subjective contours in adults is tied strongly to the support ratio (e.g., Banton & Levi, 1992; Kojo, Liinasuo, & Rovamo, 1993; Pillow & Rubin, 2002; but see Maertens & Shapley, 2008). This dependence of interpolation on the support ratio rather than on the absolute size of contours makes ecological sense (Gillam, 1981; Shipley & Kellman, 1992). Although the projected retinal size of elements or the projected retinal distance between elements varies with the observer's distance from the object, the support ratio is invariant with distance. Thus, processes determining the unity of separated projected areas, such as interpolation of contours into bounded objects, might be expected to depend on the support ratio rather than on the projected retinal size.

Developmental research on the perception of subjective contours provides contradictory findings regarding the age at which this skill emerges. Infants as young as 3 months have demonstrated sensitivity to subjective contours in some studies (Ghim, 1990; Hayden, Bhatt, & Quinn, 2008; Johnson & Aslin, 1998; Kavsek, 2002; Kavsek & Yonas, 2006; Treiber & Wilcox, 1980; see also Sireteanu, 2000, for vernier offset lines). However, in other studies, even 4- and 5-month-olds have failed to show this sensitivity (e.g., Bertenthal, Campos, & Haith, 1980; Condry, Smith, & Spelke, 2001; Csibra, 2001). For example, 8-month-olds perceive the figure formed by subjective contours as having the properties of a real object that can act as an occluding surface. However, 5-month-olds failed to treat it as an occluder, responding to the occluded object as two separated parts (Csibra, 2001). This later onset of sensitivity for subjective contours during the first year of life receives further support from electrophysiological data; by 8 months, but not at 6 months, infants show adult-like binding-related gamma oscillations while perceiving a static Kanizsa square (Csibra, Davis, Spratling, & Johnson, 2000).

Part of the discrepancy in the literature on infants may be explained by variations among studies in the properties of the subjective figure. For infants, the likelihood of responding to subjective contours depends on the support ratio (Otsuka, Kanazawa, & Yamaguchi, 2004), overall size (Kavsek, 2002), and presence of motion cues (e.g., Curran, Braddick, Atkinson, Wattam-Bell, & Andrew, 1999). Young infants (3- and 4-month-olds) respond to subjective contours when the support ratio is high (66%) (Otsuka et al., 2004) or when motion is available (Curran et al., 1999; Johnson & Aslin, 1998). In addition, 4-month-olds respond to subjective contours in relatively small figures, whereas even 7-month-olds fail to do so in a large figure, suggesting a critical influence of the spatial separation between the inducers in infants' perception of subjective contours (Kavsek, 2002).

One might assume that the evidence for early sensitivity to subjective contours implies that these processes mature during infancy or soon afterward. However, it has become clear that the development of the visual system is far from complete within the first few years of life. Although the gross anatomical structure of the cortex is constructed before birth, there is a significant increase in the number of cortical cells between birth and 6 years of age (Shankle, Landing et al., 1998), an increase implying an extended structural maturation of the human cortex, including the early visual areas (Shankle, Romney, Landing, & Hara, 1998). In addition, neural circuits within the visual cortex mature postnatally. For example, whereas vertical connections within visual cortical areas V1 and V2 begin to develop prenatally, horizontal connections within cortical layers show a much more protracted development, not reaching maturity until 15 months of age (Burkhalter, 1993; Burkhalter, Bernardo, & Charles, 1993). Furthermore, psychophysical studies indicate that some perceptual abilities remain immature well into childhood (e.g., Kaldy & Kovacs, 2003; Kimchi, Hadad, Behrmann, & Palmer, 2005; Kovacs, 2000; Kovacs, Kozma, Feher, & Benedek, 1999; Lewis et al., 2004; Rieth & Sireteanu, 1994; Sireteanu, 2000; Sireteanu & Rieth, 1992). Indeed, for several aspects of visual perception, the early onset of sensitivity during infancy is followed by a long developmental progression later during childhood (e.g., Lewis et al., 2002; Sireteanu, 2000). For example, whereas infants as young as 2 months are able to segment boundaries based on texture gradients, sensitivity to such boundaries in more complex displays improves over the next 14 years (Sireteanu, 2000).

It is possible, then, that infants' performance with subjective contours reflects some rudimentary perceptual skill that is refined as cortical circuitry develops after infancy, possibly shaped by experience. Indeed, the only study that has tested the perception of subjective contours beyond the first year of life suggests that these abilities continue to develop until 5 years of age (Abravanel, 1982). When children were asked to report the completed shapes formed by subjective contours, their recognition accuracy improved from 60% at 3 years of age to 100% at 5 years of age (Abravanel, 1982). However, conclusions regarding these age-related changes in the perception of subjective contours were based solely on young children's subjective reports. No previous study has used an objective measure to determine the developmental trajectory for these processes, particularly during the overlooked period between infancy and adulthood.

