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The effects of spatial proximity and collinearity on contour integration in adults and children

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ABSTRACT

We tested adults and children aged 7 and 14 on the ability to integrate contour elements across variations in the collinearity of the target elements, their spatial proximity, and the relative spacing of the target elements to the background noise elements (Δ). When collinearity was high, the strength of integration for adults was largely independent of spatial proximity and varied only with Δ. It was only when collinearity was less reliable because the orientation of the elements was randomly jittered that spatial proximity began to influence adults' integration. These patterns correspond well to the probability that real-world contours compose a single object: collinear elements are more likely to reflect parts of a real object and adults integrate them easily regardless of the proximity among those collinear elements. The results from children demonstrate a gradual improvement of contour integration throughout childhood and the slow development of sensitivity to the statistics of natural scenes. Unlike adults, integration in children was limited by spatial proximity regardless of collinearity and one strong cue did not compensate for the other. Only after age 14 did collinearity, the most reliable cue, come to compensate efficiently for spatial proximity.

1. Introduction

To derive a meaningful percept of a scene, the visual system must integrate spatially separated features into global shapes, fill in missing contours, and segregate those contours composing a whole object from their background. This ability has often been studied in adults by asking them to detect a subset of Gabor elements, called the target, which are aligned in orientation and position along a notional contour and embedded within a field of evenly spaced, randomly oriented Gabor elements (e.g., Achtman, Hess, & Wang, 2003; Altmann, Bülthoff, & Kourtzi, 2003; Field, Hayes, & Hess, 1993; Hess, Beaudot, & Mullen, 2001; Kovács & Julesz, 1993; Mathes & Fahle, 2007; for reviews, see Hess & Field, 1999; Hess, Hayes, & Field, 2003). Strength of integration is then studied by looking at the effect of spatial properties of the elements on the accuracy with which adults can find the target among the noise elements.

The Gestalt psychologists formulated rules, such as good continuation and spatial proximity, by which spatially separated segments are organized into a coherent whole (e.g., Koffka, 1935). More recent psychophysical studies have confirmed that good continuation affects contour integration (e.g., Field et al., 1993) and have formulized it as the degree of collinearity (e.g., Kellman & Shipley, 1991). Recent studies indicate that absolute spatial proximity is less important (Hess & Beaudot, unpublished data in Hess et al. (2003); Kovács, Kozma, Fehér, & Benedek (1999)); instead, integration depends on the relative spacing of elements in the contour compared to the background, which is referred to as Δ, the Greek symbol delta. Moreover, when the elements are highly colinear, even weak effects of spatial proximity diminish (Hadad & Kimchi, 2008). These interactive effects of collinearity and proximity can be related to average statistical properties of natural contours (Geisler, Perry, & Ing, 2008; Hadad & Kimchi, 2008): collinear elements, which are likely to reflect parts of a real object, are efficiently integrated into a global shape, regardless of the spatial proximity among them. Non-collinear elements, on the other hand, which are less likely to reflect parts of the same object, are integrated into a shape only when they are spatially close to each other. However, the influence of spatial proximity, collinearity, and relative spacing (Δ) has not always been studied with the same paradigm, and in many studies, spatial proximity and relative spacing (Δ) were confounded. One purpose of the current experiments was to assess the interactive relations between collinearity and proximity when the relative spacing between the elements and background (Δ) was controlled.

A second purpose was to examine how these interactions change with age during childhood. Despite the extensive research on contour integration in adults, little is known about the development of this ability in children. The very few studies reveal a late maturation that continues beyond 14 years of age (Kovács, 2000; Kovács et al., 1999). For example, Kovács et al. (1999) showed that

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when required to detect a contour embedded in a background of noise elements, children demonstrate weaker integration as evidenced by higher delta (Δ) values compared to adults, that gradually diminish between 5 and 14 years of age, at which point they are still not quite at adult levels. These studies also suggest that contour integration is limited by different spatial properties in children than in adults. Unlike adults, integration at age 5–6 is affected by the absolute spacing among elements in the target (Kovács et al., 1999), even when the collinearity between the elements is high (Hadad & Kimchi, 2006). Although these studies imply age-related changes in the pattern of relations among spatial proximity, collinearity, and the relative spacing between background and contour elements (Δ), none of them examined these three factors independently in the same task. That was the second purpose of our study. In Experiment 1, we examined the interactive effects of these statistical properties in contour integration in adults. Collinearity, spatial proximity, and the ratio of contour and background spacing (Δ) were manipulated independently. In Experiment 2, we used a subset of the collinearity and proximity levels to compare contour integration in 7- and 14-year-olds to that of adults.

