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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,