The current study was designed to fill this gap using an objective shape discrimination task originally developed by Ringach and Shapley (1996) with children (6-, 9-, and 12-year-olds) and adults. Observers were asked on each trial to indicate whether the shape was "skinny" or "fat." The skinny stimuli were created by rotating the inducers (corners) of a Kanizsa square toward the center, as shown in Fig. 2B. The fat stimuli were created by rotating the inducers (corners) of a Kanizsa square in the opposite direction, away from the center. Discrimination of shape formed by luminance-defined contours was compared with discrimination of shape formed by subjective contours when interpolation between their inducers was strongly supported (interpolation of contours between the inducers was over a small distance relative to the size of the inducers) or weakly supported (interpolation of contours was over a larger distance) (Fig. 1C). Stimuli in the luminance-defined condition had parabolic contours joining adjacent inducers to form the same shapes (Fig. 1D). Stimuli in the subjective contours condition consisted of only the inducers, so that observers needed to perceive subjective luminance edges between the inducers to perform the task.

The angle of rotation of the inducing elements (designated as alpha in Fig. 2B) was varied over trials according to a one-up, three-down staircase procedure (Levitt, 1971). As the angle of the inducing elements decreased, the curvature and hence fatness or thinness of the subjective shape decreased, requiring a more precise interpolation. Thresholds were defined as the minimum angle of rotation for which the observer could identify the shapes accurately as fat or skinny 79% of the time.

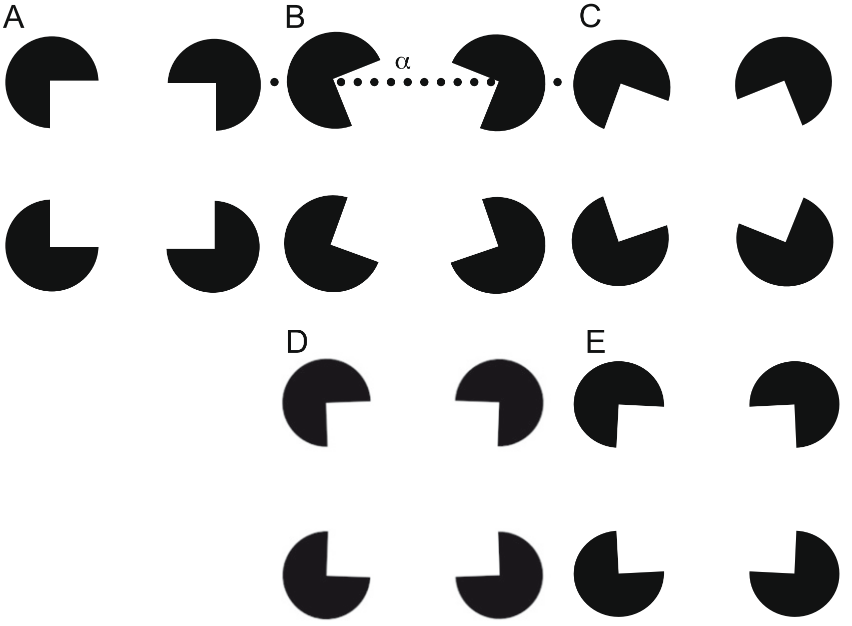

Fig. 2. Rotation of the inducers to produce fat or skinny shapes. Panel A shows a subjective square with no rotation ($\alpha = 0$), with α corresponding to the rotation of the upper left inducer around its center. In panel B, $\alpha > 0$ produces skinny shapes. In panel C, $\alpha < 0$ produces fat shapes, with α varying over trials according to a staircase. Panels D and E show skinny and fat shapes, respectively, with small angles of rotation.

