Inhibitory competition in figure-ground perception: Context and convexity

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Convexity has long been considered a potent cue as to which of two regions on opposite sides of an edge is the shaped figure. Experiment 1 shows that for a single edge, there is only a weak bias toward seeing the figure on the convex side. Experiments 1–3 show that the bias toward seeing the convex side as figure increases as the number of edges delimiting alternating convex and concave regions increases, provided that the concave regions are homogeneous in color. The results of Experiments 2 and 3 rule out a probability summation explanation for these *context* effects. Taken together, the results of Experiments 1–3 show that the homogeneity versus heterogeneity of the convex regions is irrelevant. Experiment 4 shows that homogeneity of alternating regions is not sufficient for context effects; a cue that favors the perception of the intervening regions as figures is necessary. Thus homogeneity alone does not alone operate as a background cue. We interpret our results within a model of figure-ground perception in which shape properties on opposite sides of an edge compete for representation and the competitive strength of weak competitors is further reduced when they are homogeneous.

Keywords: figure-ground perception, context, convexity, competition, suppression

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Introduction

The world we perceive is populated by shaped entities, or "figures," that are separated from adjacent regions by their bounding edges. The adjacent regions are often shapeless near the borders of the figures and seem to continue behind them as backgrounds; hence, they are called *grounds*. Such *figure-ground* distinctions are fundamental to the visual perception of objects and are essential for just about every behavioral task.

A variety of cues, including both depth cues and shape cues, affect figure-ground perception. Among the shape cues are those termed "configural cues" by the Gestalt psychologists because they play a role in determining on which side of an edge a configuration is perceived. The configural cues include convexity, symmetry, small area, and enclosure: Regions with one or more of these properties are more likely to be seen as figures than adjacent regions that are concave, asymmetric, large in area, or enclosing. Other shape properties, not included among these classic configural cues, also influence which regions are seen as figures. Familiar configuration is one such non-classical configural cue (see Peterson, 1994; Peterson & Skow-Grant, 2003, for review).

Although a variety of cues, including depth cues and subjective factors as well as configural cues can affect figure-ground perception, the research reported here focuses on the mechanisms whereby configural cues influence which side of an edge appears to have a definite shape and which appears to be unshaped. Because the attributes of shaped versus unshaped often map onto those of figure and ground, we discuss our results in terms of "figure-ground perception."

It has been proposed that figure-ground perception results from inhibitory competition between cues on opposite sides of an edge (Kienker, Sejnowski, Hinton, & Schumacher, 1986; Vecera & O'Reilly, 1998; Peterson, de Gelder, Rapcsak, Gerdhadstein, & Bachoud-Lévi, 2000; Peterson & Skow, 2008). Recent support for this mechanism has emerged from experiments comparing performance in conditions where the amount of competition between configural cues on opposite sides of an edge differed (Peterson & Enns, 2005; Peterson & Lampignano, 2003). In addition, Peterson and Skow (2008) recently showed that a familiar configuration suggested on the side of an edge that loses the competition is suppressed, as predicted by an inhibitory competition model.

In the present research we extend tests of an inhibitory competition model of figure-ground perception from a single edge to multiple edges. The question we investigate here is whether the competition between configural properties on opposite sides of an edge is affected by competitions occurring at distant *disconnected* edges, and

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if they are, what are the necessary and sufficient conditions for such effects?

For a full understanding of figure-ground perception, it is essential to look beyond single edges, yet to date, the question of how figure and ground perception at a single edge is affected by the scene context has been neglected in the behavioral literature. Not even the Gestalt psychologists, who espoused global, holistic effects examined whether the effectiveness of the eponymous configural cues varied with scene context. The situation is somewhat different in the neurophysiological literature where it has been shown that there are ample horizontal connections and feedback connections in the visual cortex (for a recent review see Gilbert & Sigman, 2007). Kapadia, Westheimer, and Gilbert (2000) showed that the "context" provided by these long-range connections can account for some grouping effects. In addition, Lamme (1995; Zipser, Lamme, & Schiller, 1996) showed that neurons respond differently when their receptive fields lie on otherwise equivalent regions that are cued as figures versus grounds by stimulus features located outside the classic receptive field; they refer to these differential responses as "contextual modulations." However, neither neurophysiologists nor behavioral scientists have examined whether figure-ground competitions occurring at disconnected edges are interdependent.

The present experiments investigate whether context alters the effectiveness of a configural cue—convexity—that has long been considered especially potent (e.g., Kanizsa & Gerbino, 1976; Koffka, 1935; Rubin, 1958; see below for further explication). We manipulated context by varying the number of edges with a convex side and a complementary concave side from 1 to 7; these edges were arranged so that they formed 2 to 8 alternating convex and concave regions. In Experiment 1, we found that subjects were increasingly likely to see the figure lying on the convex side of the central edge as the number of edges delimiting alternating convex and concave regions increased. In Experiments 2–4 we demonstrate that this effect is obtained only when the concave regions are homogeneously colored; the color of the convex regions is irrelevant. As discussed in the General discussion section, these experiments provide further evidence that an inhibitory competitive mechanism produces the perception of shape on only one side of an edge.

Experiment 1

The displays used in previous demonstrations showing that convexity is a highly effective configural cue contained more than a single edge and more than two adjacent regions. For example, Kanizsa and Gerbino (1976) used displays like Figure 1 (top) composed of 7 edges bordering 8 alternating convex and concave regions in which all convex regions were identical in shape and color, as were all concave regions; 90% of their observers reported perceiving the convex regions as figures. This was true even when the concave regions were symmetric and smaller in area than the asymmetric convex regions, leading Kanizsa and Gerbino to claim that convexity is a more important configural cue than symmetry or small area. In Experiment 1, we investigated whether the effectiveness of the configural property of convexity varies with the number of edges delimiting alternating convex and concave regions and whether repetition of the shapes of the convex and concave regions exerts an influence.

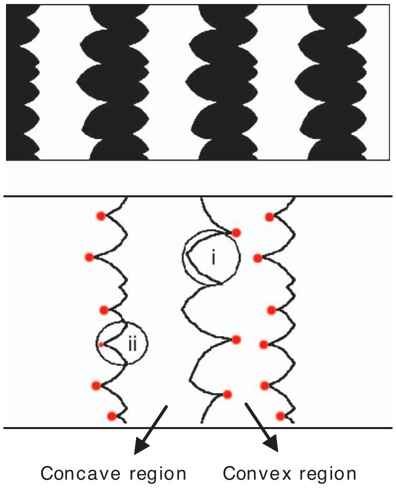

Figure 1. *Top*: A black-and-white display like those used by Kanizsa and Gerbino (1976) to assess the effects of convexity on figure-ground perception. Convex regions are black and concave regions are white. *Bottom*: A convex and adjacent concave region extracted from Top. (i) = a convex part protruding from the convex region; (ii) = a concave part protruding from the concave region. Red dots indicate the points designated as minima of curvature in the stimulus creation program (see Stimuli and apparatus section).

