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A closed curve is much more than an incomplete one: Effect of closure in figure–ground segmentation

(contour detection/field theory)

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ABSTRACT **Detection of fragmented closed contours against a cluttered background occurs much beyond the local coherence distance (maximal separation between segments) of nonclosed contours. This implies that the extent of interaction between locally connected detectors is boosted according to the global stimulus structure. We further show that detection of a target probe is facilitated when the probe is positioned inside a closed circle. To explain the striking contour segregation ability found here, and performance enhancement inside closed boundaries, we propose the existence of a synergetic process in early vision.**

An important task of the visual system, when segmenting the retinal image into separate regions, is assignment of these regions to foreground and background. Gross and rapid figure–ground segregation, initiated by early processes, can focus resources to places of interest in an image for more detailed analysis. However, detectors involved in early processing capture only restricted parts of the field, and the mechanisms which integrate local activity into coherent regions have not yet been characterized firmly. In the present study we focus on contour detection, demonstrating that contour closure has perceptual significance in binding spatially separate features: oriented segments group together to form a closed contour outside the range of local grouping constraints. Recent psychophysical studies showed that the detection of line continuity is supported by a well-defined spatial range of interconnection between neighboring detectors, where interconnection is constrained along the major orientation axes of nonoverlapping filters (1–3). Increasing evidence in cortical neurobiology also suggests that neurons with disparate receptive fields in the primary visual cortex are linked by long-range connections depending on the orientation preferences of cells (4–6), which may serve to integrate distributed neuronal activity (7–9). Although local connectivity of colinear detectors can account for segregation of long and smooth contours, it still does not explain the finding we present here: that detection of closed contours is carried out more efficiently than detection of nonclosed ones (even if both have the same length and average curvature; Fig. 1).

We presented band-pass arrays of line elements (damped sinusoidal luminance signals: GPs) on a dense field of randomly oriented and positioned background elements. A set of segments were aligned along a curved line. Extraction of a line in this stimulus condition involves integration of colinear or nearly colinear segments. There were no other features or stimulus gradients which would make line segregation possible. Examples of "jagged" (open loop) and "circular" (closed loop) contours, which were compared throughout the experiments, are shown in Fig. 1. Both closed and nonclosed loops were generated such that neighboring segments of a line were roughly aligned (having any random value in a ±30° relative angular difference range between them). In a two-alternative forced choice (2AFC) procedure, observers were required to report which frame contained the continuous line. We measured percent correct performance for different spacings between line elements to estimate maximum spacing for the jagged and circular contours. Maximum spacing, or coherence distance (Δ), we define as displacement between two adjacent segments where contour detection performance