Thresholds for the subjective contours were compared with those for the luminance-defined contours to measure the strength of interpolation of subjective contours into a shape. We examined whether there are age differences in the cost of interpolation (decreased sensitivity when contours are interpolated rather than luminance defined), which we took to reflect age differences in the mechanisms for interpolating subjective contours.[1]

Method

Participants

The participants were 20 6-year-olds (±3 months), 20 9-year-olds (±3 months), 20 12-year-olds (±3 months), and 20 adults (mean age = 20.5 years, range = 17–26). All met our criteria on a visual screening examination. Specifically, the three oldest groups had a linear letter acuity (Lighthouse Visual Acuity Chart) of at least 20/20 in each eye with a maximum of −2 diopters of optical correction (to rule out myopia >2 diopters, which would reduce vision at our testing distance of 50 cm), worse acuity with a +3 diopter add (to rule out hypermetropia >3 diopters), fusion at near on the Worth four-dot test, and stereo acuity of at least 40 arcsec on the Titmus test. The 6-year-olds met the same criteria except that their acuity was tested with the Cambridge Crowding cards. An additional 3 6-year-olds, 2 12-year-olds, and 3 adults were excluded from the final sample for not passing visual screening, and 1 other 6-year-old was excluded for refusing to complete the task.

Apparatus and stimuli

Stimuli were generated on an Apple Macintosh G5 computer using the MATLAB programming environment (Version 7.4.0.287, MathWorks) and the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997). The stimuli were presented on a 21-inch color CRT monitor (Dell P1130). The pixel resolution was 1600 × 1200, with one pixel corresponding to 0.021° at the testing distance of 50 cm, and the refresh rate was 85 Hz. The mean luminance was 90 cd/m^2, and the contrast between the black elements and the white background was 90%. Participants viewed the displays binocularly with their heads stabilized in a chin-and-forehead rest.

Fig. 2 depicts examples of the stimuli. The subjective contour stimuli were composed of four black circles, each missing a 90° notch, aligned to produce a subjective square (Fig. 2A). Using a staircase procedure, the four inducing Pacmen were rotated to produce skinny and fat shapes (Figs. 2B and C) (Ringach & Shapley, 1996). Inducers lying on the same diagonal were rotated in the same direction, with opposite directions of rotation for the two diagonals. A skinny subjective shape was produced by rotating the upper left and lower right Pacmen counterclockwise, whereas the lower left and upper right Pacmen were rotated clockwise (Fig. 2B). The opposite pattern was employed to produce the fat subjective shape (Fig. 2C).

The support ratio denotes the ratio between the two radii of the inducers (2*r*) and the length of the side of the subjective square (*l*) (see Fig. 1B). Two support ratios were created by changing the size of inducing elements while keeping the square size constant. The square in both conditions of the support ratio subtended 4.35° of visual angle. The total diameter of the inducing Pacmen (2*r*) in the relatively high support ratio subtended 2.17° of visual angle, giving rise to a support ratio of approximately 50%, and their diameter in the low support ratio subtended 1.37° of visual angle, giving rise to a ratio of approximately 30% (Fig. 1C).

Displays of the luminance-defined contour (Fig. 1D) precisely matched those of the subjective contour condition except that a luminance-defined contour was added. Specifically, an arc of 0.13° width with varying curvature, tangential to the black inducing edges, created the curved edges of the luminance-defined fat and skinny shapes.

[1] Alternatively, an observer might be able to solve the task by using a strategy other than interpolation such as the orientation of an individual inducer, or a cognitive completion process such as the overall symmetry of the Pacmen, or some other global aspect of their interrelationship. However, such solutions in adults are less spatially precise and, hence, are unlikely to produce good performance on the current task (Guttman & Kellman, 2004).

Design

The experiment employed an orthogonal combination of three factors: age (6 years, 9 years, 12 years, or adult), stimulus (fat or skinny), and contour type (luminance defined, high support, or low support). Stimulus and contour type were manipulated within participants.

Procedure

Observers sat 50 cm from the monitor with their heads positioned in a chin rest. Each observer completed three sets of tests: luminance defined, high support, and low support. Each test of threshold was preceded by demonstration trials, criterion trials, and a practice run with the same type of stimulus that was to be tested.

Demonstration trials

The purpose of the demonstration trials was to familiarize participants with the stimuli to be shown in that run. The demonstration consisted of four trials with the stimuli with 10° of rotation. The first two trials consisted of one trial with the inducers rotated to produce a skinny shape and the other trial with the inducers rotated to produce a fat shape. The second two trials showed the skinny shape, one followed by an example of positive feedback and the other followed by an example of negative feedback.

Criterion trials

The purpose of the criterion was to verify that participants understood the task. Participants were presented with a block of four trials, each of which had 10° of rotation as in the demonstration trials, with skinny and fat shapes presented in a random order. To be included in the study, participants needed to judge the shape correctly as skinny or fat on all four trials within a block. Participants had three chances to meet this criterion, and all of them did so, usually within the first block.