Methods

Participants

The subjects were 140 University of Arizona (UA) students, who participated to partially fulfill an introductory course requirement: 20, 23, 24, and 25 subjects, respectively, viewed 2-, 4-, 6-, and 8-region *non-repeating displays* and 24 each viewed 4- and 8-region *repeating displays*. In all experiments we analyzed the data only of those subjects who responded within 1800 ms on at least 85% of the trials. This resulted in the elimination of 7 of the subjects originally tested in Experiment 1.

Stimuli and apparatus

Displays composed of alternating convex and concave regions were enclosed within a virtual rectangular frame that cut the leftmost and rightmost regions in half relative to the other regions; the leftmost region was convex in half of the displays and concave in the other half. This is the standard display used in tests of the effectiveness of convexity as a figural cue.

Articulated edges internal to the displays were constructed from virtual vertical spines following Stevens and Brookes (1988) using the "Figure-Ground Generator" program (J. C. Forster, University of Arizona). For each edge a number of points (range: 3–15) designated as "minima of curvature" were placed on one side of the spine (see Figure 1, bottom). Two minor arcs curving toward the top and bottom of the display emanated from each minimum; these arcs were positive in curvature from the side of the spine on which the minima lay, henceforth called the "convex" side. Each arc extended to an endpoint on the other side of the virtual spine. In 44% of the edges of the 8-region displays the arcs emanating from two successive minima of curvature met at their endpoints and formed a single convex part (e.g., (i) in Figure 1, bottom). In the remaining edges, the endpoint of at least one of the first arcs served as a minimum of curvature for a second arc; hence, the first convex part served as the base for a second convex part. A concave part was defined from the opposite side of the virtual spine as the area surrounded by the negative curves between successive minima of curvature (e.g., (ii) in Figure 1, bottom).

Edges with 4, 5, 6, 7, and 8 convex base parts were arranged to form alternating regions. (Part number was held approximately constant within individual displays. Part number did not exert an influence on our results.) Accordingly, our experiments investigated the likelihood that the figure appears on the side of an edge with convex rather than concave parts (as did previous work). It is known that local convexity can bias the perception of where a figure lies with respect to an edge (Hoffman & Singh, 1997; Stevens & Brookes, 1988); hence, for simplicity, and to be consistent with previous research we speak of "convex" and "concave" sides of an edge, and "convex" and "concave" regions. From here on in, we discuss our displays in terms of region number rather than edge number, but we stress that we conceive of the competition as cross-edge competition, rather than between-region competition. Our results are consistent with this view, as discussed following Experiment 2 and in the General discussion section.

There were 64 unique 2-region displays, 64 unique 8-region *non-repeating* displays in which no edge was repeated (Figure 2), and 64 unique 8-region *repeating* displays in which 2 basic edges alternated across the display (Figure 1, top). The 4- and 6-region displays were created from 8-region displays. Convex and concave regions were equal in area; hence no known figural cue other than convexity distinguished between them. Convex regions were black in half of the displays and white in the rest; concave regions were filled with the contrasting achromatic shade. Displays were all equal in height (6°) and varied in width from means of 2.7°, 6.8°, 10.4° to 15.4° for 2-, 4-, 6-, and 8-region displays, respectively.

A red square probe (0.6° per side) was centered in the region to the left or right of the central edge; this region was convex in half the displays and concave in the rest, with achromatic fill balanced. On average the probe was equidistant from the edges of the convex and concave regions.

Displays were centered on a medium gray screen (18.2°W × 16.1°H). Subjects used a foot pedal to initiate each trial and made responses on a custom button box. An ACT personal computer with a 166-MHz processor was used to present the stimuli and record responses.

Procedure

Subjects were instructed on the nature of figure-ground perception and their task via computer-displayed instructions; an experimenter stayed in the room to answer questions that arose during the instructions and the practice trails. Each trial began with a central cross; subjects were instructed to fix their eyes on it and to press the foot pedal when they were ready to begin the trial. The cross was then replaced by a display that remained on the screen for 100 ms. The central edge of the display appeared on the location previously occupied by the cross. Subjects pressed one of two buttons to indicate whether the red probe appeared to lie "on" or "off" a perceived figure. This on–off method, adapted from previous research (Hoffman & Singh, 1997; Stevens &

Figure 2. Experiment 1 sample 2-, 4-, 6-, and 8-region black-and-white non-repeating displays. A gray frame surrounds the displays because they are printed on a white page. In the experiments, no frame was used; displays were presented on a gray field. In the figure, convex regions are illustrated in black in 2- and 4-region displays and white in 6- and 8-region displays. Probes are shown on one of the two regions adjacent to the central edge (the region to the left of the central edge in 2- and 6-region displays and the region to the right of the central edge in 4- and 8-region displays).

Brookes, 1988), requires subjects to report on the perceived figural status of a particular probed region-here, a region near fixation—and hence allows some confidence that subjects are not reporting about the perceived figural status of different regions in different region number conditions. Instructions stressed that we were interested in subjects' first impression of whether the probe appeared to lie on or off a region they saw as figure, and that there were no correct answers. There were 4 practice trials.

On experimental trials, each subject viewed 64 randomly presented displays while using a chinrest to maintain a viewing distance of 96 cm. The presentation software was DMDX (Forster & Forster, 2003).

Data analysis

For each subject, we averaged the proportion of "on" responses for probes on convex regions and "off" responses for probes on concave regions to yield a response-bias-free measure of the proportion of trials on which the convex region closest to fixation was seen as figure. This composite score will equal 50% if convexity does not influence figure assignment, or if observers have a strong preference for one color, one side, or one response. Hence, we assessed the likelihood that convex regions are seen as figures against 50% (chance).

Results

The first striking finding of Experiment 1 was that the effect of convexity was small in 2-region displays: Subjects perceived the figure on the convex side of the central edge on only 57% of the trials. This percentage is significantly greater than chance, $t(19) = 3.42$, $p = 0.003$, but note that convexity is not nearly as effective in 2-region displays as one would expect based on previous demonstrations using multi-region displays.

The second major finding of Experiment 1 is that subjects were increasingly likely to perceive the figure on the convex side of the central edge as the number of alternating convex and concave regions increased; this was true for both types of displays (Figure 3). For non-repeating displays: the figure was seen on the convex side of the central edge on an average of 66%, 77%, and 89% of trials with 4-, 6-, and 8-region displays, respectively. (All between region number differences were statistically significant, $ps \leq 0.01$.) For repeating displays, convex regions were seen as figure on an average of 67% and 78% of trials with 4- and 8-region displays, respectively. ANOVAs revealing significant main effects of region number indicated that these region number effects were significant for non-repeating and repeating displays, $F(2, 69) = 15.17$, $p < 0.001$ and $F(1, 46) = 6.151$, $p < 0.02$, respectively. A combined ANOVA (comparing 4- and 8-region conditions) showed that region number effects were larger for non-repeating than for repeating displays: as revealed by a significant interaction between display type and region number, $F(1,92) = 4.53$, $p < 0.04$.

