The effect of flankers on three tasks in central, peripheral, and amblyopic vision

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Using identical stimuli and methods, we assessed the effects of flankers on three different tasks, orientation discrimination, contrast discrimination, and detection, in central, peripheral, and amblyopic vision. The goal was to understand the factors that limit performance of a task in the presence of flankers in each of these visual systems. The results demonstrate that: (1) For unflanked targets, the losses in peripheral and amblyopic vision (relative to the normal fovea) are ordered, with the loss of unflanked contrast discrimination thresholds considerably smaller than those for either detection or orientation discrimination. (2) For flanked targets, in normal foveal vision and anisometropic amblyopia, the critical distance is more or less proportional to the target size, whereas in peripheral and strabismic amblyopic vision, the critical distance shows much less (or no) dependence on target size. (3) For the normal fovea, and anisometropic amblyopia, when the target is large (>=0.2 deg) the amount of threshold elevation induced by flankers is low, increasing when the target is very small. On the other hand, for the periphery and the amblyopic eyes of most strabismic amblyopes, the elevation is large over the range of sizes tested. (4) In peripheral and strabismic amblyopic vision, remote flankers elevate orientation discrimination and contrast discrimination thresholds but not detection thresholds. Our results show clearly that the effects of flankers depend on both the task and the type of visual system. We conclude that in normal foveal vision and anisometropic amblyopia, the effects of flankers largely reflect a reduction in visibility and may be explained by masking. On the other hand, in peripheral vision and strabismic amblyopic vision, the effects of flankers on orientation discrimination and to a lesser extent contrast discrimination cannot be explained by simple masking and are due to crowding.

Keywords: crowding, peripheral vision, amblyopia, psychophysics, facilitation


Introduction

Spatial interactions are a critical and ubiquitous feature of spatial vision that may be either inhibitory (reducing sensitivity) or facilitatory (enhancing sensitivity). Moreover, they may distort visual perception, as in the tilt illusion, and change the appearance of a target (Greenwood, Bex, & Dakin, 2010). These spatial interactions occur when a target is presented in the proximity of flankers and may be a consequence of one or more distinct phenomena—overlap masking, lateral masking, surround suppression, and crowding (see Levi, 2008). The effects of flankers depend on the task (e.g., detection versus discrimination), the target eccentricity (fovea versus periphery), and the type of visual system (normal versus amblyopic).

Overlap or ordinary masking

Detection of a feature or target (e.g., a patch of grating) is rendered more difficult (i.e., threshold is elevated) when the target is overlaid on a mask (e.g., a suprathreshold grating). This is overlap or ordinary masking (Pelli, Palomares, & Majaj, 2004). Overlap masking is tuned to spatial frequency and orientation and is strongest when the target and mask are similar, e.g., in spatial frequency and orientation (Graham, 1989; Legge & Foley, 1980; Polat & Sagi, 1993). Overlap masking elevates thresholds for detection and identification similarly (Thomas, 1985) by directly stimulating the channel or feature detector that is most sensitive to detecting the signal.

Lateral masking

Target and flanker need not overlap in order to interact. For example, flanking (Gabor) patches can impair detection of a (Gabor) target when they are very close and facilitate detection at wider spacing (Polat & Sagi, 1993, 1994). The model elaborated by Polat et al. assumes that excitatory and inhibitory connections form a neuronal network that determines the measured responses (Adini & Sagi, 2001; Adini, Sagi, & Tsodyks, 1997; Polat, 1999; Polat & Sagi, 2006; Sterkin, Sterkin, & Polat, 2008). It assumes that each network unit receives three types of visual input: direct thalamic-cortical input, lateral input from other units within the network, and top-down feedback. These
inputs are subdivided into excitatory and inhibitory types with the lateral excitation organized along the filters' optimal orientation and superimposed on a suppressive area surrounding the filters.

**Surround suppression**

Physiological experiments in cortex reveal two distinct forms of neural suppression—overlap suppression (Carandini, Heeger, & Movshon, 1997; DeAngelis, Robson, Ohzawa, & Freeman, 1992) similar to the psychophysical overlap masking described above and surround suppression, in which the mask is presented outside the classical receptive field of the “target” neuron (Cavanaugh, Bair, & Movshon, 2002; DeAngelis, Freeman, & Ohzawa, 1994). This suppression is divisive (DeAngelis et al., 1994) and probably reflects divisive contrast normalization (Foley, 1994; Heeger, 1992). Recent work suggests that in human observers, contrast detection thresholds may also be affected by two distinct forms of suppression. Using a double-masking paradigm, Petrov, Carandini, and McKee (2005) showed that in humans, overlay suppression precedes surround suppression in the processing sequence, and unlike overlap suppression, surround suppression is only strong in the periphery (>1° eccentricity). Although surround suppression shares a number of important attributes with crowding, a close comparison suggests that they are distinctly different. For example, unlike crowding, surround suppression is not tuned to interocular disparity and does not show the inward-outward anisotropy evident in crowding (Petrov & Popple, 2007; Petrov, Popple, & McKee, 2007). Moreover, while crowding shows a strong dependence on flanker polarity (Kooi, Toet, Tripathy, & Levi, 1994) surround suppression does not depend on the phase of the surround grating.

**Crowding**

In peripheral vision, a letter that is easily recognized on its own becomes unrecognizable if surrounded by other letters. For example, while staring at the second letter “e” in the word “letter” at the beginning of the prior sentence, notice the letter “a” to the left is much easier to discern than the letter “a” to the right in the word “that.” In foveal vision, crowding typically only occurs over very small distances (4–6 arc min., e.g., Danilova & Bondarko, 2007; Flom, Weymouth, & Kahneaman, 1963; Liu & Arditi, 2000; Toet & Levi, 1992) or is reported not to occur at all (Strasburger, Harvey, & Rentschler, 1991). In contrast, crowding in peripheral vision occurs over very large distances (up to 0.5 times the eccentricity of the target—Bouma, 1970; Kooi et al., 1994; Toet & Levi, 1992) where the retinal point spread functions of the target and flanks are clearly separate. Crowding also extends over long distances in the central visual field of strabismic amblyopes (Bonneh, Sag, & Polat, 2004; Hess & Jacobs, 1979; Levi & Klein, 1985) and sets a limit on reading speed (Levi, Song, & Pelli, 2007).


