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Constant contour integration in peripheral vision for stimuli with good Gestalt properties

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The visual system integrates discrete but aligned local stimuli to form percept of global contours. Previous experiments using “snake” contours showed that contour integration was mainly present in foveal vision but absent or greatly weakened in peripheral vision. In this study, we demonstrated that, for contour stimuli such as circles and ellipses, which bore good Gestalt properties, contour integration for shape detection and discrimination was nearly constant from the fovea to up to 35° visual periphery! Contour integration was impaired by local orientation and position jitters of contour elements, indicating that the same local contour linking mechanisms revealed with snake contour stimuli also played critical roles in integration of our good Gestalt stimuli. Contour integration was also unaffected by global position jittering up to 20% of the contour size and by dramatic shape jittering, which excluded non-contour integration processes such as detection of various local cues and template matching as alternative mechanisms for uncompromised peripheral perception of good Gestalt stimuli. Peripheral contour integration also presented an interesting upper–lower visual field symmetry after asymmetries of contrast sensitivity and shape discrimination were discounted. The constant peripheral performance might benefit from easy detection of good Gestalt stimuli, which popped out from background noise, from a boost of local contour linking by top–down influences and/or from multielement contour linking by long-range interactions.

Keywords: contour integration, peripheral vision, good Gestalt

Introduction

Humans can perceive global contours from properly aligned local stimulus elements imbedded in a random stimulus field (Field, Hayes, & Hess, 1993; Geisler, Perry, Super, & Gallogly, 2001; Kapadia, Westheimer, & Gilbert, 2000; Kovacs & Julesz, 1993; Li, 1998; Sigman, Cecchi, Gilbert, & Magnasco, 2001; see Hess & Field, 1999; Hess, Hayes, & Field, 2003 for recent reviews). This contour integration process represents important sensation to perception transition and is a fundamental component of object processing. It also plays a critical role in perception of natural images because of the edge co-occurrence statistical properties of contours in nature images (Geisler et al., 2001; Sigman et al., 2001) and, thus, serves an important function for everyday vision.

Existing experimental evidence suggests that contour integration is mainly present in foveal vision and is absent (Hess & Dakin, 1997) or greatly weakened (Nugent, Keswani, Woods, & Peli, 2003) in peripheral vision. Hess and Dakin (1997) first reported that peripheral contour integration for “snake” contours (Figure 1a) was entirely missing beyond 10° retinal eccentricity. They found that peripheral contours consisting of same-phase elements could be detected effortlessly by their observers, but those consisting of alternating-phase elements were undetectable. A single-filter model, which implied no integration of multiple filter responses, was thus proposed to explain peripheral contour detection (Hess & Dakin, 1997). This model would not respond to contours formed by alternating-phase elements, which would have been averaged out. More recently, Nugent et al. (2003) used identical stimuli to study peripheral contour integration, but they reported that contour integration declined gradually and diminished near 30° retinal eccentricity. Moreover, the performance differences for same-phase and alternating-phase stimuli were very small, which argued against Hess and Dakin’s single-filter model. However, regardless of the discrepancies of experimental results in many ways, both studies reached a consensus for poor peripheral contour integration, which became absent beyond a certain retinal eccentricity. On the other hand, Hess and Dakin (1999) discounted local position uncertainty of contour elements as an alternative account to their single-filter model. They measured equivalent positional noise for contour elements across the visual field and found that equating position uncertainty, while reducing foveal contour integration performance, was