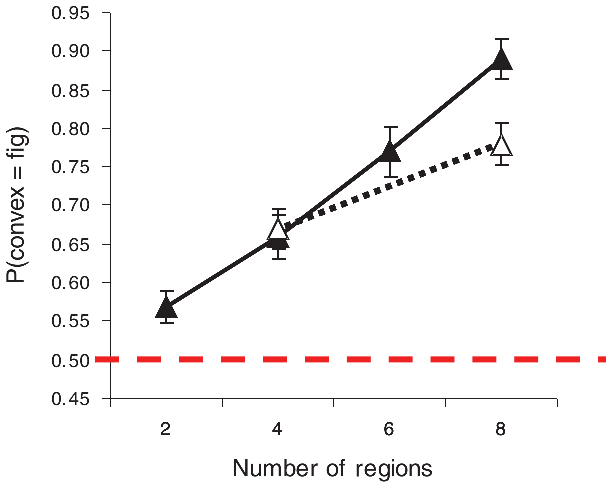

Figure 3. Results of Experiment 1. The probability that convex regions were perceived as figure [P(convex = fig)] as a function of region number for non-repeating (solid triangles) and repeating (open triangles) displays. The dashed red line indicates chance performance.

Discussion

Experiment 1 is the first empirical demonstration that context can increase the effectiveness of a figural property: The figure was seen on the convex side of the central edge much less often in 2-region than in 8-region displays. Experiment 1 also provides the first evidence that, with only one edge delimiting two regions, convexity's influence is weak (although using a modeling approach, Fowlkes, Martin, and Malik (2007) found that a local convexity operator was not a very effective configural cue). In the remainder of this paper, we attempt to elucidate the mechanisms underlying these new context effects.

We first consider three potential mechanisms of the region number effects that were ruled out by Experiment 1 and by two pilot experiments:

1. translational symmetry (shape repetition),
2. display width increases, and
3. artifacts of the response method.

First, Experiment 1 rules out *translational symmetry* because region number effects were obtained for non-repeating as well as repeating displays (indeed they were larger for the former than the latter). Second, a pilot experiment showed that region number effects are not due to *display width increases* that accompanied region number increases in Experiment 1: Subjects ($N = 19$ per group) who viewed equal width (4°H × 9°W) 4- and 8-region displays were more likely to see the figure on the convex side of the central edge in the later than the condition (85% vs. 67%, $p < 0.003$), replicating the region number effects obtained with variable width displays in Experiment 1. Third, another pilot experiment revealed that the results of Experiment 1 did not depend on the use of the on/off *response method*: Subjects who reported directly whether they saw black or white regions as figures in repeating displays without probes showed region number effects in that they were more likely to see convex regions as figure in 8- (79%) than in 4- (62%) region displays, $p < 0.009$.

In the remaining experiments we explore the viability of other potential mechanisms for the region number effects, including (1) probability summation among spatially distributed convexity detectors such as those found by Pasupathy and Connor (1999), (2) within-region spreading of competition-induced facilitation or suppression, and (3) between-region spreading of competition-induced facilitation or suppression.

Experiment 2

Experiment 2 tested the first two mechanisms listed above. On a simple probability summation view, the mere repetition of convex regions can account for region number effects; homogeneity of the color of the convex and/or the concave regions should be irrelevant. To test the probability summation account we used multicolored displays in which regions of the same type—convex or concave—were no more similar in color than regions of different types. The displays in the top row of Figure 4 are samples. If the region number effects reflect the activation of spatially distributed convexity detectors, then we should replicate the results of Experiment 1 in Experiment 2.

Experiment 2 also tested another potential mechanism for the region number effects, one that arises from inhibitory competition: Suppose suppression applied to the relatively weak side of an edge (i.e., the concave side) spreads through that region and reduces its competitive strength at its other edge as well. The repetition of this within-region process in multiple regions might account for the region number effects. (A similar process might operate for facilitation if the relatively strong side of an edge is facilitated as a result of the competition.) *Within-region* spread of competition-induced suppression (or facilitation) would be unaffected by whether or not multiple regions of the same type are the same color; hence its effects should be evident with multicolored displays.

On the other hand, if the mechanism producing region number effects exploits the homogeneous fill of the convex and/or the concave regions, region number effects will not be observed in Experiment 2.

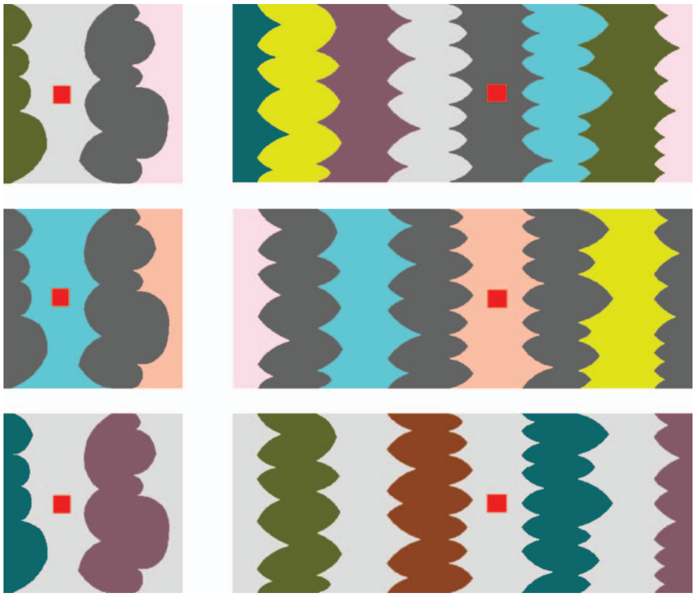

Figure 4. *Top*: Sample Experiment 2 multicolored displays with probes. *Middle*: Sample Experiment 3 HOM-convex/HET concave displays. *Bottom*: Sample Experiment 3 HOM concave/HET convex displays. *Left column*: 4-region displays. *Right column*: 8-region displays. HOM = homogeneous; HET = heterogeneous.

Methods

Participants

The subjects were 75 UA undergraduate students, participating to partially fulfill an introductory course requirement (25 per region number condition). One other subject in Experiment 2 did not meet our response rate criterion.