Four studies have directly compared the effects of flanks on target detection and discrimination or identification. Andriessen and Bouma (1976) measured the effect of flanks on peripheral orientation discrimination and contrast detection for a thin bright line. They found that flanks affected both orientation discrimination and contrast detection; however, orientation thresholds were elevated even when they compensated for the elevated contrast threshold by increasing the target contrast. Thus, they concluded that either separate mechanisms are involved in the two tasks, or that contrast “does not play a significant role at the level of processing where visual interference occurs.” However, since their line target was broadband in spatial frequency, an alternative explanation is that observers used a different range of spatial frequencies to detect the target than for discriminating its orientation.

Pelli et al. (2004) compared the effects of flanks on letter detection and letter identification in peripheral vision. They found that threshold elevation was stronger for identification than for detection and that the critical distance for detection, for a fixed letter size, was independent of eccentricity, in contrast to the critical distance for letter identification. However, like Andriessen and Bouma, their letters were also broadband in spatial frequency, leaving open the possibility that observers used a different range of spatial frequencies to detect the target than to identify it. Interestingly, when they used gratings as targets, threshold elevation was similar for detection and identification. Their identification task required observers to distinguish between orthogonal orientations, and they argued that orthogonal orientations are detected by distinct feature detectors, so the label of a single feature would allow the identification of the coarse orientation of the grating.
Levi, Klein, and Hariharan compared the effects of flankers on the detection of a single patch (either Gaussian or Gabor) with the effect on identification of the orientation of an E-like target comprised of Gaussian or Gabor patches. They found that, in general, threshold elevation for detection and identification were essentially identical in the normal fovea (Levi, Klein, & Hariharan, 2002) but were different in the normal periphery (Levi, Hariharan, & Klein, 2002a) and in strabismic amblyopia (Levi, Hariharan, & Klein, 2002b)—with thresholds being much more elevated for identification than for detection. Thus, they concluded that the effect of flankers was simple visibility masking in the normal fovea, but crowding in peripheral vision and strabismic amblyopia. Although their stimuli were narrowband in spatial frequency, the detection and identification targets were very different (local vs. extended).

Only one previous study (Livne & Sagi, 2007) compared threshold elevation for detection and orientation discrimination using identical narrowband stimuli. They found that in peripheral vision, threshold elevation for orientation discrimination was generally elevated more by flankers than for detection.

For all four studies, however, the detection task in the absence of flanks may have been subject to more uncertainty than the identification task, thus artificially elevating the unflanked detection threshold. This would have the effect that flankers would elevate detection thresholds less than they would identification thresholds.

The present study was aimed at assessing the effects of flankers on three different tasks in three distinct visual systems—foveal, peripheral, and amblyopic vision—using identical stimuli and methods. Our goal was to revisit the question of what limits performance of a task in the presence of flankers in each of these visual systems—a reduction of visibility (i.e., a form of masking) or crowding. While many previous studies have examined the effects of flankers, the stimuli and tasks used to examine crowding (e.g., letter identification) often differ from those used to examine, for example, lateral masking. In the present study, we measured thresholds for orientation discrimination, contrast discrimination, and detection of a simple feature—a Gabor patch—in the presence of flankers.

**Methods**

**Stimuli**

The target was a briefly presented Gabor patch with a horizontal carrier. The patch contained one cycle/standard deviation (full bandwidth of the stimulus was 0.55 octave), and the phase was randomized from trial to trial. The flanks were segments of an annular grating. In most experiments, the flank grating was horizontal and the spatial frequency was the same as the target. Target and flanks were presented simultaneously for 250 ms. For the orientation and contrast discrimination tasks, the target contrast was 40%, and unless otherwise specified, flank contrast was 80%. The stimuli were generated using WinVis and were presented on a CRT screen (Sony Multiscan G400) with a mean luminance of 80 cd/m². We used a Spyder3 and WinVis software to calibrate the monitor spatial scale and luminance linearity and generate the look-up table to compensate for the monitor’s gamma non-linearity. Examples of the stimuli are shown as insets in Figures 5, 6, and 7.

For foveal vision, we varied the target size and spatial frequency (scale) by varying the viewing distance, from 0.4 m (1.25 c/d, SD = 0.8 deg) to 6.4 m (20 c/d, SD = 0.05 deg). For peripheral viewing, the stimuli were presented at an eccentricity of 5 deg in the lower visual field. The carrier spatial frequency was 2.5 c/d, and the Gaussian standard deviation of the patch was 0.4 deg when presented at 5 degrees eccentricity and was scaled according to eccentricity.

To reduce uncertainty about the target location, each trial was preceded by 2 highly visible diagonal lines forming a cross with a circular gap in the center, so that it did not extend into the area of the target and flankers. These lines disappeared during each stimulus interval. The target always appeared in the center of the gap.

**Psychophysical methods**

We used the identical two-interval forced-choice (2IFC) method for each of the three tasks.

Each staircase consisted of three preliminary reversals and six experimental reversals. The initial orientation difference between the test and the reference was sufficiently large, so that the observers could always make a correct discrimination. A classical 3-down-1-up staircase rule was used, which resulted in a 79.4% convergence level. The geometric mean of the 6 experimental reversals was taken as the threshold estimate for each staircase run. In a typical experiment, 4–8 staircases were randomly interleaved, so that all flank conditions (including no flanks) were tested in the same run. Each experiment was replicated 6–8 times, and the thresholds are the geometric means of the threshold estimates.