Practice run

The practice run consisted of one full staircase with the type of stimuli to be used in the test run to follow. Observers were instructed to fixate on a 2.17° black circle in the center of the screen at the beginning of each trial, and the black circle was removed after a variable interval. After a 250-ms delay, observers were shown the test stimulus for 1000 ms. The task on each trial was to indicate whether the shape was skinny or fat, and the experimenter pressed a corresponding key. Observers received visual and auditory feedback about their accuracy.

For each contour type, one staircase was run with both skinny and fat shapes appearing on randomized trials, with equal probability to appear. The amount of rotation of the inducers (and the resulting curvature of the figure) was varied according to a one-up, three-down staircase procedure, converging on a correct response rate equivalent to 79.4% accuracy (Levitt, 1971). In the first display, the four inducing Pacmen were rotated 10°. After three consecutive correct responses, the staircase reduced the angle of rotation by one octave (where an octave is a halving or a doubling of a value) to 5°. Step size remained at one octave until an error was made, at which point step size was reduced to half-octave intervals. Following an error, the staircase reversed directions and a stimulus with a larger rotation angle was presented until three consecutive correct responses were made, after which the direction of the staircase reversed again to present successively smaller angles. Testing continued until 10 changes in the direction of the staircase ("reversals") occurred, typically requiring 5 min. The threshold for each condition, defined as the minimum angle of rotation needed to accurately discriminate the shape, was based on the geometrical mean of the rotation angle of the final six reversals. The experimenter watched participants to ensure that they maintained central fixation, providing reminders to do so.

Test run

The test run was identical to the practice run except that now the experimenter was unaware of the stimulus presented on each trial. After participants completed the demonstration trials, criterion trials, practice run, and test run for one type of stimulus (subjective contours with high support ratio, subjective contours with low support ratio, or luminance-defined contours), the entire procedure was repeated for the other two types of stimuli. Half of the participants at each age were tested first with luminance-defined stimuli, and half were tested first with the subjective contours. Within the subjective contour blocks, the order of support ratio (high or low) was counterbalanced across participants in each age group. Participants were given as many breaks as necessary, and all participants completed the testing protocol in a single session that lasted no longer than 1 h.

Results

In a trimming procedure, each threshold was first converted to a *Z* score using the mean and standard deviation for that age group and contour type. *Z* scores greater than +2.5 or less than −2.5 were replaced with the original group mean (see Kirk, 1990). Five data points were replaced: two from 6-year-olds tested in the high-support condition, one from a 9-year-old tested in the high-support condition, one from a 12-year-old tested in the low-support condition, and one from an adult tested in the luminance-defined condition.[2] Preliminary analyses revealed neither a significant effect of sex nor any interactions involving this factor. Therefore, the results were collapsed across this factor.

Fig. 3 shows performance on the shape discrimination task as a function of contour type for the four age groups. A two-way mixed designed analysis of variance (ANOVA) was conducted with age (6 years, 9 years, 12 years, or adult) as a between-participants factor and contour type (luminance defined, high support, or low support) as a within-participants factor.[3] The analysis revealed a significant effect of age on thresholds, $F(3, 76) = 24.7$, $p < .0001$. As Fig. 3 indicates, thresholds decreased with age in all conditions tested. More interesting, this effect of age interacted significantly with condition, $F(6, 152) = 4.51$, $p < .0001$, revealing a different effect of age for luminance-defined and subjective contours.

When contours were luminance defined, thresholds decreased significantly with age, $F(3, 76) = 25.31$, $p < .0001$ (*M*s = 1.62, 0.66, 0.44, and 0.36° for 6-year-olds, 9-year-olds, 12-year-olds, and adults, respectively). Curve fitting indicated that thresholds decreased exponentially with age, $R^2 = 0.49$, $y = 22.33 * \exp(-0.48x) + 0.37$, and Tukey's post hoc tests revealed a significant difference in sensitivity between 6-year-olds and the older observers (*p*s < .0001) but no significant difference in sensitivity between 9-year-olds and the older observers (*p*s > .10). The best-fitting exponential function for the luminance-defined contours is shown as the lowest smooth black curve in Fig. 3B.

Sensitivity to shape formed by subjective contours had a longer developmental trajectory. Thresholds for the high-support contours improved significantly with age, $F(3, 76) = 39.85$, $p < .0001$ (*M*s = 3.11, 1.35, 0.54, and 0.59° for 6-year-olds, 9-year-olds, 12-year-olds, and adults, respectively). Curve fitting revealed an exponential trend, $R^2 = 0.60$, $y = 31.54 * \exp(-0.413x) + 0.493$. Tukey's post hoc tests showed a significant difference in sensitivity between 6-year-olds and the older groups (*p*s < .0001) and, unlike the luminance-defined contours, also a significant difference between 9-year-olds and the older groups (*p*s < .03). Only by 12 years of age were children as sensitive as adults to shape formed by highly supported contours ($p > .90$). As is evident from Fig. 3, the change in sensitivity with age was greater for the subjective contours with high support than for luminance-defined contours, but by 12 years of age, sensitivity to those subjective contours had improved to nearly equal sensitivity to luminance-defined contours, $F < 1.0$.