Stimuli, apparatus, and procedure

Multicolored versions of the 4-, 6-, and 8-region nonrepeating displays were created by painting the regions gray (G), yellow (Y), magenta (M), or cyan (C), in one of two luminance settings: low (L) or high (H). Luminance differences were maintained because a luminance step between adjacent regions is necessary for figure-ground perception (Grossberg, 1994; Livingstone & Hubel, 1988). The L and H colors were equal luminance steps below and above the medium gray screen backdrop; hence, contrast with the backdrop did not serve as a depth cue (see O'Shea, Blackburn, & Ono, 1994). In Adobe Photoshop (cs 2, v. 9.0), the PANTONE® solid coated color library value for these colors are: 809C (Y-H), 385C (Y-L), 705c (M-H), 8062C (M-L), 3255C (C-H), 5473C (C-L), cool gray 1C (G-H), and 11C (G-L). The screen backdrop was cool gray 5C.

The regions on either side of fixation were always G-L and G-H, balanced across left–right location. The red probe was located on one of these two regions. The colors Y, M, and C were used to paint the remaining regions with the constraints that the same basic color was not used to paint either adjacent regions or two regions of the same type. In half of the displays convex regions were L- and concave regions were H-luminance: this was reversed for the remaining displays. Thus, although the regions of a given type in a display differed in color, they were the same luminance. We used 72 displays to maintain an equal number of trials with each color arrangement in each region number condition. The apparatus and procedure were the same as Experiment 1, except that there were 6 practice trials.

Results

As can be seen in Figure 5, region number effects were not obtained with multicolored displays. The figure was perceived on the convex side of the central edge on 59% of the trials in 4-region displays and not significantly more often in 6- (62%) or 8- (59%) region displays. An ANOVA showed no main effect of region number, $F < 1$. None of the post hoc comparisons between region number conditions was significant, all *ps* > 0.80.

Despite the absence of region number effects, convex regions were seen as figure more often than expected on the basis of chance (50%) in all region number conditions, all *ps* < 0.05. Thus, although region number effects were absent with multicolored displays, the more local process producing weak convexity effects was intact and approximately equally effective regardless of region number.

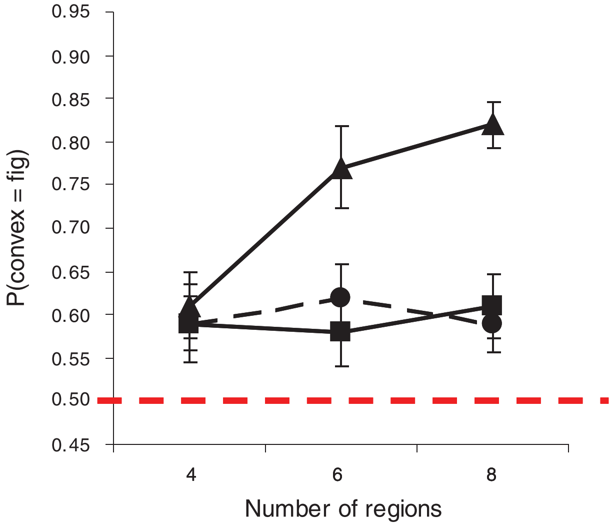

Figure 5. The probability that convex regions were perceived as figure [P(convex = fig)] as a function of region number. Experiment 2: dashed line and disks. Experiment 3: HOM convex/HET concave (squares); HOM concave/HET convex (triangles). The dashed red line indicates chance performance. HOM = homogeneous; HET = heterogeneous.

Discussion

Region number effects were not obtained with multicolored displays in which same-type regions (convex or concave) were no more similar in color than different-type regions. By showing that repetition of convex regions alone does not produce region number effects, Experiment 2 eliminates a simple probability summation account. The results of Experiment 2 also eliminate *within-region* spreading suppression and/or facilitation as an account of the region number effects. Region-based suppression/facilitation should operate just as well in multicolored displays as in black and white displays. Taken together, the results of Experiments 1 and 2 imply that region number effects require interactions among homogeneously colored same-type regions—or portions thereof. This follows because region number effects were evident in Experiment 1 where convex regions were one achromatic shade and concave regions another achromatic shade, but not in Experiment 2 where both convex and concave regions were colored heterogeneously.

Although region number effects were absent, convex regions were seen as figure more often than expected on the basis of chance guessing or response bias, *but not much more often*. Thus, the results of Experiment 2 support the conclusion that convexity is not a very effective configural cue at a single edge or at multiple edges in multicolor displays. In the multicolored displays used in Experiment 2, competitions occurring at individual edges remained independent as region number increased.

Experiment 3

In Experiment 3, we investigated whether homogeneity of the features filling either the convex or the concave regions (or both) was essential for the region number effects observed in Experiment 1. The answer to this question will be important in elucidating whether the third potential mechanism raised earlier—between-region spreading of competition-induced suppression or facilitation—underlies the region number effects.

Two groups of observers participated. Subjects in one group viewed displays in which the convex regions were homogeneous in color and the concave regions were heterogeneous in color (HOM convex/HET concave displays; Figure 4, middle row). Subjects in the other group viewed displays in which the concave regions were homogeneous and the convex regions were heterogeneous

(HOM concave/HET convex). These groups were each divided into three subgroups that viewed 4-, 6-, and 8-region displays.

Methods

Participants

The subjects were 138 UA students who participated to partially fulfill a requirement for an introductory course. Of these, 24, 23, and 22 viewed 4-, 6-, and 8-region homogeneous convex displays, respectively; and 24, 21, and 24 viewed 4-, 6-, and 8-region homogeneous concave displays.

Stimuli and apparatus

HOM convex/HET concave displays were created from Experiment 2 displays by painting the convex regions gray (G-L or G-H) and the concave regions heterogeneous colors in the contrasting luminance. HOM concave/HET convex displays were created by painting the concave regions gray and the convex regions heterogeneous colors in the contrasting luminance. We added orange (O) to the color repertoire in order to have different colors on each of the heterogeneous regions in 8-region displays.

Procedure

The procedure was the same as Experiment 2, except that 72 multicolored displays were randomly intermixed with the 72 homogeneous displays to discourage a bias to report either gray or colored regions as figure. (We report only the results for homogeneous displays.)

Results

Homogeneity of the concave regions was critical for the region number effects, as can be seen in Figure 5. The figure was increasingly likely to be seen on the convex side of the central edge in HOM concave/HET convex displays as region number increased from 4 to 6 to 8 (61%, 77%, and 82%, respectively), $F(2, 66) = 8.134$, $p = 0.001$. In contrast, the figure was seen on the convex side of the edge approximately equally often in 4-, 6- and 8-region HOM convex/HET concave displays: displays (59%, 58%, and 61%, respectively, $F(2, 66) = 0.153$, $p < 0.85$). An ANOVA with 2 between subjects factors (homogeneous region and region number) revealed main effects of homogeneous region, $F(1, 132) = 18.432$, $p < 0.01$, and region number, $F(2, 132) = 4.421$, $p < 0.02$, and an interaction between the two, $F(2, 132) = 3.599$, $p < 0.03$.