Our index of crowding is the “Threshold Elevation” (i.e., the flanked thresholds divided by the unflanked thresholds). A threshold elevation of 1 indicates no crowding.

**Tasks**

**Orientation discrimination**

On each trial, the reference (0°) and test (reference plus an orientation offset) were separately presented in the two brief stimulus intervals (250 ms each) in a random order separated by a 500-ms interstimulus interval. An observer’s
task was to judge which stimulus interval contained the more counterclockwise Gabor.

**Contrast detection**

On each trial, one interval contained the target, and the other interval contained a blank. The two brief stimulus intervals (250 ms each) were presented in a random order separated by a 500-ms interstimulus interval. An observer’s task was to judge which stimulus interval contained the Gabor patch.

**Contrast discrimination**

On each trial, the reference ($C = 0.4$) and test ($C - \Delta C$) were separately presented in the two brief stimulus intervals (250 ms each) in a random order separated by a 500-ms interstimulus interval. An observer’s task was to judge which stimulus interval contained the higher contrast Gabor. The contrast discrimination task has the advantage that the target was in all respects (including no uncertainty as to the location, spatial frequency, phase, etc.) identical to that used for orientation discrimination. For all three tasks, auditory feedback was given following each correct response.

**Observers**

Fourteen observers, nine with amblyopia (2 anisotropic, 4 strabismic, and 3 with both strabismus and anisometropia—see Table 1 for details) and five with normal or corrected-to-normal vision (including author DL) served as observers, although not all observers performed every experiment. Color coding of amblyopia type in the table is also used in the figures. All testing was monocular with the untested eye patched (to allow comparison with amblyopic observers). Observers were given substantial practice prior to data collection. For peripheral viewing, during practice normal observers’ eye movements were visually monitored to ensure proper fixation. All experiments were performed in compliance with the relevant laws and institutional guidelines.

**Results**

**Varying the target–flank distance**

Figure 1 shows the effect of varying the flank–target distance. The three top panels show threshold vs. center-to-center distance for orientation discrimination (left), contrast discrimination (center), and contrast detection (right) for the “standard” condition (SF = 2.5 c/d; SD = 0.4 deg; target contrast, $T_c = 0.4$; flank contrast, $F_c = 0.8$) for normal fovea (open circles), the preferred eyes of amblyopic observers (open squares), normal periphery (5 deg lower visual field—solid gray circles), and 9 amblyopic eyes viewing directly (colored symbols). For the amblyopic observers, different colors represent different types of...
amblyopia (red—strabismic, green—anisometric, and blue—both strabismic and anisometric).

There are several points that stand out clearly in Figure 1. First, consider the unflanked thresholds for each of the three tasks (for each observer in each panel, the rightmost datum represents the unflanked threshold). For orientation discrimination, the unflanked thresholds of the normal controls is less than 2 degrees, lower than that of the preferred eyes of the amblyopes and normal periphery (by approximately a factor of 2 or more) and substantially lower than all but one of the amblyopic eyes (BN). A similar ordering of unflanked thresholds is evident for the other tasks. Second, consider the effect of flankers on orientation discrimination thresholds. In the fovea, and the non-amblyopic eyes of amblyopic observers, flankers have only a small effect, raising threshold by about 30% at the two smallest center-to-center distances. In contrast, the amblyopic eyes and normal periphery show substantially greater flanker effects.

To make the effects of flankers more obvious, the results are replotted as “Threshold elevation” (flanked/unflanked thresholds) in the bottom panels of Figure 1. For some of the amblyopic eyes (e.g., GW and CL), the effects are very substantial—raising orientation thresholds 4- to 6-fold.
8-fold—and occur over long distances (2–4 degrees), similar to the normal periphery. Note that the ordinate scale for detection and contrast discrimination is twice that for orientation discrimination. The curves fit to orientation and contrast discrimination data are Gaussians (described below).

Importantly, the effectiveness of flankers in raising thresholds depends on the task. In general, it is greatest for orientation discrimination, smallest for contrast discrimination, and intermediate for detection. It is also noteworthy that for detection, but not the other two tasks, flankers can also lower thresholds (facilitation—threshold elevation less than 1). This facilitation will be discussed later.

**Varying target scale**

In normal fovea, size matters! Figure 2 (top panels) shows the effect of target scale (Gaussian SD and spatial frequency) in normal fovea. Each panel shows threshold elevation vs. center-to-center distance for orientation discrimination (left), contrast discrimination (center), and contrast detection (right) for different target scales (coded by symbol size). Clearly, there is a substantial effect of scale, with the curves shifting leftward as the spatial frequency increases. In contrast, in periphery (Figure 2, lower panels) there is little effect of size on orientation discrimination (shown by gray symbols of different size in the bottom left panels) but a substantial effect of eccentricity (5 deg—gray symbols; 2.5 deg—red; 10 deg—blue). Crowding depends on eccentricity, not target size. Interestingly, there does appear to be an effect of size on the amount of threshold elevation for peripheral detection and contrast discrimination but not on the critical distance for contrast discrimination (Figure 4).

Figure 3 shows the effect of scale on orientation discrimination (left column), contrast discrimination (center column), and detection (right column) for each eye of several of the amblyopic observers (solid symbols—
amblyopic eye; open symbols—non-amblyopic eye.) For anisometropic amblyope GD (top), the data are similar to that of the normal observers, and the two eyes are also quite similar. In contrast, the strabismic amblyopic eyes are markedly different, showing a much smaller or no effect of spatial scale. This can be seen in the overlap of the data for different scales. To quantify this effect, we fit the threshold elevation vs. flank distance (FD) data for orientation and contrast discrimination with Gaussian functions (curves in Figures 1–3) of the form:

\[ \text{TE}_f = (1 + P^* (1 - \text{FD}/\text{CD})^2), \]

where \( \text{TE}_f \) is the flanked threshold elevation, \( P \) is the peak amplitude of the Gaussian (its height in threshold elevation units for a flank distance of zero), and \( \text{CD} \) is the critical distance—i.e., the flank distance that causes the amplitude to drop to half its peak value. Non-linear regression was used to estimate the two parameters, \( P \) and \( \text{CD} \) (Levi, Klein et al., 2002), and Figure 4 shows how these parameters depend on target size for both orientation (left columns) and contrast discrimination (right columns).