2. Experiment 1: contour integration in adults

The effects of spatial proximity and collinearity in adults were studied by contrasting 12 combinations of these factors that allowed their independent and interactive effects to be examined while controlling for the relative spacing of elements in the target and background (Δ). Adults identified the orientation of an egg-shape formed from target Gabors in a background of randomly oriented and positioned noise Gabors.

2.1. Methods

2.1.1. Participants

Twenty-four adults, (11 males, 13 females; mean age = 19.6 - years, range = 18–26 years) participated. All met our criteria on a visual screening examination. Specifically, participants had a linear letter acuity (Lighthouse Visual Acuity Chart) of at least 20/20 in each eye with a maximum of −2 dioptres of optical correction (to rule out myopia greater than two dioptres which would reduce vision at our testing distance of 50 cm), worse acuity with a +3 dioptre add (to rule out hypermetropia greater than three dioptres), fusion at near on the Worth four dot test, and stereo acuity of at least 40 arcsec on the Titmus test. An additional three participants were excluded from the final sample for not passing visual screening.

2.1.2. Apparatus and stimuli

Stimuli were generated on an Apple Macintosh G5 computer using the MATLAB programming environment (version 7.4.0.287. The MathWorks, Inc., Natick, MA, USA) and the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997). The stimuli were presented on a 21 in. colour CRT monitor (Dell P1130). 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. Mean luminance was 60 cd/m^2. Participants viewed the displays binocularly with their heads stabilized in a chin-and-forehead rest.

We used a closed figure made up of 14 Gabor patches (Gaussian windowed sinusoidal gratings) arranged in a global pattern of an egg-like shape (see Fig. 1). The Gabor patches were positioned on the imaginary elliptical contour with a random starting point. The position of the contour was jittered up to 2° around the centre of the screen so that its elements appeared in different spots but at roughly the same radius so as to minimize positional uncertainty (e.g., Hess & Dakin, 1997, 1999). Gabor elements were created by multiplying a sine wave grating with a spatial frequency of 3 cpd by a circular Gaussian envelope with standard deviation (σ) of 0.25°. Contrast within the elements was 88%.

The contour was embedded in a field of noise Gabor patches with random orientations that were distributed randomly across the visual field. The screen was divided into imaginary circles of increasing radii, with the number of circles varying with the spacing between the background elements, which was specified by a staircase procedure (i.e., averaged spacing among the background elements decreased over trials by adding circles of background elements). Noise Gabors were assigned randomly to the imaginary radii and the centre of each was positioned randomly within ±5 pixels along the imaginary radius. A new random noise background was generated on each trial. All Gabor patches, both background noise and contour elements, were identical physically except for their locations and orientations.

There were four levels of collinearity of the target contour elements crossed with three levels of spatial proximity. Collinearity was manipulated by jittering the local orientation of the contour elements. This jittering is described by the angle α (Field et al., 1993). Specifically, for each proximity level we used α of 0°, 10°, 20°, and 30°. For $\alpha = 0°$, the orientations of the contour elements were parallel to the imaginary egg-shaped contour. For $\alpha > 0°$, the orientations of the contour elements differed randomly either clockwise or anti-clockwise by α degrees from the imaginary contour. The global curvature of the imaginary egg-shaped contour was kept constant across these different collinearly conditions. Therefore, varying the local orientation of each of the Gabors in the four collinearity conditions did not alter the pointedness of the egg-shape. Spatial proximity was manipulated by varying the distance among the target contour elements while keeping constant the total number of elements in the background noise display as well as the total number of elements in the target contour. Consequently, changes in spatial proximity co-occurred with changes in the size of the target contour but without changes in the number of elements. Specifically, the distance between the elements in the target contour was set at 1.64°, 1.92°, and 2.21° (when viewed from the testing distance of 50 cm) and resulted in a radius of the target ellipse of 5.71°, 6.84°, and 7.97°, respectively. Variations in spatial proximity are necessarily confounded with either changes in the size of the target or in the number of target elements. Previous studies show that these two ways of varying spatial proximity produce the same results in adults (Hess & Beaudot, unpublished data in Hess et al. (2003).