We compared the region number effects obtained with black and white displays (Experiment 1) to those obtained with HOM concave/HET convex displays in the present experiment. A main effect of region number was observed, but there was no main effect of experiment, $F(1,135) = 1.99$, $p = 0.16$; and no interaction between experiment and region number, $p > 0.70$. These results indicate that the homogeneity of the convex regions is irrelevant to the region number effects because they were homogeneous in Experiment 1 displays and heterogeneous in the Experiment 3 displays that showed region number effects (HOM concave/HET convex displays). The *absence* of region number effects with both multicolored displays and HOM convex/HET concave displays supports the same conclusion because the convex regions were heterogeneous in the former and homogeneous in the latter.

Discussion

Region number effects were obtained with HOM concave/HET convex displays but not with HOM convex/HET concave displays. Indeed, convex regions were no more likely to be seen as figure in 8-region HOM convex/HET concave displays (58%) than in 2-region black and white (57%) displays or in multicolored displays (59%). The absence of region number effects with HOM convex/HET concave displays eliminates two potential explanations of the region number effects.

Consider first a probability summation account in which figure responses are based on spatially distributed detectors responding to a *combination* of hue and convexity; this explanation would predict a pattern of results opposite to that we found: That is, region number effects should have been observed with HOM convex/HET concave displays but not with HOM concave/HET convex displays.

Consider next an explanation in terms of spreading facilitation among homogeneous regions that win the cross-edge competition (i.e., convex regions). Again region number effects would be expected with HOM convex/HET concave displays but not with HOM concave/HET convex displays. The absence of region number effects with HOM convex/HET concave displays suggests that, for these displays, facilitation of the region that wins the cross-edge competition either does not occur or is not amplified when like regions are homogeneous. Consistent with the former possibility, using fMRI, Likova and Tyler (2008) observed retinotopic suppression in the ground regions of their stimuli, but no retinotopic facilitation in the figure regions.

Region number effects as large as those obtained in Experiment 1 with displays composed of alternating black and white concave and convex regions were obtained in Experiment 3 with HOM concave/HET convex displays. These results suggest that the mechanism of the region number effects is spreading of competition-induced suppression between homogeneous concave regions.

The concave regions were homogeneous in both Experiments 1 and 2, whereas the convex regions were homogeneous in Experiment 1 and heterogeneous in Experiment 3.

We next consider whether these results can be explained without appealing to competition-induced suppression by supposing that homogeneous alternating regions themselves constitute a background cue, even in the absence of another configural property. This alternative interpretation would have a hard time accounting for the results obtained with HOM convex/HET concave displays in Experiment 3, where the likelihood of seeing convex regions as figure did not decrease with the number of homogeneous convex regions. Nevertheless, we test this alternative account in Experiment 4.

Experiment 4

In Experiment 4, we tested whether homogeneous alternating regions are themselves a background cue in the absence of other configural properties. If they are, then region number effects should be observed with displays composed of homogeneous regions alternating with heterogeneous regions that are equal in size and shape. On the other hand, if suppression is necessary we do not expect to observe region number effects in the absence of a configural cue to bias the competition toward one side of display edges.

We used displays with straight edges and equal-area alternating homogeneous and heterogeneous regions of H- and L-luminance; neither region was more enclosed, symmetric, or familiar than the other (hence none of those configural cues favored one region over the other; Figure 6). We began by testing 8-region displays, reasoning that if subjects reported seeing the heterogeneous regions as figure substantially more often than chance, we would search for region number effects by testing smaller region number conditions. In fact, we never tested smaller region number conditions because in 4 experiments (Experiments 4A–4D), using both probe on–off and direct reports we failed to find evidence that homogeneity of alternating regions alone exerted an influence large enough to account for the region number effects.

Methods

Participants

The participants were 87 UA students; 80 participated to partially fulfill an introductory course requirement and 7 were paid at a rate of $10 per hour. There were 27, 20, 20, and 20 subjects in Experiments 4A, 4B, 4C, and 4D, respectively.

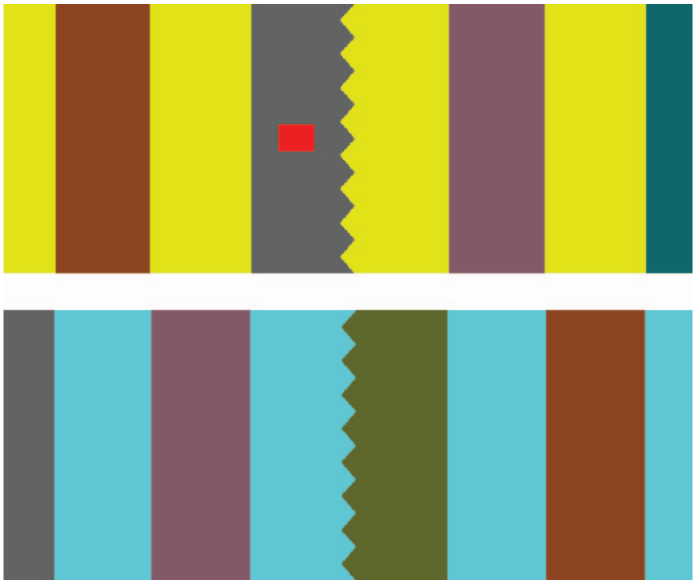

Figure 6. Samples of Experiment 4 homogeneous/heterogeneous no-cue displays. *Top*: displays with probes. *Bottom*: displays without probes.

Stimuli and apparatus

Displays had 8 regions separated by straight edges, except for the central edge, which was a zigzag edge so that subjects could localize the regions lying to its right and left. All of the zigzag segments were equal in length and all met at right angles. Hence the central edge did not contain any cues that favored perceiving the figure on one side versus the other. Alternating regions differed in color and luminance.

Two sets of displays were used in Experiment 4A, with 5 colors (M, C, Y, O, and G) in each display. One set of displays was modeled on the homogeneous conditions of Experiment 3 in that every other region was homogeneous and the intervening regions were heterogeneous (*homogeneous/heterogeneous no-cue displays*); all homogeneous regions were filled with gray. The combination of 4 hues and 2 luminance values yielded 8 displays. The other, equal size, set was modeled on the multicolored displays used in Experiment 2 in that the colors of alternating regions were dissimilar (*multicolored no-cue displays*). These two sets were intermixed without repetition in Experiment 4A.

For Experiment 4B stimuli, each of the five colors was the homogenous color equally often (sample display in Figure 6, top). There were 20 different left to right combinations; crossed with two luminance values this produced 40 homogeneous/heterogeneous no-cue displays.

Multicolored no-cue displays were not used in Experiments 4B–4D. Experiment 4A and 4B displays had a red probe on the region to the left or the right of the central zigzag edge. The probe was removed to make the

Experiment 4C and 4D displays (sample display in Figure 6, bottom).

Procedure

Experiments 4A and 4B procedures were the same as those in previous experiments (the probe on/off task was used). In Experiments 4C and 4D observers were instructed to press one of two buttons to indicate whether they saw the region to the left or to the right of the central edge as figure. In Experiment 4D the exposure duration was increased to 170 ms.