For normal fovea (open circles) and non-amblyopic eyes (open squares), the critical distance is more or less proportional to the target size (standard deviation). This is consistent with the results of Levi, Klein et al. (2002), who measured contrast thresholds for discriminating the orientation (left, right, up, down) of E-like patterns made up of Gaussian or Gabor patches, and Hariharan, Levi, and Klein (2005), who made similar measurements for a more compact C-like pattern. Note that the use of a single high-contrast patch in the current study allowed us to make measurements over a range that included much smaller pattern sizes; because each arm of the E-like patterns consisted of 5 patches, the E-like pattern was 15 times the Gaussian standard deviation. Similarly, for the C-like pattern, the target radius was 3.33 times the patch standard deviation. Most importantly, both the E- and C-like pattern data and the single Gabor patch results fall near the same unity slope line, suggesting that in normal foveal vision, the effects of flankers on orientation discrimination (whether coarse as in Levi, Klein et al., 2002 or fine as in the present study) has a critical distance of \( \approx 2.2 \) times the target standard deviation (black lines in the top panels of Figure 4). A similar size dependence is also evident for contrast discrimination with the normal fovea (Figure 4, top right).

Anisometropic amblyope (GD—green triangles) shows a similar scale invariance (data close to the unity slope line); however, for the normal periphery (5 deg—solid gray symbols) and strabismic amblyopic eyes (solid red and blue symbols), the critical distance shows much less (or no) dependence on target size (see also Levi, Hariharan et al., 2002b).

The middle panels in Figure 4 show how the magnitude of interaction depends on target size. For the normal fovea, fellow eye, and the amblyopic eyes of GD and SM, when the target is larger than \( \approx 0.2 \) deg, the peak amplitude is low (\( \approx 0.5 \)), increasing substantially when the target is small. On the other hand, for the periphery and the amblyopic eyes of most of the strabismic amblyopes, the amplitude is high (\( \approx 2 \)) over the range of sizes tested.

It is also worth noting that while the critical distance for orientation discrimination and contrast discrimination are quite similar for all eyes (near the 1:1 line—Figure 4, lower left panel), for the strabismic amblyopic eyes and normal periphery the amplitudes are quite different (smaller for contrast than for orientation—Figure 4, lower right panel).

**Varying target and flank contrast**

In the experiments described above, the target and flank contrasts were fixed (typically target contrast, \( T_c \) at 40% and flank contrast, \( F_c \) at 80%). Here, we varied both the flank and target contrasts. Adding flankers in foveal vision does not elevate thresholds for either orientation (triangles) or contrast discrimination (squares) but facilitates detection (circles). This can be seen in Figure 5 (top left), where threshold elevation versus \( F_c \) is shown for different values of \( T_c \) (coded by symbol size) for both a small (\( SD = 0.1 \) deg) high spatial frequency (10 cpd) target (black symbols) or a larger (\( SD = 0.4 \) deg) lower spatial frequency (2.5 cpd) target (gray symbols). In peripheral vision, unflanked orientation thresholds are about 50% higher (not shown), but flanked thresholds are elevated substantially more (Figure 5, top right). In peripheral vision, the flanker effect for orientation discrimination, as indexed by threshold elevation, is more or less independent of target contrast (Levi & Carney, 2009). Thus, thresholds begin to rise when the flanker contrast is just visible (at about 4%) independent of target contrast. Interestingly, in periphery, contrast discrimination thresholds are not elevated until the flankers are above \( \approx 10\% \) contrast, and then rise rapidly, while detection thresholds are more or less unaffected at all flank contrast levels.

The lower panels in Figure 5 show the effects of flank contrast on ambylopes’ orientation discrimination. Unlike the normal fovea, amblyopic eyes show threshold elevation increasing with flank contrast. The effect is smallest in anisometropic amblyope, GD (bottom right panel), but substantial in strabismic amblyopes. It can also be seen that the effect of target contrast is similar to that in the normal periphery. For example, GW and AW’s data show similar orientation threshold elevation when target contrast is 40% and 80%, and BN shows that low flanker contrasts affect orientation discrimination to a greater extent than contrast discrimination. Interestingly, in both peripheral and amblyopic vision, at these separations, flankers have either no effect, or actually facilitate detection (circles in Figure 5).
Figure 3. The effect of scale on orientation discrimination (left column), contrast discrimination (center column), and detection (right column) for each eye of several of the amblyopic observers (solid symbols—amblyopic eye; open symbols—non-amblyopic eye.)
Figure 4. (Top) The effect of target size on the critical distance (top panels) and amplitude (middle panels) for both orientation (left columns) and contrast discriminations (right columns). The black lines show critical distance = 2.2 times the target SD (top panels). The bottom panels compares the critical distances (left) and amplitudes (right) for orientation versus contrast discrimination. The dotted gray lines are the 1:1 line.
Varying flank size and distance