2.1.3. Procedure

The experimental protocol was approved by the McMaster Research Ethics Board. The procedures were explained and informed consent was obtained. Observers sat 50 cm from the monitor with their head positioned in a chin rest. Each observer completed twelve tests (12 combinations of collinearity and proximity). Each test of threshold was preceded by demonstration and criterion trials. The three proximity levels were blocked and a practice run with perfect collinearity was given before the participant began the four collinearity levels for that proximity. The order of the three levels of proximity was counterbalanced across participants. Within each proximity level, the order of the four levels of collinearity was determined by a Latin Square. Observers completed the whole set of tests in one session that lasted approximately 55 min (including visual screening and breaks).

2.1.4. Demonstration trials

The purpose of the four demonstration trials before each test was to familiarize the subject with the stimuli to be shown in that run. The first two trials showed stimuli with no background noise,

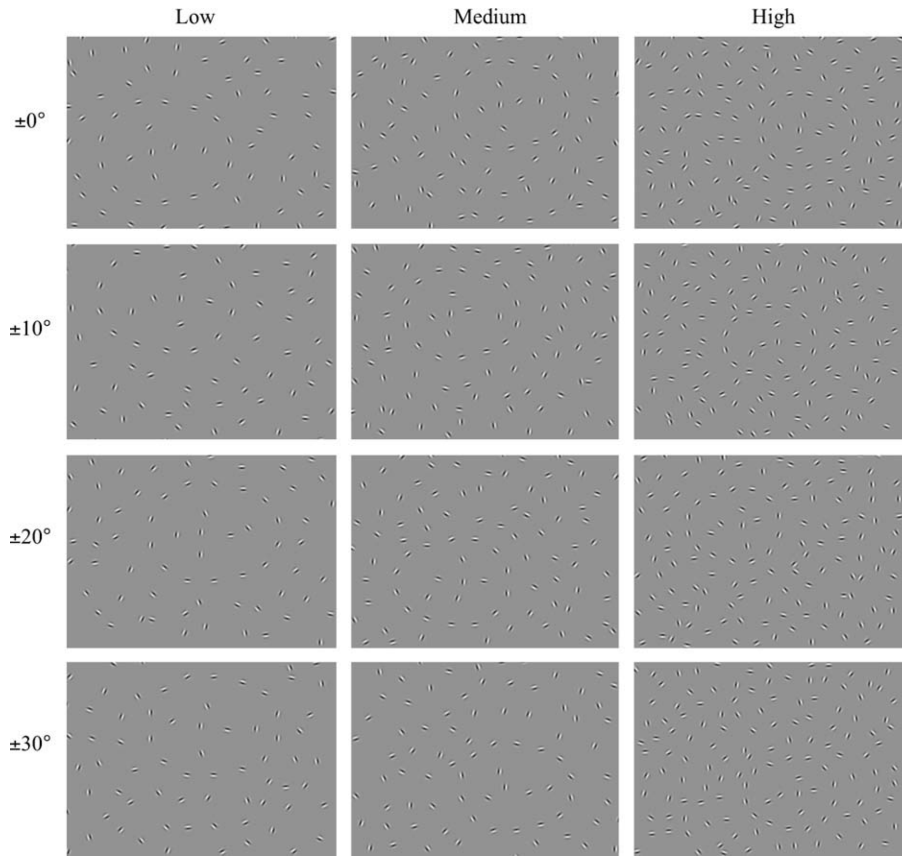

Fig. 1. The complete set of conditions presented to adults in Experiment 1. For each of these 12 combinations of proximity (high, medium, low) and collinearity (α of 0°, 10°, 20°, and 30°), a staircase procedure was used in which the average spacing between the background elements was reduced over trials. The first display with Δ = 1 is shown for each of these combinations, where Δ represents the relative spacing of elements in the contour compared to the background. Experiment 2 used only the high and medium proximities with α = 0° and 20°.

one with the egg-like shape pointing to the right and the other with the shape pointing to the left. The second two trials showed the same shapes embedded in background noise with Δ = 1, one trial followed by an example of the positive feedback, and the other followed by an example of negative feedback.

2.1.5. Criterion trials

The purpose of the criterion was to verify that subjects understood the task. Before each test, observers were presented with a block of four trials, each of which had Δ = 1 as in the Demonstration trials, with left and right pointing egg-like shapes presented in a random order. To be included in the study, participants had to judge the shape correctly as pointing right or left on all four trials within a block. Subjects had three chances to meet this criterion and all subjects did so, usually within the first block.