Results and discussion

Contrary to the hypothesis that alternating homogeneous regions alone serve as a background cue, the figure was not seen on the heterogeneous side of the central edge substantially more often than chance in Experiment 4. Heterogeneous regions were seen as figure on 54% and 49% of the trials in Experiments 4A and 4B, respectively. These percentages did not differ from 50%, $t(19) \leq 1.07$, $p \geq 0.30$. Similar effects were obtained with direct report: In Experiment 4C heterogeneous regions were seen as figure on 57% of the trials, which was significantly greater than chance $t(19) = 2.46$, $p < 0.03$, but did not leave room for context effects to emerge when compared to smaller region number displays. The Experiment 4C results most likely reflect chance aberration, because in Experiment 4D when displays were exposed for an additional 70 ms, heterogeneous regions were seen as figure on 51% of the trials, which did not differ from chance, $t(19) = 0.45$, $p > 0.65$.

Experiment 4 shows that, *ceteris paribus,* homogeneously alternating regions do not support the region number effects. Thus, taken together with the preceding experiments, Experiment 4 shows that suppression as well as homogeneity of the alternating regions is necessary for the region number effects observed in Experiments 1 and 3.

General discussion

In Experiment 1 we found that the effectiveness of the configural property of convexity varied with *context*: As the number of alternating black and white, convex and concave, regions increased from 2 to 8, convex regions were increasingly likely to be seen as figures (e.g., 57%–89%). Thus, Experiment 1 showed that figure-ground determinations at a single edge are influenced by figure-ground determinations at distant disconnected edges. This is an important new finding. Furthermore, our finding that convexity is not very effective in single edge displays overturns the traditional assumption that convexity per se is a potent configural cue. Our results show that convexity operates probabilistically and its efficacy varies with context. Experiments 2 and 3 revealed that homogeneity of the concave regions alternating with the convex regions was necessary for the region number effects; the homogeneity/heterogeneity of the convex regions was irrelevant. Experiment 4 showed that, in the absence of configural properties, there was no general tendency for homogeneous alternating regions to be seen as grounds.

We call the region number effects **"concatenation effects"** because they depend upon both the number of regions in a display and the characteristics of the chain of regions (or, at least of the portions near the edges). We interpret the concatenation effect within a model in which portions of potential shapes on opposite sides of an edge compete for awareness at each edge. Each potential shape is assigned a weight reflecting the statistical likelihood that objects in the environment have its properties (e.g., see Knill, 2007). Conceiving of shape properties relevant to figure ground as probabilistic rather than categorical allows the shape attribute of figure-ground perception to be explained in terms of competition between candidate shapes.

For displays like ours, we suppose that portions of candidate convex shapes compete with portions of candidate concave shapes at every edge. Convex candidates have a small but significant advantage at individual edges (e.g., 57–60%); as a consequence the concave candidates are suppressed slightly at each edge. Likova and Tyler's (2008) evidence for a reduced neural signal in the retinotopic projection of the ground region of their figure-ground stimulus is consistent with our proposal that in our stimuli the concave side of the edge is inhibited. Peterson and Skow's (2008) behavioral evidence for inhibition of a portion of a familiar configuration shown on the groundside of an edge is also consistent with our proposal that suppression is applied on the concave side of an edge.

We propose that the mechanism for the concatenation effects is a weight linkage process that spreads suppression among homogeneously colored low-weight candidates, and in the process amplifies the suppression of each low-weight candidate. As the number of suppressed homogeneous low-weight candidates increases, the weight difference between the high- and low-weight candidate shapes increases, hence, the cross-edge competition is reduced, and the high-weight (convex) shape candidates become increasingly likely to win the competition. Consistent with the view that differential weights and suppression are both necessary, Experiment 4 showed that concatenation effects are not observed when there are no weight differences between the candidate shapes on opposite sides of edges delimiting homogeneous from heterogeneous regions. Weight linkage could be accomplished via a variety of mechanisms. One possibility is long-range connections operating to synchronize the activity of populations of suppressed neurons representing same color concave candidate shapes. Other possibilities include connections within a region such as V4 that represents both color and shape, or feedback from higher levels.

A weight-linkage mechanism provides a parsimonious account of our results that is consistent with explanations of other phenomena. For instance, Bundesen and Pedersen (1983) Duncan and Humphreys (1989) demonstrated that visual search for a target is more efficient when the non-target distractors are homogeneously rather than heterogeneously colored. They hypothesized that in visual search, targets and non-target distractors compete for attention. The competitive weights of the distractors are reduced in service of the search task and weight linkage occurs among homogeneously colored distractors (cf. Bundesen, Habekost, & Kyllingsbaek, 2005). Beck and Kastner (2005, 2007) recently reported fMRI evidence for reduced competition from homogeneous rather than heterogeneous distractors near a singleton in a variant of a visual search task. Duncan and Humphreys hypothesized that weight linkage would operate to enhance the representation of targets too if there were numerous targets.

In our displays, where candidate concave shapes compete with candidate convex shapes for representation, the concave competitors are analogous to distractors in visual search. Of course, this is an analogy only: Figure-ground perception is not the same as visual search. One difference is that in figure-ground perception subjects are not searching for a target among homogeneous distractors that can be intentionally inhibited in service of the search for a different color target; instead, in figure-ground perception inhibition is hypothesized to result from competition. Our results indicate a further difference: for figure-ground perception, weight linkage does not occur for high-weight, potentially facilitated, candidates (e.g., the convex regions), whereas Duncan and Humphreys (1989) hypothesized it would occur for targets in visual search tasks. Another difference is that our results suggest that the weight linkage mechanism amplifies suppression of the concave regions (because the competitive strength of the concave regions decreases as the number of same color concave regions increases); such synergy was neither predicted nor observed in visual search experiments.

Many questions concerning the concatenation effects remain, some of which are currently under investigation in our laboratory. We discuss some of them below.

Perceptual completion

Is it possible that, for our displays, suppression applied to the concave side of an edge initiates the potential for an amodal completion process that is facilitated when the concave regions are homogeneous and inhibited when they are heterogeneous? Perhaps the convex regions became increasingly likely to win the cross-edge competition as the likelihood of the concave regions completing behind the convex region increased. This interpretation has a descriptive appeal—in homogeneous concave displays, the concave regions are perceived as a uniform surface completing behind multiple convex shapes rather than as separate shapes.