Under certain conditions, increasing the size of flankers results in a paradoxical decrease in the magnitude of crowding—i.e., the bigger the flanks, the smaller the crowding (Levi & Carney, 2009; Malania, Herzog, & Westheimer, 2007; Saarela et al., 2009). These results are consistent with a model in which the visual system extracts the centroids of ≈4 independent features within ≈0.5 times the target eccentricity and integrates them into a texture beyond the stage of feature analysis. Figure 6A shows that in normal periphery, fixing the inner edge of
Figure 6. Effect of flank size and distance. (A) Normal periphery, fixing the inner edge of the flankers and increasing their size, reduces threshold elevation for both orientation (diamonds) and contrast (squares) discriminations, while having no effect on detection thresholds (circles). (B) The data are replotted as a function of the center-to-center distance between target and flankers (triangles). (C) A similar effect of target size in the central field of a strabismic amblyope, and like peripheral vision, (D) the results can be explained on the basis of the distance of the target centroid. (E, F) Little effect of the flankers on the non-amblyopic eye. The lines in (F) are the fits to the amblyopic eye from (D).
the flankers and increasing their size reduces threshold elevation for both orientation (diamonds) and contrast (squares) discrimination, while having no effect on detection thresholds (circles). The solid symbols in Figure 6B replotted the data as a function of the center-to-center distance between target and flanks. Open symbols in Figure 6B are the peripheral data from Figure 1, obtained by fixing the flank size (width) and varying the target–flank distance. Both data sets superimpose when plotted in this way. Thus, we argued that it is the distance, not the size of the flankers that determines the strength of crowding (Levi & Carney, 2009). Figure 6C shows a similar effect of target size in the central field of a strabismic amblyope, and like peripheral vision, the results can be explained on the basis of the distance of the target centroid (Figure 6D). Figures 6E and 6F show little effect of the flankers on the non-amblyopic eye.

Varying the number of flanking elements

All of the experiments reported here used 4 segments of an annular surround as the flanking elements. In the normal periphery, increasing the number of flank segments from 1 to 4 substantially elevated orientation discrimination thresholds, following the prediction of linear integration of independent segments. However, increasing the number of segments from 4 to 8 (a full annular surround) actually resulted in slightly reduced crowding and substantially less than predicted by the integration theory (Levi & Carney, 2009). Figure 7 (top panel) shows a similar result in the central field of a strabismic amblyope who shows a substantial effect of flankers. Threshold elevation increases more or less in agreement with the prediction of linear integration of independent segments (gray dotted line), with threshold increasing in proportion to \( \sqrt{N} \) for \( N > 1 \) (\( N = 1 \) is taken as the measured elevation with a single flank) up to \( N = 4 \). For \( N = 8 \) (full surround with no gaps), threshold is elevated substantially less than the prediction. Interestingly, there is almost no effect of the flankers on the preferred eye, and very little effect on either eye for contrast discrimination (Figure 7, middle panel) or detection (Figure 7, lower panel). By placing the flankers at a substantial distance from the target (center-to-center distance of 1.8 degrees), we are able to more or less isolate the effect of the flankers to the orientation discrimination task.

There is a well-established anisotropy in peripheral crowding—the magnitude of crowding is stronger when two flanks are arranged radially rather than tangentially (Levi & Carney, 2009; Toet & Levi, 1992). No such anisotropy is evident in the central field of the amblyopic eye when comparing 2 flankers above and below the target (propellers) with two flankers on either side (bow ties), so we conclude that the anisotropy is a characteristic that is specific to peripheral crowding.

Discussion

Our goal was to try to better understand the factors that limit performance of a task in the presence of flankers in foveal, peripheral, and amblyopic vision, using identical stimuli and methods. In particular, to revisit the question of what limits performance of a task in the presence of flankers in each of these visual systems—a reduction of visibility (i.e., a form of masking) or crowding.

Four visual systems, 3 tasks

In the first experiment, we compared the effects of flankers (4 segments of an annular grating) at varying distances on orientation discrimination, contrast discrimination, and contrast detection for a Gabor patch (Figures 1–3) in four distinct visual systems. Figure 8 provides a succinct summary, showing the average threshold elevation for each of the 3 tasks for the “average” fovea, periphery (5 deg lower visual field), and anisometropic and strabismic amblyopes. Because there is considerable individual variation among amblyopes, we do not recommend that you try this at home, but the averaged data (i.e., the metric mean of the threshold elevations) do provide a reasonable qualitative view of the group differences. For the normal fovea, there is only a very small threshold elevation, similar in magnitude for orientation and contrast discrimination, at target–flank separations of 1 degree or less, and facilitation of detection at all separations. For anisometropic amblyopes, the results are similar; however, the threshold elevation at the smallest separation is larger (≈2 fold), and facilitation of detection turns to suppression at the smallest separation. We acknowledge the fact that two anisometropic amblyopes may not be sufficient to draw strong conclusions; however, our results are consistent with large-scale studies showing that the effect of flankers is different in anisometropic and strabismic amblyopes (Bonneh et al., 2004; Polat, Bonneh, Ma-Naim, Belkin, & Sagi, 2005) and that anisometropic amblyopia is like blurred normal foveal vision, while strabismic amblyopia is similar to peripheral vision (Levi & Klein, 1985; Song, Levi, & Pelli, in preparation). For both anisometropic amblyopia and normal fovea, the threshold elevation for orientation and contrast discrimination are similar and probably have the same basis—in visibility masking. For strabismic amblyopia and peripheral vision, threshold elevation is more substantial and is greater for orientation discrimination than for contrast discrimination, and facilitation of detection is smaller and is evident only at larger separations than in foveal and anisometropic vision.

Previous studies (Andriessen & Bouma, 1976; Levi, Hariharan et al., 2002a, 2002b) have suggested that the difference between the magnitude of threshold elevation for orientation discrimination and detection reflects the
Figure 7. Varying the number of flanking elements in a strabismic amblyope. (Top) Orientation discrimination threshold elevation increases more or less in agreement with the prediction of linear integration of independent segments (gray dotted line), up to \( N = 4 \). For \( N = 8 \) (full surround with no gaps), threshold is elevated substantially less than the prediction. There is almost no effect of the flankers on the preferred eye and very little effect on either eye for contrast discrimination (middle panel) or detection (lower panel).
effects of crowding (Figure 8, bottom right panel); however, the stimuli differ in their contrast, and detection is subject to the effects of uncertainty. We suggest that the difference between the magnitude of threshold elevation for orientation discrimination and contrast discrimination may better reflect the effects of crowding after accounting for visibility, and this difference is plotted for each of the 4 visual systems in the bottom left panel of Figure 8. For fovea and anisometropia, the difference is negligible; for periphery and strabismic amblyopia, it is substantial. On the other hand, when comparing orientation and contrast discrimination the stimuli are identical, and uncertainty is not a factor. It remains unclear whether this reflects the effects of different mechanisms (e.g., crowding vs. masking) or the differential effects of the same mechanism on different tasks.