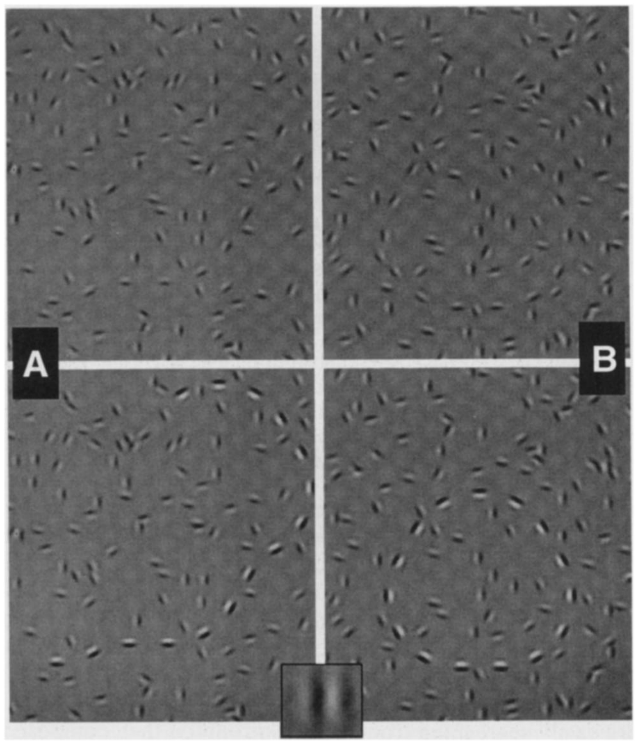

Fig. 1. Examples of contours used in the contour detection experiment. (*Upper*) Two contours embedded in the background of randomly oriented elements. (*Lower*) The same contours are highlighted for didactic reasons. (*A*) A nonclosed contour composed of aligned Gabor patches (GPs) is only barely visible against the background. (*B*) A closed contour with the same angular difference and distance between elements is still perceivable against the background. Perception of closed contours in this stimulus configuration is the best for brief presentations. For more than 180-msec duration, the observer starts to scrutinize other global structures at the expense of the primordial closed structure. (*Inset*) One GP element, which is a product of a sine wave luminance grating and a circular Gaussian envelop. GP wavelength (λ) was 0.12°; Gaussian envelop size was equal to λ; GP amplitude was 24% of mean luminance (30 cd/m^2).

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Abbreviations: GP, Gabor patch; λ, Gabor signal wavelength; Δ, coherence distance; 2AFC, two-alternative forced choice.

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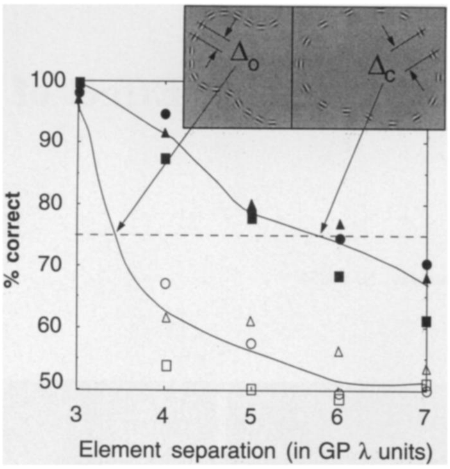

FIG. 2. Psychophysical results corresponding to Fig. 1. Percent correct performance for the detection of curved contours was measured as a function of distance between neighboring elements in a 2AFC paradigm. Results of three subjects (triangles, FP; circles, IK; squares, HM) are shown. Targets were presented on a 16° × 16° field containing 2000 randomly placed GPs. Target contours were built up from 19–23 GPs (giving rise to the maximal length across the field with all different displacements) of the same parameters as background, having ±30° relative angular difference between neighbors. Center of gravity of the lines was randomized around the center of the field in a 1° range. Stimulus duration was 160 msec. Detection of the stacked line at 75% correct response defined Δ. Δ_o (open contours) was 3.3 times the wavelength of the patches (open symbols). Δ_c (closed contours) was 6 times the wavelength (closed symbols). (*Insets*) Δ_o and Δ_c separation.

reaches threshold (75% correct). Δ is expressed in GP wavelength (λ) units. Results are shown in Fig. 2. We found an unexpected advantage of circular arrangements: Δ_c (maximum spacing for closed contours) was extended by a factor of 1.8 relative to Δ_o (maximum spacing for open ones). This is not predicted by local rules of grouping, indicating that linkage of colinear segments is strongly affected by the global arrangement. In other words, equally aligned line segments are easily segregated from the background if they compose a circle, but they blend into the background when not closed. This robust "pop-out" effect requires that adjacent line segments be quasi-colinear. For example, if the closed curve formed a half-moon, closure enhancement would disappear, although both a circle and a half-moon are topologically closed. This implies that the closed curves cannot contain "kinks."

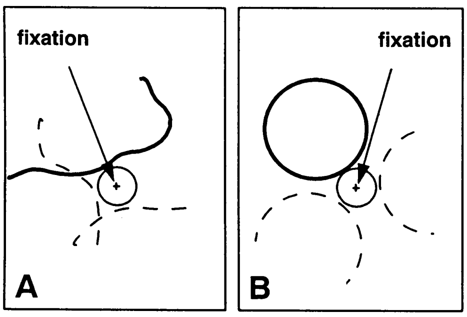

FIG. 3. Stimulus configuration for the second contour detection task. Performance was measured as a function of the number of adjacent visible elements along jagged (*A*) and circular (*B*) contours. Central elements of each path crossed a small virtual circle (1° diameter) around the fixation mark in the center of the field. The contours could appear at any direction from the center. Circular contours were regular circles. Complete circles contained 12 elements.