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center of each random Gabor was randomly positioned within ±0.5 grid size in both horizontal and vertical directions from the grid center; hence, in the extreme cases, half of the Gabor would overlap with the neighboring grid. A contour element would replace a random Gabor element in the same grid to get rid of density cues. In contour detection tasks (see below), the same contour stimuli were also shown in the nontarget image, but the equal-spacing contour elements were randomly repositioned along the contour path and were randomly oriented. This manipulation would further avoid local density cues around the contour stimuli. The stimulus images were regenerated for each interval within a 2AFC trial (see below) and across each trial. The locations of the equal-spacing contour elements varied along the contour path from image to image. The randomly oriented and randomly placed background Gabors were rerandomized in each new image. All Gabors, whether random or contour elements, were physically identical except for their locations, orientations, and phases. The phases of neighboring contour elements typically alternated at 0° and 180°, whereas the phases of random Gabors randomized at 0° or 180°. The contour was typically centered on the full-screen Gabor field (except in global position jitter conditions, Figure 4a); thus, for circular contours, the elements were located at the same retinal eccentricity. The standard deviation of the Gabor Gaussian envelope (σ) was always equal to 0.425 times the Gabor wavelength (λ). The contrast of the Gabors was 0.90. Viewing was monocular, and a chin-and-head rest stabilized the heads of the observers.

Contour integration performance was measured with a temporal 2AFC staircase procedure. The target and nontarget stimuli (a circular contour within the random Gabor field vs. the random field only in detection tasks or circular vs. elliptical contours in discrimination tasks)

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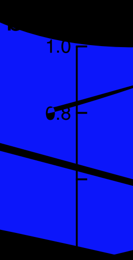

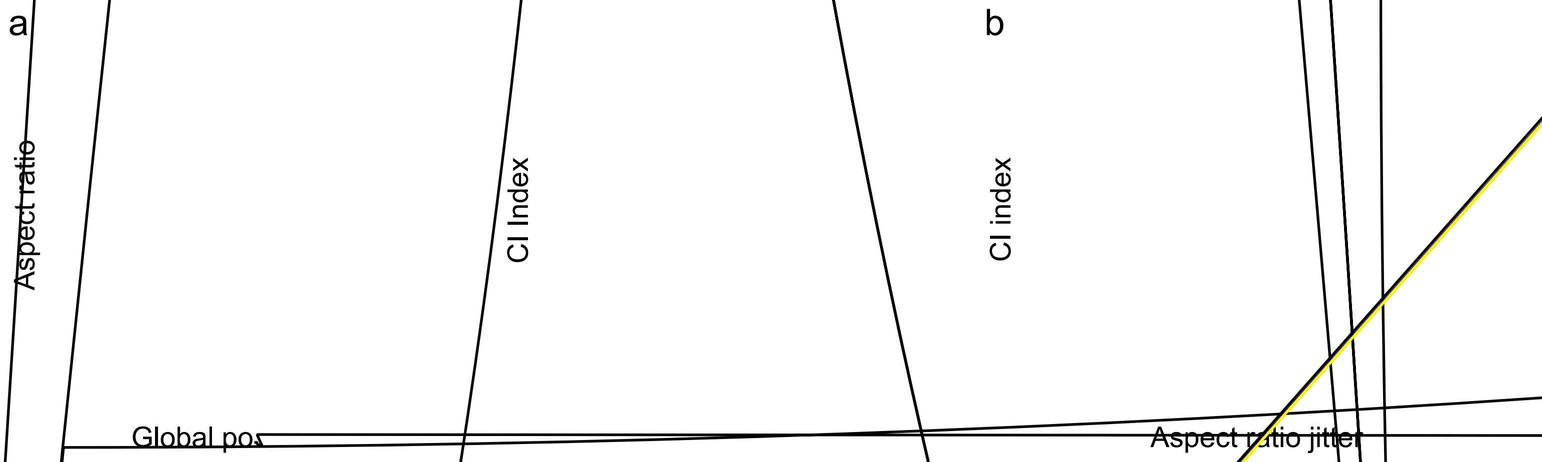

area constant. The elliptical contour kept rotating from trial to trial as in the earlier experiments. However, the random shape changes due to aspect ratio jitter had no effect on contour integration performance either, $F(1,2) = 0.405$, $p = .590$ (Figure 4b). The mean CI indices were 6.63 ± 0.17 and 6.74 ± 0.18 for fixed and jittered aspect ratio conditions, respectively, discounting the role of shape uncertainty reduction in peripheral contour integration for good-Gestalt stimuli. The CI indices for ellipse detection with or without aspect ratio jitter were actually not different from those for circle detection (6.94 ± 0.20, Figure 1c). These data together indicated that it was the good Gestalt nature of our stimuli, and not stimulus position and shape uncertainty reduction, that was responsible for constant peripheral contour integration.