The developmental trajectory for low-support contours changed more gradually. Thresholds in this condition improved significantly with age, $F(3, 76) = 15.36$, $p < .0001$, (*M*s = 3.49, 1.94, 1.17, and 1.06° for 6-year-olds, 9-year-olds, 12-year-olds, and adults, respectively). Curve fitting revealed that thresholds decreased exponentially with age, $R^2 = 0.36$, $y = 20.96 * \exp(-0.35x) + 0.98$, and Tukey's post hoc

[2] When we reanalyzed the data with outliers included, the pattern of results remained the same.

[3] As expected, tests of sphericity reveal differences in variance among the age groups for all types of contours: luminance defined, $F(3, 76) = 11.59$, $p < .0001$; high support, $F(3, 76) = 9.27$, $p < .0001$; and low support, $F(3, 76) = 4.09$, $p < .009$. Therefore, all ANOVA results in the article are provided in Greenhouse–Geisser values to correct for this violation of the sphericity assumption. Variability was higher for the younger observers than for the older observers, presumably because of differences in the rate of development, especially at the younger ages.

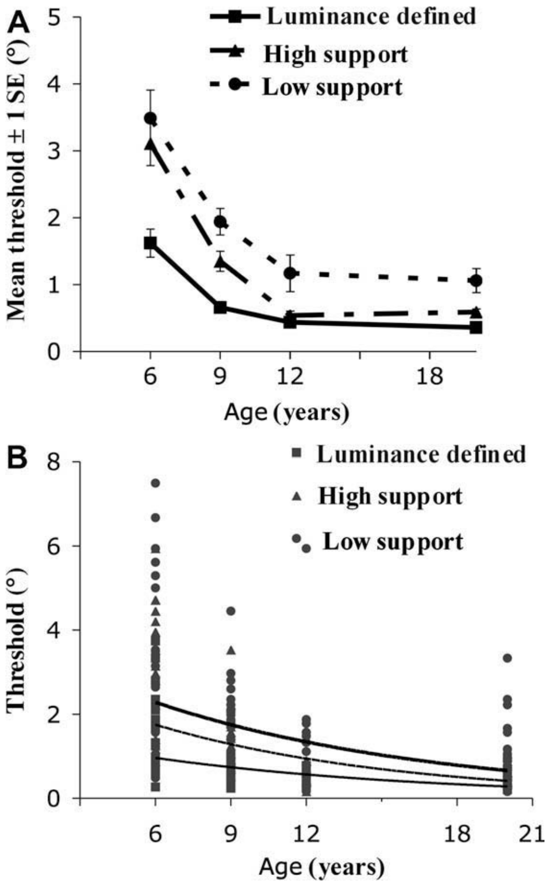

Fig. 3. (A) Mean thresholds ± 1 standard error (SE) (in degrees) as a function of age for luminance-defined, high-support, and low-support ratios. (B) Best-fitting functions for each condition. Each symbol in panel B represents the threshold for one participant at the age indicated.

tests showed a significant difference in sensitivity between 6-year-olds and the older observers ($ps < .001$) as well as a marginally significant difference in sensitivity between 9-year-olds and adults ($p < .07$). However, 9-year-olds did not differ from 12-year-olds ($p > .20$). Combined, the results suggest a gradual improvement in sensitivity after 6 years of age. The best-fitting exponential function for the low-support contours is shown as the highest black line in Fig. 3B.

Given the different developmental trajectories of luminance-defined and interpolated contours, we conducted a more direct examination of the effect of support ratio on interpolation. For each participant, we calculated the interpolation cost for each support ratio as the difference in sensitivity for luminance-defined and subjective contours. Computationally, the amount of interpolation cost was defined as the difference in thresholds divided by the luminance-defined threshold (i.e., low support: [(low – luminance defined)/luminance defined]; high support: [(high – luminance defined)/luminance defined]). The expected effect of support ratio should manifest itself in higher interpolation cost for the low-support contours compared with the high-support contours.