The most notable feature of this figure is that even after taking into account the effects of flankers on contrast discrimination, in peripheral and strabismic amblyopic vision, flankers influence orientation discrimination over a substantial distance. This figure also helps to explain why under some conditions, threshold elevation for contrast and orientation discrimination are quite similar (e.g., periphery at large flank distances) whereas under other conditions, they are substantially different (e.g., periphery or strabismic amblyopia at small flank distances).

Remote flankers

The most obvious difference among the three tasks is that for each of the 4 visual systems, when the flankers are remote, detection is facilitated, while orientation and contrast discrimination thresholds may be either elevated or not affected at all. However, the effect of the flankers also depends on the target size/spatial frequency and on the type of visual system. Figure 9 is an attempt to summarize this. The three left panels show the threshold elevating effect of flankers that are remote from the target, with the distance specified relative to the target size (center-to-center distance = 4.5 times the target standard deviation/wavelength) for orientation discrimination (top), detection (middle), and contrast discrimination (bottom). The picture is actually complementary to Figure 4, which shows the effect of closely spaced flankers with the distance specified in degrees of visual angle. In Figure 9, regardless of the target size, the flankers were always separated from the target by 4.5 times the target size (standard deviation or wavelength).

Consider the top panel in Figure 9. When the flankers are remote, they have little or no effect on orientation discrimination in the normal fovea (open circles) or preferred eye of amblyopes (open squares) over the entire range of target sizes used here. This is also the case for the anisometropic amblyopes (green triangles). It is clearly not the case for either the normal periphery (solid gray circles) or for strabismic amblyopia (red and blue symbols). For these visual systems, threshold elevation is large with small target sizes and decreases as target size increases, as would be expected if flankers operate over a more or less fixed angular distance, as shown in Figure 4. This is a hallmark of crowding in peripheral (Bouma, 1970; Levi, Hariharan et al., 2002a; Pelli et al., 2004) and amblyopic vision (Levi, Hariharan et al., 2002b). We will consider the question of whether there is crowding in the normal fovea further below.

The two lower left panels in Figure 9 show that the effects of remote flankers are substantially smaller for both contrast discrimination and detection. This can be seen more directly in the two right-hand panels and suggests that these three tasks may have different limiting factors. Indeed, for detection (but not contrast discrimination), remote flankers induce substantial facilitation. There are three possible explanations for facilitation of detection:

1. Lateral interactions (e.g., Polat & Sagi, 1993, 1994) that occur outside the classical receptive field. Lateral interactions can reduce thresholds for low-contrast targets and elevate thresholds for high-contrast targets (Chen & Tyler, 2008).
2. Uncertainty reduction—i.e., flankers could reduce uncertainty for detection by indicating the location, spatial frequency, orientation, and/or phase of the target, which is not present for contrast or orientation discrimination (Levi, Klein et al., 2002; Petrov, Verghese, & McKee, 2006; but see Chen & Tyler, 2008). While uncertainty reduction may be one explanation for the facilitatory effect of flankers on detection, it cannot explain the strong inhibitory effects on orientation discrimination. Moreover, one would expect uncertainty to be greater in peripheral and amblyopic vision than in normal vision, which would predict more facilitation rather than less in these visual systems.
3. Pedestal effect. This explanation suggests that facilitation is a special case of the pedestal effect in masking (Solomon, Watson, & Morgan, 1999; Williams & Hess, 1998). For example, the high-contrast flanks, being located in the periphery of the cell’s receptive field, would behave like a low-contrast pedestal, resulting in facilitation. Both the facilitation in detection and the threshold elevation in contrast discrimination may be explained by the pedestal effect; however, the pedestal effect would only operate over a limited range of flank distances.
(related to the size of the receptive field), and it is not clear that it could explain the strong effect of remote flankers on orientation discrimination. The substantial threshold elevating effect of flankers on orientation discrimination with much smaller (or even opposite signed) effects on detection is consistent with extant studies of crowding in peripheral and strabismic amblyopic vision and has been explained on the basis that crowding occurs at a stage beyond the stage of feature detection (see Levi, 2008 and Pelli & Tillman, 2008 for reviews).

Our finding of a smaller effect of flankers on contrast discrimination than on orientation discrimination (under identical conditions) is somewhat surprising and a bit trickier to explain. We are aware of only one other study of the effects of flankers on both orientation and contrast discrimination (Saarela et al., 2009), and while the pattern of results was similar for the two tasks, they did not make a quantitative comparison of the magnitude of threshold elevation in the two tasks. Close inspection of their data suggests that for the identical flanker conditions, threshold elevation was substantially greater for orientation discrimination than for contrast discrimination. For example, with a single row of identical length flankers, orientation discrimination thresholds were elevated by ≈4-fold (Saarela et al., Figure 5b) compared with about a factor of 2 for contrast discrimination (Saarela et al., Figure 3b).

While it is simple to explain the differential effect of flankers on detection and feature discrimination based on crowding taking place downstream from detection, the differential effect of flankers on two different discrimination tasks seems, at least on a first glance, to challenge the two-stage explanation. Why would crowding affect some discriminations more than others? One possibility is that the way in which features are combined in the second stage may have different effects on different tasks. For example, combining the (horizontal) flankers with a (slightly tilted) target would increase the effective pedestal contrast, thus elevating contrast discrimination thresholds. However, the combined, jumbled orientations might also result in a large orientation bias (Solomon, Felisberti, & Morgan, 2004; Song & Levi, 2010), and thus elevate thresholds even more.

Is there crowding in the normal fovea?