Contour integration in the lower and upper visual fields

In peripheral vision, many tasks are performed better when the same stimulus pattern is presented in the lower visual field (LVF) than in the upper visual field (UVF; He, Cavanagh, & Intriligator, 1996; Rubin, Nakayama, & Shapley, 1996). Consistent with this asymmetry, the retinotopic presentation of the LVF in V1 is larger (Van Essen, Newsome, & Maunsell, 1984). Would this asymmetry also apply to contour integration? We first measured and discounted asymmetries for contrast thresholds and ARTs in the LVF and UVF so that clean LVF versus UVF contour integration could be compared. Contrast thresholds for a circle (20 elements, mean SF = 1.7 cpd, radius = 7.5°, Figure 5a) centered 15° above or below the fixation cross in a blank field showed larger threshold asymmetry in one observer and less significant asymmetry in the other two, $F(1,2) = 1.074$, $p = .409$ (Figure 5b). In addition, ARTs for discriminating circular and elliptical contours (20 elements, contrasts matched at four times contrast threshold) imbedded in the random Gabor field showed a consistent and significant LVF advantage in all three observers, with the ARTs consistently smaller for the LVF stimuli, $F(1,2) = 45.356$, $p = .021$ (Figure 5c). However, after stimulus contrasts (four times contrast threshold) and aspect ratios (1 + 1.5 × ART) were matched, contour integration was surprisingly symmetric in the LVF and UVF, $F(1,2) = 0.152$, $p = .734$ (Figure 5d)!

It was unclear what mechanisms could be responsible for this UVF–LVF symmetry. If contour integration occurred in early visual cortex like V1, the equal maximal spacing of contour elements in the UVF and LVF was actually not necessarily inconsistent with a “bigger” V1 representation of the LVF (Van Essen et al., 1984). This could simply be due to the distance in the visual field being scaled with V1 representation so that the equal space between neighboring contour elements could correspond to longer V1 distance for the LVF and shorter V1 distance for the UVF. On the other hand, if contour integration mainly occurred in higher visual areas, neurons with large receptive fields received inputs from multiple V1 neurons and integrated inputs that obey the rules of collinearity and cocircularity to form the percept of continuous contours. Because the input strength from the early visual cortex representing the UVF and LVF had been matched and if these higher visual area neurons had no response bias toward the UVF or UVF inputs, then a UVF–LVF symmetry of contour integration was likely to occur.

Discussion

Our study revealed nearly constant contour integration for shape detection and discrimination from the fovea to up to 35° retinal eccentricity for circular and elliptical

positions of both the circular and elliptical contours were independently jittered up to ±20% of the contour size, which was equivalent to 8° or more than 3 grids (2.4°/grid) in both horizontal and vertical dimensions. This strong trial-by-trial position uncertainty of contour elements would have completely wiped out both local orientation cues and local texture-orientation cues, but we showed that these global position jitters had no significant influence on contour integration (Figure 4a). It was clear that our observers did not use any local cues mentioned above to perform their tasks. They probably had to attend to the entire contours to make decisions.

Besides local cues, the observers might use template matching rather than contour integration to detect well-defined stimuli. During template matching, the brain recognizes an object by comparing it to images of objects already stored in memory. Consistent with many of our findings, a template-matching model would suffer from local orientation and position jitters (Figure 3), and it would be immune to global position jitters (Figure 4a) because the model could easily match the displaced stimuli through image translation. However, template matching was expected to be impaired by contour shape jitters, which contradicted with our aspect ratio jitter data that showed unaffected CI indices (Figure 4b). This inconsistency effectively excluded simple template matching as an alternative mechanism underlying perception of our good-Gestalt contour stimuli.