Fig. 4 shows the mean interpolation cost as a function of age for the high- and low-support conditions. Planned specific comparisons (two-tailed t tests) showed that although 6-year-olds' interpolation cost did not vary with the support ratio, $t(19) = 1.44$, $p > .10$, interpolation cost for the older children and adults was higher for low-support contours compared with high-support contours:

9-year-olds, $t(19) = 2.15$, $p < .05$; 12-year-olds, $t(19) = 2.94$, $p < .0001$; adults, $t(19) = 2.59$, $p < .02$. As shown in Fig. 4, the advantage of high support over low support increased with age.

Discussion

When the support ratio was high (50%), performance with subjective contours was nearly as good as that with luminance-defined contours by 12 years of age. Like previous studies with adults (e.g., Dresp & Bonnet, 1991, 1993; Greene & Brown, 1997), this finding indicates that by 12 years of age, boundary completion with subjective contours is nearly as precise as direct sensing of luminance boundaries. However, the results also indicate that the interpolation process, which emerges during infancy, takes many years to achieve adult-like precision. The developmental trajectory for sensitivity to a shape formed by subjective contours was longer than that for a shape formed by luminance-defined contours; only by 12 years of age were children as sensitive as adults to subjective contours, whereas sensitivity for luminance-defined contours did not differ from that of adults by 9 years of age. Moreover, the effect of support ratio on the interpolation process increased during this period. Despite the rather weak manipulation of the support ratio (30 vs. 50%), for 9-year-olds and the older observers, interpolation was significantly better with the higher support ratio, with the size of the effect increasing across this age range. These results show that interpolation is tied to a factor that remains constant across changes in viewing distance and, thus, allows a single object to be perceived as a bounded entity despite changes in the observer's position (Kellman & Shipley, 1991; Kojo et al., 1993; Shipley & Kellman, 1992). Interpolation at 6 years of age, in contrast, was insensitive to the support ratio. This insensitivity to the support ratio implies that interpolation is not scale invariant, such that the child is less likely to perceive a single object as a bounded entity as its distance from the child increases. We elaborate on this point later in this section.

A fundamental concern, associated with studying development in general, is that poorer performance in younger children might not necessarily reflect poorer performance in the perceptual abilities at hand (interpolation of the contours into a shape in our case) and instead might reflect poorer motivation, shorter span of attention, and/or poorer cognitive inference. Therefore, procedures were implemented in the current study to ensure that the age-related changes indeed reflect developmental changes in interpolation abilities rather than improvements with age in the other obvious, but irrelevant, aspects. Each phase included demonstration trials, criterion trials, and a practice staircase to verify that children understood the task. Feedback was given to keep children motivated and engaged in the task. Moreover, the pattern of results is not easily explained by nonvisual factors. If poorer motivation, span of attention, and/or cognitive inference of children underlie the age-related changes

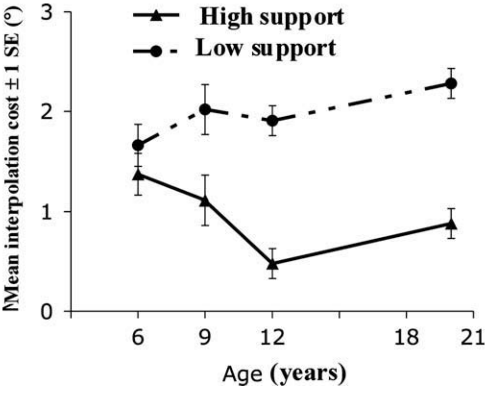

Fig. 4. Mean interpolation cost ± 1 within-participants standard error (SE) (in degrees) as a function of age for low- and high-support ratios (see Loftus & Masson, 1994). Interpolation cost was calculated for each participant and for each support ratio as the difference between the subjective contour threshold (low or high support) and the luminance-defined threshold divided by the luminance-defined threshold (see text for details).

obtained for the subjective contours condition, worse performance should have been observed in the condition proven to be more demanding for the older observers (i.e., the low-support condition). However, this was not the case. The results showed no significant difference between the low- and high-support conditions for 6-year-olds and showed no change with age in cost for the low-support condition, although the low-support condition was clearly more difficult than the high-support condition for the older observers.