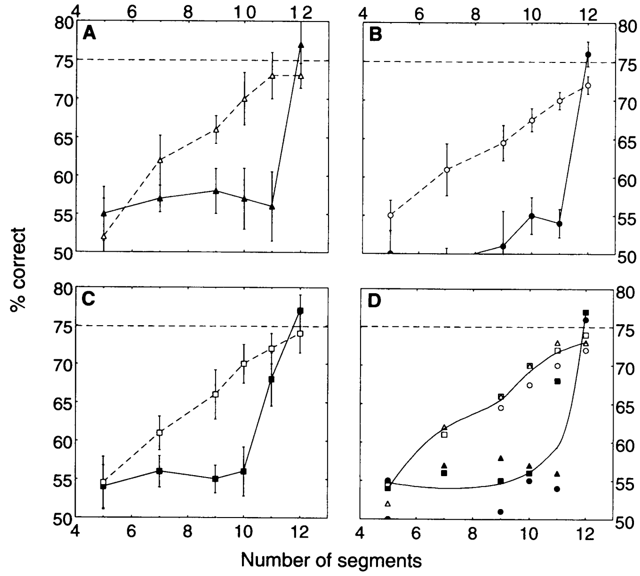

FIG. 4. Contour detection performance as a function of the number of segments (results corresponding to Fig. 3). Gap size was Δ_o for jagged contours and Δ_c for circular contours. (*A–C*) Individual performance curves of three observers (triangles, FP; circles, IK; squares, HM). Open symbols represent performance for jagged contours, closed symbols for circular contours. (*D*) Averaged result for the three observers. Performance increased continuously from chance level to threshold for nonclosed jagged contours. For circular contours performance stayed at chance level, and threshold performance occurred only when the contour was closed or nearly closed (11–12 presented elements).

In measuring Δ_o and Δ_c, a possible confounding feature was that a large part of the jagged lines went to the periphery, whereas circle elements were always at about the same retinal eccentricity. A second experiment was done to verify that the results were not contaminated by the diminishing visibility of peripheral parts. We varied the number of presented adjacent segments. Starting with five visible segments, every additional element was placed symmetrically at the terminations of the lines, going toward the periphery for both open and closed contours (the circles were closed by adding elements at about 3° eccentricity; Fig. 3). The detection task was the same as in the first experiment. Gap size was constant: we used Δ_o and Δ_c, respectively, measured at maximum path length for all observers. Fig. 4 shows that detection performance increases continuously from chance level to threshold for nonclosed contours with Δ_o gap size, while partly presented circles (i.e., with missing segments) cannot be detected at Δ_c until they become closed by addition of the last peripheral segments. The thresholded nature of the second curve, again, means that closure has a global binding effect which makes an otherwise undetectable dashed curve "pop out" from the background. The effect of closure causes

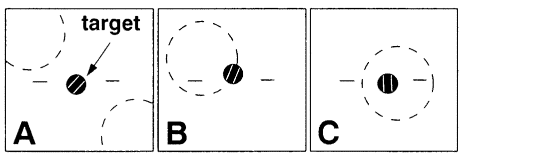

FIG. 5. Stimuli configuration for the contrast discrimination task. In a 2AFC procedure subjects were required to detect a high-contrast foveal GP target against the random background, which contained a closed contour. Two small fixation marks (dashes) helped to locate the randomly oriented target, which was always parallel to the closest line segment. Target was positioned outside the circle (*A*), on the contour (*B*), or inside the circle (*C*) with variable target–contour distance.

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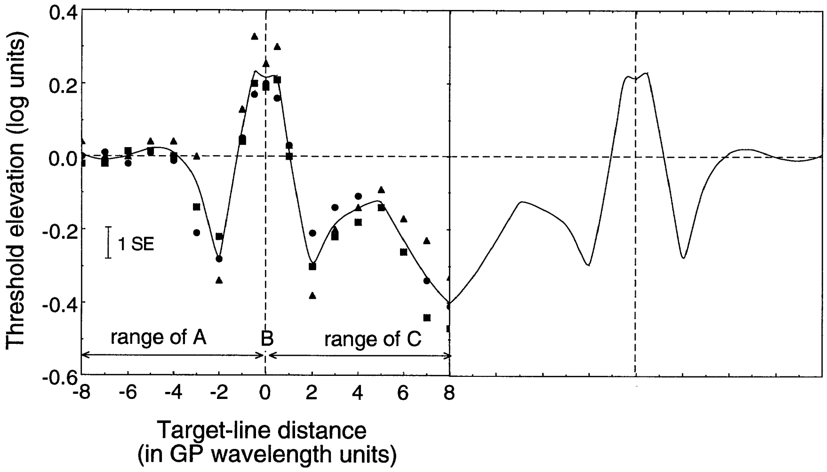