There is some evidence that uniformity of color enhances amodal completion of two bar segments behind a rectangle provided that the bars have “relatable” edges (i.e., edges that can be connected by a smooth monotonic curve; Yin, Kellman, and Shipley (1997, 2000). In Yin et al.’s displays, T-junctions as well as edge relatability facilitated the perception that the bars continued behind the rectangles. There were no T-junctions or relatable edges in our displays. The two candidate shapes on opposite sides of an edge merely differed in competitive strength, and by hypothesis, in the degree of suppression applied to them. Without further research we cannot be certain whether the potential for amodal completion plays a causal role in the concatenation effects. If it does, then our experiments show that competition-induced suppression can initiate amodal completion, but homogeneity of suppressed regions is necessary for completion to occur. This possibility is not necessarily distinct from a weight linkage mechanism; amodal completion may be instantiated by weight linkage.

Grouping effects

Grouping and figure-ground perception were both studied by Gestalt psychologists. Using these two terms from the traditional perceptual organization literature to describe the concatenation effects, one could say that convexity is an increasingly effective configural cue when growing numbers of homogeneous concave regions group together, but convexity’s effectiveness is unaffected by the grouping of homogeneous convex regions. This description begs a number of questions regarding both substrate and mechanism. For instance, it has been assumed that figures, but not grounds, are the substrate for grouping operations (e.g., Palmer & Rock, 1994). But a grouping-based description of concatenation effects hypothesizes that grouping operates on regions seen as grounds rather than as figures. Perhaps this problem could be evaded by supposing that both convex and concave regions were determined *without prejudice* to be figures at some initial stage; grouping of homogeneous concave regions then took place and affected what was perceived as figure at some later stage. However, on this account there is no a priori reason why homogeneous concave, but not homogeneous convex regions, should be grouped. An assumption such as ours regarding differential competitive weights for the convex and concave regions is necessary. Furthermore, without inhibitory competition, the grouping explanation fails to provide a reason why grouping *reduces* rather than enhances the likelihood that a set of regions will be perceived as figures. Thus, although the weight linkage mechanism we propose to account for our effects could be described as a form of grouping, doing so creates problems for theories of grouping and at this stage does not shed light on concatenation effects.

Are the probe on/off reports a good index of concatenation effects?

For experiments like ours where there are no correct or incorrect answers, questions can arise regarding whether subjects' responses reflect what they perceive or instead a response bias provoked by what they believe the experimenter expects them to perceive. We took the following five methodological precautions to guard against response bias in our results. First, our displays were created so that neither luminance (high vs. low) nor location (left vs. right) was confounded with convexity, so a tendency to map figure reports onto one value of either of these factors could not produce our results. Second, probe location was balanced across these factors and also across convexity/concavity, so a bias to favor either an "on" or an "off" response could not produce our effects either. Third, all of our conditions (both region number and display type) were tested between-subjects, and no subject participated in more than one condition; hence, subjects could not compare the different conditions and form hypotheses about how to respond differentially to them. Fourth, the same written instructions were used in all experiments; hence, they could not engender different expectations in the different conditions/experiments. Fifth, in Experiments 3 and 4 we discouraged a bias to report either the gray or the colored regions as figures in homogeneous/heterogeneous displays by mixing them with multicolored displays. Because we designed our experiments to rule out potential sources of response bias, we consider the probe on/off reports a good index of concatenation effects.

In addition, we examined means based on subjects' first 20 responses in the two different homogeneous conditions of Experiment 3. The overall results were replicated in these means, indicating that subjects were not adopting different strategies in these two conditions during the experiment.

Finally, there are two other reasons to prefer direct subjective measures like the probe on/off reports to indirect objective measures as assays of concatenation effects. A practical reason is that objective measures such as longer RTs to recognize the shapes of figures versus grounds (e.g., Driver & Baylis, 1996) do not provide an index of the percentage of trials on which subjects saw a region as figure, and therefore cannot be used to compare percentages across a number of conditions, a comparison that is essential to the concatenation effects. A second, more conceptual reason is that memory can affect indirect objective measures, rendering them less pure as indices of figure-ground perception than direct reports.

Other remaining questions

A question that remains at this time is: Must the concave and convex regions differ in color in order for concatenation effects to be observed? The answer appears to be "no." Peterson and Salvagio (in preparation) observed concatenation effects with displays in which both convex and concave regions were white, with a black edge between them (i.e., outline displays). These data provide further evidence that the color of the convex regions is completely irrelevant, that weight linkage occurs only among suppressed low-weight candidate shapes regardless of whether or not the high-weight candidates are the same color as the low-weight candidates.

Another question concerns whether edges or regions are the substrate for concatenation effects; that is, are concatenation effects observed only when entire bounded regions represent the high- and low-weight candidate shapes? The lack of concatenation effects in Experiment 2 indicates that, at least in multicolored displays, region-wide spread of suppression does not play a role in concatenation effects: Convex regions were not seen as figure any more often in 4-, 6-, or 8-region multicolored displays in Experiment 2 than in 2-region black and white displays in Experiment 1, even though any within-region spread of suppression should be intact in multicolored displays as should local between-region competitions. (The same was true for HOM convex/HET concave displays in Experiment 3.) These data suggest that weight linkage mechanisms do not necessarily operate on whole bounded regions; had they done so, some increase in the effectiveness of convexity with region number would be expected yet there was none. Indeed, other experiments indicate that configural properties such as convexity and familiar configuration may influence figure-ground perception only near the edge where they are expressed (Nelson & Palmer, 2007; Peterson, 2003; Peterson & Gibson, 1993). To investigate directly whether or not weight linkage mechanisms can operate on suppressed sub-regions of bounded regions, Peterson and Salvagio (in preparation) are using outline displays with multiple edges with convex sides facing in the same, rather than alternating, directions. Each region in these displays is convex on one side and concave on the other side.

Another question on which we have preliminary data is whether suppression of a single region near fixation is sufficient for concatenation effects, provided that alternating regions are the same color as the suppressed region or whether suppression of all same color regions is necessary. Salvagio, Mojica, and Peterson (2008) found that concatenation effects require suppression of more than a single region near fixation.

Answers to these and other questions raised by the new concatenation effects reported here will shed light on the mechanisms of figure-ground perception.

Conclusions

The concatenation effects identified in the experiments reported here show that figure-ground competitions occurring at disconnected edges are interdependent, at least when suppressed low-weight shape candidates are the same color. We propose a synergistic weight linkage mechanism to account for these effects. These results, together with other recent findings (e.g., Peterson & Skow, 2008), are consistent with the view that a competition for awareness between portions of candidate shapes on opposite sides of an edge results in the perception of a shaped figure on one side and a shapeless ground on the other.