Our foveal results, consistent with previous studies (Hariharan et al., 2005; Levi, Klein et al., 2002; all plotted in Figure 10), suggest that the effect of flankers on orientation discrimination in the normal fovea depends on target size (i.e., are scale invariant) and is qualitatively distinct from the effects in peripheral vision or strabismic amblyopia where they are more or less independent of target size, depending only on eccentricity (periphery) or visual angle (strabismic amblyopia). The near perfect scaling with target size (Figure 10) found in the fovea is not seen in the periphery until the stimulus blur exceeds the (very substantial) internal blur at that eccentricity. It is not yet clear whether the normal fovea is special. The fovea may appear to be special because it is subject to optical blur that is well matched to the neural limits of resolution. In the fovea, it has proven difficult to make the stimuli (i.e., target and flankers) smaller than the internal blur and still be able to measure a “critical distance” using letters. Our current thinking is that there is a genuine foveal crowding limit (illustrated by the horizontal red dotted line segment in Figure 10), with a critical distance of approximately 0.05 deg (3′), as shown by Toet and Levi (1992—see the T in Figure 10) and Danilova and Bondarko (2007). A similar critical distance is observed with foveal Vernier acuity targets that are small and impervious to blur (Levi et al., 1985; Westheimer & Hauske, 1975). Similarly, the critical distance for foveal orientation discrimination for a thin, high-contrast line is on the order of 3′ (Westheimer et al., 1976). It is very

![Figure 10. The effect of target size on the critical distance for foveal orientation discrimination. Circles and squares replot the foveal and non-amblyopic eye data of Figure 4. E’s and C’s replotted data from Hariharan et al. (2005) and Levi, Klein et al. (2002). The T is from Toet et al. The gray dotted line shows critical distance = 2.2 times target standard deviation (SD). The red dotted line represents the putative foveal crowding critical distance.](https://jov.arvojournals.org/pdfaccess.ashx?url=/data/journals/jov/933479/)
difficult to make visible Gabor patches or letters that are small enough to reach that limit. It would be interesting to explore foveal crowding using adaptive optics, which make it possible to resolve letters that are considerably smaller (Rossi & Roorda, 2010). One hint that our smallest foveal target (SD = 0.05 deg; SF = 20 cpd) may have been subject to crowding is that the peak amplitude (Figure 4, left center panel) is ≈3, approaching that of the periphery and strabismic amblyopic eyes.

The effect of flank contrast and the locus of crowding

We (Levi & Carney, 2009 and Figure 5 of the current paper) examined this by measuring the effects of flank contrast at different target contrasts (Figure 5). Like Pelli et al. (2004), we note that flanks become effective once they are visible. Our results show that it is also essentially independent of target contrast, both in peripheral and strabismic amblyopic vision (Figure 5). Thus, at low target contrasts (below ≈30%), the effect of flank contrast is essentially independent of target contrast. If flanks were to act at the level of individual features, one might expect that the crowding would depend strongly on both flank contrast and target contrast. On the other hand, if the crowding effect of the flanks takes place at a higher level (beyond that of individual features) where textural combination occurs, the effect of flank contrast should be independent of the contrast of the target feature.

The effect of flank size and the “faulty integration” hypothesis

In peripheral vision, fixing the inner edge of the flanks and increasing its size results in a paradoxical decrease in the magnitude of crowding, i.e., the bigger the flanks, the better the orientation discrimination (Levi & Carney, 2009 and Figure 6, top left panel). Here we show a similar effect in the central field of a strabismic amblyope (Figure 6, center left panel). A similar improvement also occurs for contrast discrimination, while under identical conditions, detection is essentially unaffected by the flanks.

Crowding is thought to reflect faulty integration of the target and flanks in peripheral vision (see Levi, 2008 and Pelli & Tillman, 2008 for reviews). The faulty integration model is based on the notion that crowding occurs because the visual system erroneously combines signals from the target and the flanks and that this combination is compulsory. At first glance, these results (bigger flanks reduce crowding) seem at odds with this hypothesis. However, we conclude that bigger is better in our experiment because of the change in the center-to-center distance of the flanks. Our data show that flanks with very different sizes have the same effect on threshold when their centroids are the same (right panels in Figure 6). For both periphery and strabismic amblyopia, the results can be explained by a model in which the visual system extracts the centroids of ≈4–8 independent features within a fixed distance and integrates them into a texture beyond the level of feature analysis (Levi & Carney, 2009 and see Figure 7).

The notion that “bigger is better” is not new. For example, Malania et al. (2007) reported that in foveal vision, adding more flankers in a Vernier task partially relieves “crowding,” so that thresholds are about halved when the number of flankers is increased from 4 to 8. More recently, Saarela et al. (2009; Saarela, Westheimer, & Herzog, 2010) found that increasing or decreasing the height of a horizontal row of flankers relative to that of the target decreased crowding on an orientation discrimination task and that varying the regularity of the spacing in multi-element stimulus arrays can modulate crowding. Thus, the faulty integration theory by itself is insufficient, unless grouping is taken into account: both grouping of the flankers themselves (Banks & White, 1984; Levi & Carney, 2009; Livne & Sagi, 2007, 2010) and grouping between the flanks and the target (Kooi et al., 1994; Malania et al., 2007; Saarela et al., 2009, 2010). Grouping, similarity, and context are important factors in determining whether the features are independent or not, and in our model, this modulates the strength of crowding. Thus, when the flanks are part of a coherent texture, they lose their effectiveness in crowding. We argue that the faulty integration model operates on independent features.

It is worth noting that recent experiments suggest that in normal peripheral vision a weighted average of noisily encoded target and flanker feature positions can predict both threshold elevation and biases (Greenwood, Bex, & Dakin, 2009) as well as changes in appearance (Greenwood et al., 2010).