FIG. 6. Results corresponding to Fig. 5. Threshold elevation is presented for the detection of a single GP as a function of distance from the surrounding line. Note the strong threshold enhancement effect inside the circle between 5 and 8 λ distance. λ = 8 represents the center of the circle. Averaged results of three observers are shown (triangles, JV; circles, IK; squares, HM). Observer JV completed only the contrast discrimination task, whereas HM and IK were presented with the contour detection tasks first. SE, standard error (averaged across observers).

an abrupt change in sensitivity, i.e., the target is perceived only when the contour is complete.

The Gestalt tradition left us with a number of principles governing global interpretation of an image. They drew special attention to the fact that a line forming a closed figure is not simply a line, but a bounded surface region (10). We used differential threshold measurements for a target probe, positioned inside and outside of a circle (Fig. 5), to test whether there was any specific activity across interiors of closed contours generated in conjunction with the contour completion process. Subjects reported the presence of a foveal probe (GP) with a luminance difference from the background patches. The background always contained a circular contour (with a diameter of 3.2°) in addition to the noise elements. Thresholds for the target probe were estimated by a staircase procedure (11) as a function of the distance from the contour. Threshold elevation was calculated relative to the standard threshold where only background and target were presented. Sensitivity for the target probe was affected by the distance between the target and the perimeter of the circle (Fig. 6). Between 0 and 1 λ distance from the contour thresholds were elevated; at 2–4 λ, thresholds were reduced for targets both within and outside of the contour. In addition to the threshold variations which occurred on both sides of the contour, further toward the center of the circle we found a second strong enhancement region: 5–8 λ inside the perimeter it was much easier to detect the target patch when it was within the circle than when it was outside of it. In fact, between 5 and 8 λ outside of the circle, threshold was not affected by the presence of the contour, while in the center of the circle contrast threshold was decreased by a factor >2. This result shows that activity inside the figure is indeed different from the activity outside the figure. Inside a closed contour, the range of lateral interaction between detectors is extended, which may act to separate the inner area as well, not only the contour itself.

One way to interpret the sensitivity enhancement for the target probe is to take it as a sign of contrast suppression via lateral inhibition (in which case target detection involves smaller increment contrast steps to reach threshold performance, in accordance with Weber's law). Lateral effects along the contour, with the narrow suppressive region and the facilitatory region beyond that, are consistent with observed contrast threshold variations for a foveal Gabor signal flanked by two high-contrast Gabor signals (3, 12) and are supposed to play a role in the integration of long and smooth contours. In the case of our contours presented on a background containing several accidentally aligned elements, the "winner" direction of excitation is probably amplified by suppressing the neighborhood with a system of inhibitory connections. Additionally, within the closed region, subthreshold inhibitory effects might be strengthened, inducing the segregation of the whole surrounded area. We suggest a colinear excitatory mechanism that perceptually connects incomplete segments, and an orthogonal inhibitory mechanism that acts over longer distances and favors long lines and closed loops. This dualism can be related to the mechanism described as the neural background of illusory contours (13).

Gestalt psychologists, particularly Kurt Koffka (10), were fascinated with closure phenomena and talked much about "good-Gestalt" and "Prägnanz." These concepts, however, were difficult to quantify with classical line drawings. It is only in perception of random element textures—for which the geometry and statistics of the field and targets are under computer control—that these Gestalt concepts gain some concrete meaning. We have demonstrated in two ways that closure is a key issue in contour segregation. First, we showed that contour segregation is strongly enhanced by closure. A jagged "snake" or a nonclosed circle cannot be detected in a brief flash provided that the gap between its constituent segments is above a critical size. However, when the snake "bites its tail" the target protrudes from the clutter. Second, closure elicited a center-specific sensitivity change for a target probe, indicating that the mass of the surrounded region also gains different properties from the field outside the circular contour. The discovered line-segregating process can induce autonomous figure–ground segmentation early in the visual processing, without prior knowledge about the figure.

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