2.1.6. Practice run

The practice run consisted of one full staircase procedure with perfect collinearity (α = 0°) and the level of proximity to be used in the four tests to follow. Observers were instructed to fixate on a 2.17° black circle in the centre of the screen at the beginning of each trial. The fixation circle was removed after a variable interval and after a 250 ms delay, observers were shown the test stimulus for 1000 ms. The observers' task was to judge whether the "head" of the egg-like shape was pointing to the right or to the left side of the screen and the experimenter pressed a corresponding key. Observers received visual and auditory feedback about their accuracy. Contours pointing to the left or to the right appeared with equal probability and in random order. Averaged spacing among the background elements was varied according to a 1-up, 3-down staircase procedure, producing correct response rate equivalent to 79.4% accuracy (Levitt, 1971). In the first display, spacing among the background elements were 1.64°, 1.92°, and 2.21°, for high, medium, and low proximities, respectively (to produce Δ of 1 in each of these conditions). After three consecutive correct responses, the staircase reduced the spacing of the background elements by 0.1 octave (where an octave is a halving or a doubling of a value). Step-size remained at this size until an error was made, at which point step-size was reduced to 0.05 octave intervals. Following an error, the staircase reversed directions and a display with a larger spacing was presented until three consecutive correct responses were made, after which the direction of the staircase reversed again to present successively smaller spacing. Testing continued until 10 changes in the direction of the staircase ("reversals") occurred, which typically required 5 min. Threshold for each condition, defined as the minimum spacing among the background elements that permitted accurate discrimination of the direction of the egg-shape, was based on the geometrical mean spacing of the final six reversals. The experimenter watched the observers to ensure that they maintained central fixation and provided reminders to do so.

2.1.7. Test run

The test run was identical to the practice run except now the experimenter was unaware of the stimuli presented on each trial. A break was given before the test and at other times as needed. For that level of proximity, the demonstration and criterion were repeated before each of the three other levels of collinearity tested.

Table 1
Results of Experiment 1. Mean thresholds expressed as the mean spacing (in pixels) of the background elements at threshold as a function of collinearity and proximity.

Proximity	±0°	±10°	±20°	±30°
Low	48.45	51.08	57.58	68.00
Medium	41.46	44.02	50.64	57.35
High	34.70	36.34	40.44	47.11

2.2. Results

Table 1 shows the mean thresholds (minimum spacing among the background elements for which the target contour could be detected) for each collinearity and proximity level.

In order to examine the spatial range of contour integration (i.e., effect of spatial proximity) independently from the effect of background spacing, thresholds were converted to delta values (Δ) by dividing them by the contour spacing of the target. A repeated measure ANOVA on the delta values was carried out with collinearity ($\alpha = 0°$, 10°, 20°, and 30°) and proximity (high, medium, low) as within-subject factors. Significant differences in delta thresholds reflect limitations in the spatial range of contour integration rather than simply the effect of signal to noise ratio (Kovács et al., 1999).

In a trimming procedure, each delta value was first converted to a Z score using the mean and standard deviation for a specific condition. Z scores greater than +2.5 or less than −2.5 were replaced with the original group mean (see Kirk, 1990; Lewis, Kingdon, Ellemberg, & Maurer, 2007). Two data points from different participants tested in low proximity, 20° and 30° collinearity, were replaced.[1] The resulting Δ values (background to contour spacing ratio) are presented in Fig. 2. Preliminary analyses revealed no significant effect of sex or order of conditions, nor any interactions involving these factors. The results were thus collapsed across these two factors.

The ANOVA revealed, as expected, a significant effect of collinearity on delta values, $F(3, 69) = 394.57$, $p < .0001$, indicating higher tolerance for dense background elements as collinearity of the contour elements increased. The analysis also revealed a significant effect of spatial proximity, $F(2, 46) = 10.79$, $p < .0001$; however, this effect was qualified by a significant interaction with collinearity, $F(6138) = 2.37$, $p < .03$. When contour elements were perfectly collinear ($\alpha = 0°$), no effect of spatial proximity on delta values was observed, $F(2, 46) = 1.02$, $p > .37$, indicating a relatively strong integration of the elements into a contour, regardless of proximity. As can be seen in Fig. 2, the effect of proximity increased as collinearity decreased ($F(2, 46) = 3.39$, $p < .042$; $F(2, 46) = 5.75$, $p < .006$; $F(2, 46) = 9.78$, $p < .0001$, for $\alpha = 10°$, 20°, and 30°). Tukey post hoc comparisons showed that when contour elements were jittered by 10° and 20°, delta values for elements with medium and low proximities (means: 0.66 and 0.65 for $\alpha = 10°$, 0.76 and 0.75 for $\alpha = 20°$, respectively) were worse than for elements with high proximity (0.63 and 0.71, for $\alpha = 10°$ and $\alpha = 20°$, respectively). When collinearity was extremely low ($\alpha = 30°$), the effect of proximity seems even stronger, with high proximity (0.83) better than medium (0.86), and medium better than low (0.88; $ps < 0.01$).