Relationship to previous studies of flanker effects in amblyopia

Previous studies have examined the effects of flankers on acuity (Bonneh et al., 2004; Bonneh, Sagi, & Polat, 2007; Flom et al., 1963; Hess & Jacobs, 1979), Vernier acuity (Levi & Klein, 1985), letter identification (Chung, Li, & Levi, 2008), contrast detection for both luminance-defined (Polat et al., 2005; Polat, Ma-Naim, Belkin, & Sagi, 2004; Polat, Sagi, & Norcia, 1997) and contrast-defined (Wong, Levi, & McGraw, 2005) stimuli, and perceived contrast (Ellelmberg, Hess, & Arsenault, 2002) in amblyopia. While previous studies have measured the contrast threshold for identifying the orientation of the gap in a C-like (Hariharan et al., 2005) or E-like pattern (Levi, Hariharan et al., 2002b), the orientation changes were large (90 deg). In brief, these studies have shown that strabismic amblyopes show deleterious flanker effects over longer distances than normal observers (Bonneh et al.,...
Averaged across observers and conditions, the maximum facilitation is not very different from the normal fovea. For the normal fovea, averaged across observers and conditions, the maximum suppression is 1.0 (95% CI) for anisometropic amblyopia, the critical distance is 0.73 ± 0.03. For many (but not all) of the strabismic amblyopic eyes, the maximum suppression (abscissa) far exceeds that of the normal fovea, while the maximum facilitation is not very different from the normal fovea. Averaged across observers and conditions, the maximum suppression was 1.9 ± 0.74 (95% CI) for strabismic amblyopes and 1.28 ± 0.38 (95% CI) for anisometric amblyopes, while the maximum facilitation was 0.72 ± 0.06 and 0.66 ± 0.02, respectively. We note that an important difference between this study and previous studies of facilitation is that our stimulus consists of 4 annular flankers (two collinear with the target and two side by side), whereas previous studies have typically used a single pair of flankers, either side by side or collinear.

Clinical implications

In their classical study, Flom et al. (1963) estimated the extent of crowding by having normal and amblyopic observers judge the orientation of a Landolt C and varying the distance of surrounding flanks from the C. They found that the extent of crowding (i.e., the distance over which the flanks interfered with performance) was proportional to the observers’ acuity and concluded that crowding is related to the size of the receptive fields that are most sensitive to the target. Their results led to an important but largely untested principle of acuity chart design—that is the idea that letter spacing should be proportional to letter size in order to keep the effect of contour interaction consistent across acuity levels. This concept of proportional spacing is now a prominent feature of widely used clinical charts. Our results and those of others (reviewed above) show that proportional spacing charts in fact do not guarantee consistent contour interaction across acuity levels in patients with strabismic amblyopia or those who use peripheral vision due to macular degeneration. In strabismic amblyopia and peripheral vision, crowding is independent of target size, depending only on the distance between target and flankers.

Recent work (Chung, 2007) suggests that it is possible to reduce the effects of crowding in normal peripheral vision through perceptual learning. It will be interesting to see whether this approach might alleviate crowding in amblyopia too.

Summary and conclusions

Previous studies have examined the effects of flankers on contrast detection (Bonneh et al., 2004; Polat & Sagi, 1993, 1994), orientation discrimination (Felisberti, Solomon, & Morgan, 2005; Parkes, Lund, Angelucci, Solomon, & Morgan, 2001; Saarela et al., 2009; Solomon et al., 2004; Solomon & Morgan, 2000), and contrast discrimination (Chen & Tyler, 2008; Saarela et al., 2009), but to our knowledge, none have examined all three in the same observers with identical stimuli and methods. The current study allows a direct comparison in four distinct visual systems and enabled us to draw several new observations and conclusions:

1. For unflanked targets, the losses in peripheral and amblyopic vision (relative to the normal fovea) are ordered, with the loss of unflanked contrast discrimination thresholds considerably smaller than those for either detection or orientation discrimination.
2. For flanked targets, in normal foveal vision and anisometric amblyopia, the critical distance is more or less proportional to the target size, whereas in peripheral and strabismic amblyopic vision, the critical distance shows much less (or no) dependence on target size.
3. For the normal fovea, and anisometropic amblyopia, when the target is large (>0.2 deg) the amount of threshold elevation induced by flankers is low (<0.5), increasing substantially when the target is very
small. On the other hand, for the periphery and the amblyopic eyes of most strabismic amblyopes, the elevation is high (>2) over the range of sizes tested.

4. In peripheral vision and strabismic amblyopia, the flanker effect, as indexed by threshold elevation, is more or less independent of target contrast. In both peripheral and amblyopic vision, at these separations, flankers have either no effect or actually facilitate detection.

5. Remote flankers (4.5 times the target size or wavelength) have little or no effect on orientation discrimination in the normal fovea or anisometropic amblyopia but substantial effect on orientation discrimination in the normal periphery and in strabismic amblyopia, with much smaller effects for both detection and contrast discrimination. Indeed, for detection (but not contrast discrimination), remote flankers can induce substantial facilitation in peripheral and amblyopic vision.

6. In peripheral vision and strabismic amblyopia, fixing the position of the inner edge of the flankers and increasing their size reduces threshold elevation for both orientation and contrast discrimination, while having no effect on detection thresholds. These results are consistent with a model in which the visual system extracts image statistics of independent features over a large distance (~0.5 E in the periphery) and integrates them into a texture (Nandy & Tjan, 2010) beyond the stage of feature analysis.

7. A particular focus of this study was to revisit the question of what limits performance of a task in the presence of flankers in each of these visual systems—a reduction of visibility (i.e., a form of masking) or crowding. Our results show clearly that the effects of flanks depend on both the task and the type of visual system. In normal foveal vision and anisometropic amblyopia, the effects of flankers largely reflects a reduction in visibility and may be explained by masking. On the other hand, in peripheral vision and strabismic amblyopia, the effects of flankers on orientation discrimination and to a lesser extent contrast discrimination cannot be explained by simple masking and are due to crowding.

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