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References

Beck, D. M., & Kastner, S. (2005). Stimulus context modulates competition in human extrastriate cortex. *Nature Neuroscience, 8,* 1110–1116. [PubMed] [Article]

Beck, D. M., Kastner, S. (2007). Stimulus similarity modulates competitive interactions in human visual cortex. *Journal of Vision, 7*(2):19, 1–12, http://journalofvision.org/7/2/19/, doi:10.1167/7.2.19. [PubMed] [Article]

Bundesen, C., Habekost, T., & Kyllingsbaek, S. (2005). A neural theory of visual attention: Bridging cognition and neurophysiology. *Psychological Review, 112,* 291–328. [PubMed]

Bundesen, C., & Pedersen, L. F. (1983). Color segregation and visual search. *Perception & Psychophysics, 33,* 487–493. [PubMed]

Driver, J., & Baylis, G. C. (1996). Edge-assignment and figure-ground segmentation in short-term visual masking. *Cognitive Psychology, 31,* 248–306. [PubMed]

Duncan, J., & Humphreys, G. W. (1989). Visual search and stimulus similarity. *Psychological Review, 96,* 433–458. [PubMed]

Forster, K. I., & Forster, J. C. (2003). DMDX: A windows display program with millisecond accuracy. *Behavior Research Methods, Instruments, & Computers, 35,* 116–124. [PubMed]

Fowlkes, C. C., Martin, D. R., & Malik, J. (2007). Local figure-ground cues are valid for natural images. *Journal of Vision, 7*(8):2, 1–9, http://journalofvision.org/7/8/2/, doi:10.1167/7.8.2. [PubMed] [Article]

Gilbert, C. D., & Sigman, M. (2007). Brain states: Top-down influences in sensory processing. *Neuron, 54,* 677–696. [PubMed] [Article]

Grossberg, S. (1994). 3-D vision and figure-ground separation by visual cortex. *Perception & Psychophysics, 55,* 48–121. [PubMed]

Hoffman, D. D., & Singh, M. (1997). Salience of visual parts. *Cognition, 63,* 29–78. [PubMed]

Kanizsa, G., & Gerbino, W. (1976). Convexity and symmetry in figure-ground organization. In M. Henle (Ed.), *Vision and artifact* (pp. 25–32). New York: Springer.

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]

Kienker, P. K., Sejnowski, T. J., Hinton, G. E., & Schumacher, L. E. (1986). Separating figure from ground with a parallel network. *Perception, 15,* 197–216. [PubMed]

Knill, D. C. (2007). Learning Bayesian priors for depth perception. *Journal of Vision, 7*(8):13, 1–20, http://journalofvision.org/7/8/13/, doi:10.1167/7.8.13. [PubMed] [Article]

Koffka, K. (1935). *Principles of Gestalt psychology.* Oxford, England: Harcourt, Brace.

Lamme, V. A. (1995). The neurophysiology of figure-ground segregation in primary visual cortex. *Journal of Neuroscience, 15,* 1605–1615. [PubMed] [Article]

Likova, L. T., & Tyler, C. W. (2008). Occipital network for figure/ground organization. *Experimental Brain Research, 189,* 257–267. [PubMed]

Livingstone, M., & Hubel, D. (1988). Segregation of form, color, movement, and depth: Anatomy, physiology and perception. *Science, 240,* 740–749. [PubMed]

Nelson, R. A., & Palmer, S. E. (2007). Familiar shapes attract attention in figure-ground displays. *Perception & Psychophysics, 69,* 382–392. [PubMed]

O'Shea, R. P., Blackburn, S. G., & Ono, H. (1994). Contrast as a depth cue. *Vision Research, 34,* 1595–1604. [PubMed]

Palmer, S. E., & Rock, I. (1994). Rethinking perceptual organization: The role of uniform connectedness. *Psychonomic Bulletin and Review, 1,* 29–55.

Pasupathy, A., & Connor, C. E. (1999). Responses to contour features in macaque area V4. *Journal of Neurophysiology, 82,* 2490–2502. [PubMed] [Article]

Peterson, M. A. (1994). Object recognition processes can and do operate before figure-ground organization. *Current Directions in Psychological Science, 3,* 105–111.

Peterson, M. A. (2003). On figures, grounds, and varieties of amodal surface completion. In R. Kimchi, M. Behrmann, & C. Olson (Eds.), *Perceptual organization in vision: Behavioral and neural perspectives* (pp. 87–116). Mahwah, NJ: LEA.

Peterson, M. A., de Gelder, B., Rapcsak, S. Z., Gerdhadstein, P. C., & Bachoud-Lévi, A. (2000). Object memory effects on figure assignment: Conscious object recognition is not necessary or sufficient. *Vision Research, 40,* 1549–1567. [PubMed]

Peterson, M. A., & Enns, J. T. (2005). The edge complex: Implicit memory for figure assignment in shape perception. *Perception & Psychophysics, 67,* 727–740. [PubMed]

Peterson, M. A., & Gibson, B. S. (1993). Shape recognition contributions to figure-ground organization in three-dimensional displays. *Cognitive Psychology, 25,* 383–429.

Peterson, M. A., & Lampignano, D. W. (2003). Implicit memory for novel figure-ground displays includes a history of cross-border competition. *Journal of Experimental Psychology: Human Perception and Performance, 29,* 808–822. [PubMed]

Peterson, M. A., & Salvagio, E. (in preparation). The substrate for concatenation effects in figure-ground perception.

Peterson, M. A., & Skow, E. (2008). Inhibitory competition between shape properties in figure-ground perception. *Journal of Experimental Psychology: Human Perception and Performance, 34,* 251–267. [PubMed]

Peterson, M. A., & Skow-Grant, E. (2003). Memory and learning in figure-ground perception. In B. Ross & D. Irwin (Eds.), *Cognitive vision: Psychology of learning and motivation* (vol. 42, pp. 1–34). New York: Academic Press.

Rubin (1958). Figure and ground. In D. Beardslee (Ed.), *Readings in perception* (M. Wertheimer, Trans.; pp. 35–101). Princeton, NJ: Van Nostrand. (Original work published 1915.)

Salvagio, E., Mojica, A. J., & Peterson, M. A. (2008). Context effects in figure-ground perception: The role of biased competition, suppression and long-range connections [Abstract]. *Journal of Vision, 8*(6):1007, 1007a, http://journalofvision.org/8/6/1007/, doi:10.1167/8.6.1007.

Stevens, K. A., & Brookes, A. (1988). The concave cusp as a determiner of figure-ground. *Perception, 17,* 35–42. [PubMed]

Vecera, S. P., & O'Reilly, R. C. (1998). Figure-ground organization and object recognition processes: An interactive account. *Journal of Experimental Psychology: Human Perception and Performance, 24,* 441–462. [PubMed]

Yin, C., Kellman, P. J., & Shipley, T. F. (1997). Surface completion complements boundary interpolation in the visual integration of partly occluded objects. *Perception, 26,* 1459–1479. [PubMed]

Yin, C., Kellman, P. J., & Shipley, T. F. (2000). Surface integration influences depth discrimination. *Vision Research, 40,* 1969–1978. [PubMed]

Zipser, K., Lamme, V. A., & Schiller, P. H. (1996). Contextual modulation in primary visual cortex. *Journal of Neuroscience, 16,* 7376–7389. [PubMed] [Article]