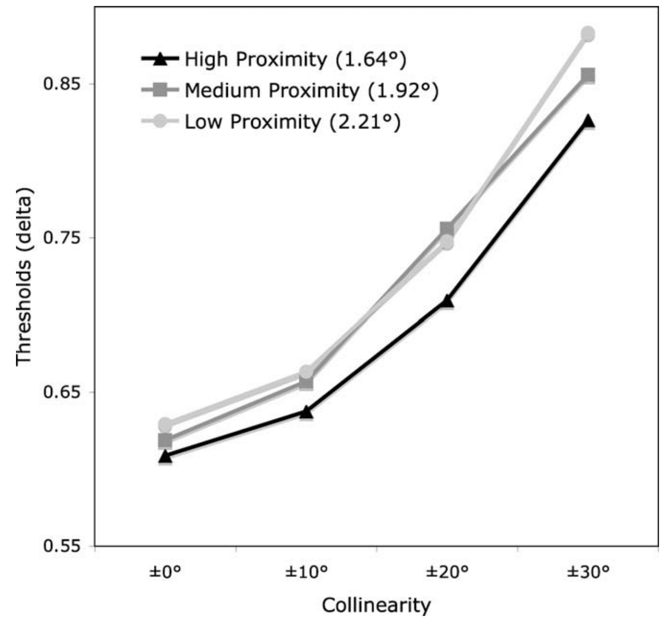

Fig. 2. Results of Experiment 1: Thresholds in Δ as a function of collinearity and proximity, where Δ represents the relative spacing of elements in the contour compared to the background (i.e., the values used in the analyses).

2.3. Discussion

Adults' contour integration was affected by both spatial proximity and collinearity but the effects were not independent. When collinearity was high, observers' performance was largely independent of spatial proximity. These results are consistent with previous findings showing that when collinearity is high, contour integration in adults is sensitive to the ratio of the spacing of background versus contour elements (Δ), rather than to the absolute spacing between the contour elements (Kovács, 2000; Kovács et al., 1999). However, the present findings show that, in addition, when collinearity is relatively low, contour integration in adults becomes more sensitive to the absolute spacing among the contour elements, with spatially close elements more easily integrated into a contour. Thus, adults seem able to use collinearity as a cue to compensate for poor proximity. This ability to use one strong cue to compensate for another seems symmetrical. As can be seen clearly in Fig. 2, when spatial proximity is high, the detrimental effect of low collinearity decreases. The interactive effects of collinearity and spatial proximity are consistent with the "association field" model (Field et al., 1993) in which the linking between orientation-tuned cells depends on their joint relative orientation and spatial position.

This relation between collinearly and spatial proximity in contour integration matches well the edge-alignment structure found in natural images. The probability that non-collinear segments compose the same object is not high, but it is much increased when these segments are spatially close. Collinear segments, however, are better candidates for integrating into a unified contour because they are more likely to reflect portions of a real object's contour, even when they have low proximity. This reflects the fact that natural contours are relatively smooth (Geisler, Perry, Super, & Gallogly, 2001), even when there is a large spatial discontinuity between two parts of the contour caused, for example, by occlusion. An efficient computation of collinearity between elements that is less sensitive to spatial proximity (within a certain range) would therefore match the statistics of object contours in the real world. The adults in Experiment 1 appeared to use such a mechanism. In Experiment 2, we examined the development of this ability.

[1] When we re-analyzed the data with outliers included, the pattern of results remained the same.

Table 2
Results of Experiment 2. Mean thresholds expressed as the mean spacing (in pixels) of the background elements at threshold as a function of collinearity and proximity for the three age groups.