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References

Braun, J. (1999). On the detection of salient contours. *Spatial Vision, 12,* 211–225. [PubMed]

Field, D. J., Hayes, A., & Hess, R. F. (1993). Contour integration by the human visual system: Evidence for a local "association field." *Vision Research, 33,* 173–193. [PubMed]

Geisler, W. S., Perry, J. S., Super, B. J., & Gallogly, D. P. (2001). Edge co-occurrence in natural images predicts contour grouping performance. *Vision Research, 41,* 711–724. [PubMed]

Gilbert, C., Ito, M., Kapadia, M., & Westheimer, G. (2000). Interactions between attention, context and learning in primary visual cortex. *Vision Research, 40,* 1217–1226. [PubMed]

He, S., Cavanagh, P., & Intriligator, J. (1996). Attentional resolution and the locus of visual awareness. *Nature, 383,* 334–337. [PubMed]

Hess, R. F., & Dakin, S. C. (1997). Absence of contour linking in peripheral vision. *Nature, 390,* 602–604. [PubMed]

Hess, R. F., & Dakin, S. C. (1999). Contour integration in the peripheral field. *Vision Research, 39,* 947–959. [PubMed]

Hess, R., & Field, D. (1999). Integration of contours: New insights. *Trends in Cognitive Sciences, 3,* 480–486. [PubMed]

Hess, R. F., Hayes, A., & Field, D. J. (2003). Contour integration and cortical processing. *Journal of Physiology, 97,* 105–119. [PubMed]

Ito, M., & Gilbert, C. D. (1999). Attention modulates contextual influences in the primary visual cortex of alert monkeys. *Neuron, 22,* 593–604. [PubMed] [Article]

Kapadia, M. K., Westheimer, G., & Gilbert, C. D. (2000). Spatial distribution of contextual interactions in primary visual cortex and in visual perception. *Journal of Neurophysiology, 84,* 2048–2062. [PubMed] [Article]

Kovacs, I., & Julesz, B. (1993). A closed curve is much more than an incomplete one: Effect of closure in figure-ground segmentation. *Proceedings of the National Academy of Sciences of the United States of America, 90,* 7495–7497. [PubMed] [Article]

Levitt, H. (1971). Transformed up–down methods in psychoacoustics. *Journal of the Acoustical Society of America, 49*, 467–477. [PubMed]

Li, Z. (1998). A neural model of contour integration in the primary visual cortex. *Neural Computation, 13,* 903–940. [PubMed]

Nugent, A. K., Keswani, R. N., Woods, R. L., & Peli, E. (2003). Contour integration in peripheral vision reduces gradually with eccentricity. *Vision Research, 43,* 2427–2437. [PubMed]

Orbach, H. S., & Wilson, H. R. (1999). Factors limiting peripheral pattern discrimination. *Spatial Vision, 12,* 83–106. [PubMed]

Pettet, M. W. (1999). Shape and contour detection. *Vision Research, 39,* 551–557. [PubMed]

Pettet, M. W., McKee, S. P., & Grzywacz, N. M. (1998). Constraints on long range interactions mediating contour detection. *Vision Research, 38,* 865–879. [PubMed]

Rubin, N., Nakayama, K., & Shapley, R. (1996). Enhanced perception of illusory contours in the lower versus upper visual hemifields. *Science, 271,* 651–653. [PubMed]

Sigman, M., Cecchi, G. A., Gilbert, C. D., & Magnasco, M. O. (2001). On a common circle: Natural scenes and Gestalt rules. *Proceedings of the National Academy of Sciences of the United States of America, 98,* 1935–1940. [PubMed] [Article]

Tversky, T., Geisler, W. S., & Perry, J. S. (2004). Contour grouping: Closure effects are explained by good continuation and proximity. *Vision Research, 44,* 2769–2777. [PubMed]

Van Essen, D. C., Newsome, W. T., & Maunsell, J. H. (1984). The visual field representation in striate cortex of the macaque monkey: Asymmetries, anisotropies, and individual variability. *Vision Research, 24,* 429–448. [PubMed]