Neither can changes in sensitivity to local orientation explain the pattern of results. In theory, it is possible to solve the fat/skinny task by judging the orientation of a single inducer rather than interpolating between inducers; thus, developmental changes in sensitivity to orientation might lead to age changes in apparent interpolation.[4] If this were the cause, performance should have been similar for the subjective and luminance-defined contours. However, children as young as 6 years were more sensitive to shape formed by luminance-defined contours compared with subjective contours, a pattern suggesting that their lower sensitivity in the latter case can be attributed to immature interpolation mechanisms. However, one could still argue that 6-year-olds might have used local cues to solve the task if they were unable to see the subjective contours and, like adults (Ringach & Shapley, 1996), had difficulty in doing well based on local cues. This alternative explanation seems unlikely for several reasons. First, in the current study, children of all ages appeared to easily extract the subjective figures during the criterion phase. Second, by 7 or 8 months, infants respond to the shape formed by subjective contours when the support ratio is as low as 37% (Otsuka et al., 2004). Third, when the support ratio is extremely high (80%), 6-year-olds' thresholds for the fat/skinny task used here are nearly as good as in the luminance-defined condition (1.80 and 1.72°, respectively) (unpublished data). These findings indicate that local orientation cues are not likely to explain the current results because these local cues are present equally in the different support ratio conditions. It is still possible, however, that 6-year-olds cannot *easily* extract the subjective shape when the support ratio is low (30 and 50%) and, under those conditions, use local orientation cues. Even if this is the case, however, the conclusions regarding immaturity of the interpolation process remain the same; 6-year-olds' interpolation is immature and is not affected by the support ratio in the same way as in adults (50% contours are not significantly better than 30% at 6 years of age but are significantly better from 9 years of age onward).

One might argue that the age differences in the subjective contour conditions reflect developmental changes in the ability to perceive the concave versus convex curvature differences or in sensitivity to connectedness (i.e., subjective contours are disconnected, whereas luminance-defined contours are completely connected). However, the high sensitivity of 6-year-olds in the luminance-defined condition (this study) and in the 80% support ratio condition (unpublished data) rule out the first alternative interpretation. Furthermore, previous results demonstrating 5-year-olds' ability to perceive the shape of disconnected line configurations when strong perceptual cues are present (Hadad & Kimchi, 2006) make it unlikely that differences in sensitivity to connectedness underlie the observed age differences.

It seems, then, that interpolation of subjective contours is immature at 6 years of age and still not as precise as that of adults even at 9 years of age. Furthermore, the support ratio has a different effect on interpolation across ages. As in adults, sensitivity to subjective contours was better with higher support ratio than with lower support ratio by 9 years of age, and the effect of support ratio increased thereafter. However, sensitivity at 6 years of age was independent of support ratio, at least for the values of support ratio employed here. These results suggest that, during middle childhood, the interpolation of subjective contours becomes tied to the support ratio, so that contours that are more likely to

[4] Adults are unlikely to have used this alternative strategy. In the original version of the skinny/fat task, Ringach and Shapley (1996) had adults discriminate between clockwise and counterclockwise rotation of the same four inducers, all facing the same direction. Observers reported using a strategy of attending to only one inducer (usually the upper left one). Performance in this control condition was significantly worse (thresholds were $\sim$2.5°) compared with the condition in which a subjective figure was formed among the four inducers (thresholds were <1°). In the current study, 9- and 12-year-olds and adults demonstrated thresholds that were lower than 2.5°, indicating that this alternative explanation for the results is unlikely. Similarly, adults' thresholds to discriminate the orientation of a grating are around 1° (Lewis, Kingdon, Ellemberg, & Maurer, 2007), whereas thresholds for discriminating shape in the current study were 0.59° for highly supported subjective contours. The better thresholds for subjective contours than for the orientation of individual Pacmen or gratings indicate that interpolation of the contours between the inducers and overall shape discrimination, rather than discrimination of the orientation of one of the inducers in the display, underlies adults' performance in the current study.

reflect real objects' contours (i.e., highly supported contours) are more easily interpolated. This ratio of the physically specified contours to the physically specified contours plus the interpolated contours ($2r/l$ in Fig. 1B) is invariant across viewing distances, as opposed to the visual angle formed by the absolute length of the interpolated contour that varies with distance (l in Fig. 1B). That is, strength of interpolation of a single object with a given support ratio remains constant across different distances, allowing a single object to be perceived as a bounded entity regardless of its distance from the observer (i.e., perceptual constancy). Our results suggest that this scale-invariant mechanism, allowing perceptual constancy and unified perception of objects, evolves gradually during development, emerging by 9 years of age and becoming stronger thereafter. This hypothesis receives further support from studies of size constancy in children. For example, 5- and 6-year-olds underestimate the size of a distant object, and it is only at 9 years of age that children exhibit size constancy for distant objects (Granrud & Schmechel, 2006). The age at which size constancy is observed coincides with the age at which we found that contour interpolation varies with support ratio.