Proximity	7 years		14 years		Adults	
	±0°	±20°	±0°	±20°	±0°	±20°
Medium	45.39	57.92	42.37	52.05	41.14	50.81
High	36.77	47.21	35.26	41.69	35.10	40.35

3. Experiment 2: development of contour integration

Children 7- and 14-years-old were tested with the same task as that used in Experiment 1 but with a subset of the 12 conditions. Specifically, they were tested with the mid and high proximity conditions crossed with two levels of collinearity ($\alpha = 0°$ and 20°) to create four conditions. A new group of adults was tested for comparison. We chose to test 7-year-olds because basic visual abilities like contrast sensitivity are mature by that age (Ellemberg, Lewis, Liu, & Maurer, 1999); we included 14-year-olds because of previous evidence that contour integration is still not quite adult-like at that age (Kovács, 2000; Kovács et al., 1999).

3.1. Methods

3.1.1. Participants

The final sample consisted of 24 7-year-olds (±3 months; 12 boys, 12 girls), 24 14-year-olds (±3 months; 11 boys, 13 girls), and 24 adults (mean age = 20.5 years, range = 17–26 years; 12 males, 12 females), all of whom met our criteria on the visual screening examination described in Experiment 1. An additional two 7-year-olds, two 14-year-olds, and two adults were excluded from the final sample for not passing visual screening.

3.1.2. Stimuli and procedure

The displays were identical to the ones used in Experiment 1, except that only two conditions of collinearity ($\alpha = 0°$ and 20°) and two conditions of spatial proximity (medium—1.92°, and high—1.64°) were used. Conditions were presented in counterbalanced orders. A practice run with perfect collinearity was given before the participant began the two collinearity levels for that proximity. All other details were identical to Experiment 1 except that we obtained consent from a parent of the children and assent from the children themselves.

3.2. Results

Table 2 shows the mean thresholds (averaged spacing among the background elements) as a function of age, for each collinearity and proximity level. As in Experiment 1, thresholds were converted to Δ (background to contour spacing ratio). Fig. 3 shows Δ thresholds as a function of age for the different levels of collinearity and proximity. One data point from a 7-year-old tested in $\alpha = 10°$ high proximity condition was replaced using a trimming procedure identical to that described in Experiment 1.[2] Preliminary analyses revealed no significant effect of sex or order of conditions, nor any interactions involving these factors. The results were thus collapsed across these two factors.

A mixed design ANOVA with age as a between-subjects factor and collinearity and proximity as within-subjects factors was carried out.[3] The analysis revealed a significant effect of age, $F(2, 69) = 11.62$, $p < 0.0001$, proximity, $F(1, 69) = 31.78$, $p < 0.0001$, and collinearity, $F(1, 69) = 474.67$, $p < 0.0001$, as well as an interaction between age and collinearity, $F(2, 69) = 9.35$, $p < 0.0001$, an interaction between proximity and collinearity, $F(1, 69) = 8.59$, $p < 0.005$ and a nearly significant three-way interaction among age, collinearity and proximity, $F(2, 69) = 1.67$, $p = 0.06$. For adults, the interactive effect of collinearity and proximity found in Experiment 1 was replicated, $F(1, 23) = 6.63$, $p < 0.017$. The interaction in adults resulted from there being no effect of spatial proximity on integration when collinearity was perfect ($\alpha = 0°$), $F(1, 23) = 1.31$, $p > 0.26$, but a significant effect of proximity when collinearity was relatively low ($\alpha = 20°$), $F(1, 23) = 9.14$, $p < 0.006$.

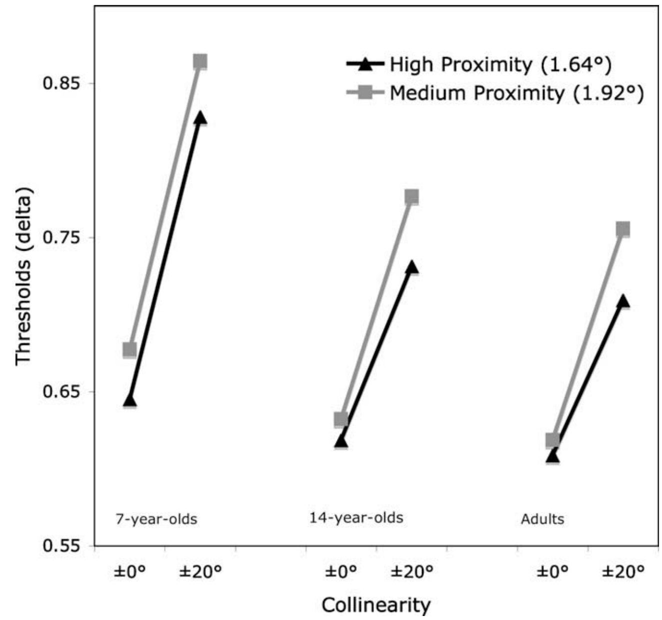

Fig. 3. Results of Experiment 2: Thresholds in Δ as a function of collinearity and proximity for the three different age groups.

The results for the 7-year-olds revealed a quite different pattern. Both collinearity and spatial proximity had a significant effect on integration, $F(1, 23) = 194.91$, $p < 0.0001$, and $F(1, 23) = 12.54$, $p < 0.002$, respectively. Tukey post hoc comparisons showed a stronger integration for higher collinearity levels (means: 0.61 and 0.73 for 0° and 20°, respectively, *ps* < 0.01), and for higher proximities (means: 0.65 and 0.68 for high and medium proximities, respectively, *ps* < 0.01). Most interestingly, however, there was no interaction between collinearity and proximity, $F < 1$, indicating a similar effect of spatial proximity on contour integration, regardless of whether collinearity was high with $\alpha = 0°$, $F(1, 23) = 8.39$, $p < 0.008$ or low with $\alpha = 20°$, $F(1, 23) = 6.17$, $p < 0.021$. In contrast to adults, contour integration at 7 years of age was limited by both collinearity and spatial proximity so that even when collinearity was high, children did not use this cue to bolster long-range integration.

[2] When we re-analyzed the data with the outlier included, the pattern of results remained the same.

[3] As expected, tests of sphericity reveal differences in variance among the age groups for all four conditions, $F(2, 69) = 6.78$, $p < 0.0001$, $F(2, 69) = 9.25$, $p < 0.0001$, $F(2, 69) = 5.01$, $p < 0.008$, and $F(2, 69) = 4.89$, $p < 0.008$ for high proximity 0° jittering, high proximity 20° jittering, low proximity 0° jittering, and low proximity 20° jittering, respectively. Therefore, all ANOVA results in the manuscript are provided in Greenhouse–Geisser values, to correct for this violation of the sphericity assumption. Higher variability between subjects in the younger age groups compared to the older groups might be related to differences among young observers in the rate of development.

Like adults, 14-year-olds showed significant main effects for both collinearity, $F(1, 23) = 125.23$, $p < 0.017$, and proximity, $F(1, 23) = 13.13$, $p < 0.001$, as well as an interactive effect of these two factors on contour integration, $F(1, 23) = 5.51$, $p < 0.028$. A breakdown of this interaction shows, however, a significant effect of spatial proximity on contour integration for both $\alpha = 0°$ and 20°, $F(1, 23) = 6.39$, $p < 0.019$, and $F(1, 23) = 10.63$, $p < 0.003$, respectively. As can be seen in Fig. 3, the effect of proximity was smaller for high collinearity ($\alpha = 0°$) than for lower collinearity ($\alpha = 20°$). These results demonstrate that the mechanism of compensation for one weak cue by the other is present at 14 years of age but that is not as efficient as in adults: proximity limits long-range integration even when collinearity is perfect, albeit less than when collinearity is poorer.

The present results show age-related changes in the ability to use statistics of natural images in contour integration. However, the present study also reveals that when perceptual cues are strong, even 7-year-olds can exhibit adult-like performance. As Fig. 3 shows clearly, there is no age-related difference in Δ thresholds when both collinearity and proximity are high, $F(2, 69)=2.24$, $p > 0.10$. Significant differences do emerge when one or both of these cues are weaker, $F(2, 69) = 12.73$, $p < 0.0001$, $F(2, 69) = 6.80$, $p < 0.002$, and $F(2, 69) = 8.14$, $p < 0.001$, for high proximity $\alpha = 20°$, low proximity $\alpha = 0°$ and 20°, respectively. In all these three cases, Tukey post hoc comparisons show that contour integration is immature at both 7 and 14 years of age, *ps* < .05.

3.3. Discussion

The results of Experiment 2 reveal a protracted development of contour integration. Performance in the contour integration task had not reached adult-like levels even at 14 years of age. These results are consistent with previous studies demonstrating that children as old as 14 are not as accurate as adults when shown stimuli involving relatively large contour spacing (Kovács, 2000; Kovács et al., 1999). However, the present study also showed that when contour elements were spatially close and perfectly collinear, the thresholds of 7-year-olds were not significantly different from those of adults.