At first glance, these data, suggesting that young children are less affected by the support ratio than older children and adults, seem to be inconsistent with previous data demonstrating an effect of support ratio on perception of subjective contours during infancy (Otsuka et al., 2004). However, in the study by Otsuka et al. (2004), the support ratio varied from 37 to 66%, which is a larger manipulation of the support ratio than the one employed here (30 and 50%). In addition, as Otsuka et al. (2004) noted, the support ratio in their stimuli was confounded with the absolute size of the interpolated contours; thus, the effect obtained might reflect the effect of absolute size rather than, or in addition to, the effect of support ratio. Indeed, Kavsek (2002) found that 4-month-olds can perceive subjective contours in small figures, whereas even 7-month-olds show no evidence of doing so in a large figure. These results imply that the absolute length of the interpolated contours affects infants' perceptions of subjective contours. A more careful examination in future studies is needed, however, to determine the role of the absolute spatial range over which interpolation is required, on the one hand, and the role of support ratio, on the other, on interpolation strength at different points during development.

The increased effect of support ratio on interpolation with age during middle childhood might be a result of statistical learning of natural contours accumulating over the years. With development, the visual system may increasingly use this information on natural contours in perceiving the unity of objects, treating highly supported contours as better candidates for composing a single bounded object. Viewing objects from different angles and acting on the visual environment allow feedback about the accuracy of interpolation and presumably modify the mechanism of interpolation to gradually become tied to these ecological constraints.

The formation of shape formed by subjective contours is related to a group of visual functions with protracted developmental sequences. Each of these visual functions involves integration among elements into a global visual pattern. Developmental studies beyond the second year of life suggest that contour integration (Kovacs, 2000; Kovacs et al., 1999), the ability to use collinearity to enhance the perception of a closed shape (Hadad & Kimchi, 2006), the detection of a global form in glass patterns (Lewis et al., 2002), configural face processing (Mondloch, Le Grand, & Maurer, 2002; but see Crookes & McKone, 2009), and configural processing of hierarchical patterns (Burack, Enns, Iarocci, & Randolph, 2000; Kimchi et al., 2005; Mondloch, Geldart, Maurer, & de Schonen, 2003) all remain immature well into childhood. It has been suggested that immature cortical connections beyond the primary visual cortex underlie the protracted development of these perceptual integration processes (e.g., Kovacs et al., 1999).

The exact anatomical substrate involved in processing our stimuli and the anatomical source of the limitations in interpolation during middle childhood is beyond the scope of this study; however, an examination of the literature points to feedback from V2 to V1 as a likely candidate. Psychophysical evidence (e.g., Kellman & Shipley, 1991; Shipley & Kellman, 1992) and neural evidence (e.g., Dresp & Bonnet, 1993; Pillow & Rubin, 2002) suggest that subjective contours may be built up by a fast, low-level system mediated by early visual areas V1/V2. The functional properties of the receptive fields (small and spatially organized in retinotopic coordinates) allow efficient detection of local details; thus, the formation of edges and contours, even when these contours are interrupted by gaps or are lacking luminance gradient (Heider, Spillmann, & Peterhans, 2002). This local process, taking place in early cortical areas, can occur fast, presumably 100 ms after stimulus presentation (e.g., Lee, 2002a).

It has been argued, however, that this initial response around 100 ms in V1 may already integrate the effect of "late" processing mediated by top-down influences (e.g., Foxe & Simpson, 2002; Lee, 2002b; Lee & Nguyen, 2001). If so, there must exist some rapid feedback projections from V2 to V1 that can boost and sharpen visual processing at a relatively local scale (Bullier, Hupe, James, & Girard, 2001; Roe, Lu, & Hung, 2005). Then segmented features from the subjective figure might be forwarded to the subsequent higher cortical areas in temporal and parietal lobes, such as the lateral occipital complex, for figure recognition and integration into a global shape according to the alignment of the detected local features (e.g., Saarinen & Levi, 2001). The important role that these feedback connections from V2 to V1 play in the perception of subjective contours, along with the evidence for delayed development of these feedback connections during childhood (Burkhalter, 1993), may well explain the protracted development of sensitivity to subjective contours obtained in the current study.

In summary, we have shown that interpolation of subjective contours develops well into childhood and that only by 12 years of age are children as sensitive as adults to shape formed by subjective contours. We also showed that interpolation is less affected by the support ratio in 6-year-olds than in older children and adults. Future studies varying the support ratio over a larger range and determining the interaction of its effect with absolute size will be helpful in revealing the spatial factors that limit interpolation during middle childhood.

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