A fundamental concern, associated with studying development in general, is that poorer performance in younger children may not necessarily reflect poorer performance in the perceptual abilities at hand (integration of elements into a contour in our case) but rather poorer motivation, shorter span of apprehension, and/or poorer cognitive inference. To reduce such non-visual influences, each phase included demonstration, criterion trials, and a practice staircase to verify that the children understood the task. Feedback was given to keep the children motivated and engaged in the task. In addition, the pattern of results indicates that development is specific to a particular visual mechanism rather than to these non-visual factors: when both collinearity and proximity are high, even 7-year-olds show adult-like performance. Under those conditions, the factor that affects the difficulty of the task for adults (i.e., signal to noise ratio or delta) had the same effect on 7-year-olds as it did in adults. Moreover, had children's accuracy been affected by a dip in motivation or in attention as the task became harder, their performance would have been expected to tolerate less noise than adults in all conditions. This analysis suggests that children's integration was limited more than that of adults by the spatial range over which integration was required rather than by differences in motivation or attention.

The results also revealed age-related changes in the interactive effects of collinearity and spatial proximity on contour integration. While adults are able to use one strong cue to compensate for the other, children are limited by the absolute contour spacing, lacking the ability to use collinearity in order to overcome poor proximity among the elements. This mechanism becomes more efficient with age but it is not completely mature even at 14 years of age. To the extent that this mechanism in adults reflects the ability to use cues that match the statistics of object contours in the real world, the results in children suggest a gradual improvement over the years in the ability to extract this contour information while interpreting natural scenes.

These age-related changes in the ability to use statistics of natural scenes are consistent with our recent developmental findings on contour interpolation of subjective contours (Hadad, Maurer, & Lewis, in press). In that study, the youngest children (6-year-olds) were able to detect the subjective contours, specifically, a rectangle induced by corner pacmen which were not connected by any physical contours. However, unlike older children and adults, their sensitivity was independent of support ratio (i.e., ratio of the physically present contours to the total length of contour), a cue correlated with the probability that contours are connected in the real world. From age 9 to 12 to adulthood, the effect of support ratio increased gradually. The results suggest that only during middle childhood does the interpolation of subjective contours become tied to 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. Together with the current results, these findings suggest a gradual improvement in the ability of the visual system to use statistics of contours in natural images in interpolation and integration of fragmented contours into a coherent shape. The improvement may reflect the slow accumulation of visual experience and/or the slow maturation of higher visual areas sensitive to those statistics.

This pattern of results may have implication for the way children experience and interpret visual scenes. Unlike adults, children may treat two parts of the same objects as fragmented, if, for example, they are occluded by a relatively wide occluder (i.e., large spatial discontinuity between the two edges). With age, the visual system comes to rely more on the edge-alignment of the two parts of the contours, grouping aligned parts across occlusion regardless of occluder size.

4. General discussion

The protracted development of contour integration and the critical effect of spatial proximity at younger ages in particular, are likely to be explained by functional immaturity of long-range orientation-specific spatial interactions, which develop slowly and which may be tuned by exposure to the statistics of natural scenes. Psychophysical studies indicate that children are slower to develop the ability to segment elements based on differences in orientation than based on differences in luminance or direction of motion (Atkinson & Braddick, 1992; Sireteanu & Rieth, 1992). It is only by school age that children demonstrate adult-like performance in orientation-based segmentation. Consistent with the psychophysical findings, neuroanatomical data show that the horizontal connections of the primary visual cortex, particularly in layer 2/3, which are assumed to provide the anatomical substance for long-range interactions subserving contour integration (e.g., Rockland, Lund, & Humphrey, 1982), are immature even at 5 years of age (Burkhalter, Bernardo, & Charles, 1993). Alternatively, or in addition, the behavioural findings might be related to slow postnatal development of feedback connections between V2 and V1 (Burkhalter, 1993), which have also been postulated to underlie contour integration (Kovács et al., 1999).

The ability to integrate elements into a contour 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 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, Hadad, Behrmann, & Palmer, 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., Kovács et al., 1999).

In summary, the results demonstrate the gradual improvement of contour integration throughout childhood and the slow development of sensitivity to the statistics of natural scenes. The improvements with age may reflect protracted cortical development and/or increased experience with the statistics of natural scenes. Whatever the cause, it is only after age 14 that collinearity, the most reliable cue, comes to compensate efficiently for spatial proximity.

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