Foveal contour interaction: detection and discrimination

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Contour interaction, the detrimental effect of flanking features on the discrimination of optotypes, has been studied mainly close to the visual acuity limit. We were interested to know how these results compare with those for the detection of targets. According to the simplest model of contour interaction, comparable detection effects would be expected. The case for low-level masking would be further strengthened if the form and nature of the dependence on flank separation and flank polarity followed that typically found in studies of lateral spatial masking [Vision Res. 33, 993 (1993)]. Landolt Cs subtending a visual angle of 0.25°, 0.5°, and 1.0° were presented and contrast thresholds for detecting the presence of the Landolt C and discriminating its orientation were measured in five normal subjects as a function of flank separation and flank polarity. The results obtained for the relationship between detection and discrimination depend on the size of the target used. For small letters, discrimination but not detection was significantly affected by flanking bars. For large letters, detection and discrimination were affected to the same extent. However, in this case the effectiveness of opposite-polarity flanks and the finding that facilitation occurred at close, not far, flank separations suggests that the simplest explanation in terms of masking may not be applicable. © 2005 Optical Society of America


1. INTRODUCTION

Identification of an optotype is affected by the presence of adjacent contours. This effect is known as contour interaction in general1 and as crowding in particular, in the situation of letter–letter interactions.2 In clinical practice this is an important consideration when visual acuity is measured with charts that have different optotype separations. The effect is especially important in cases of amblyopia and for patients with central scotomas, because they experience exaggerated crowding.1,2

Contour interaction and crowding were first noticed in peripheral viewing3,4 and in amblyopia.2,5 Its effect, however, is also present in the normal fovea but extends only up to 4 arc min away from a target at the visual acuity limit1 or 1.5–2 times target size6,7 compared with up to half the eccentricity in peripheral viewing.4,7,8 This difference and the lack of attentional influences on foveal contour interaction have led some to consider it to be qualitatively different from peripheral contour interaction.9 Despite investigations of the psychophysical aspects of contour interaction, there are still important unresolved issues, especially for foveal contour interaction. Here we investigate whether the low discriminative performance in the presence of adjacent flanking stimuli, which is the hallmark of contour interaction, can be explained by an inability to detect the target as a result of lateral spatial masking. The fact that previous studies have not explicitly compared detection with discrimination for the same stimulus means that this simple explanation has never been assessed. If detection and discrimination were affected similarly as flanks approach a target, it would solidify the case for this particularly simple model of low-level masking for foveal contour interaction. If contour integration were due to low-level masking, then one would also expect to see masking at small flank–test distances and facilitation at large flank–test distances.10 Also, such effects should be absent when flank and target are of opposite polarity.11,12

A. Detection versus Discrimination

Most previous studies of contour interaction have quantified the magnitude of contour interaction in terms of letter identification. In the original experiments of Flom and co-workers1 the measure was the discrimination of the orientation of a Landolt C, a standard optotype for visual acuity assessment (see Fig. 1). Very few studies of foveal contour integration (where spatially broadband stimuli are traditionally used) have used a simple detection measure,11 and no studies have compared simple detection with discrimination for such a broadband target. Solomon and Morgan compared detection with discrimination for a spatially narrowband target (i.e., a Gabor patch, a strip pattern with soft borders, referred to here-
after as “Gabor” and found discrimination deficits due to adjacent flanking Gabors that could not be accounted for by a knowledge of the detectability of the target. The study of Levi et al. also compared detection with discrimination and came to the opposite conclusion, although a different measure was used for detection and discrimination (orientation versus direction). Thus it is unresolved whether the reduced detectability of flanked targets is the main reason for their reduced discriminability. Such a comparison is potentially important for evaluating this simple model involving low-level masking. If true, in addition there should be predictable detection effects that depend on flank distance and polarity.

### B. Letter Size

Most previous studies of contour interaction have quantified the effect in terms of the limit of resolution. More recently contrast detection has been used for letters that are much larger than the resolution limit. The form of the interaction has been shown to depend on letter size in some studies but not others. This issue needs to be resolved because it, too, has a bearing on whether the underlying effects are mediated by a unitary mechanism and whether they are due to masking or feature integration. Large letters enjoy a larger-scale support because the higher spatial frequencies that define their edge features are easily detectable (i.e., they are suprathreshold). The underlying spatial tuning function for contour interaction is much broader in the case in which larger letters are used, and this implies combination of information from what are believed to be narrower low-level channels. Thus for larger letters it remains a possibility that detection and discrimination will be affected differently.

### C. Polarity

The effect of the contrast polarity of the adjacent flanks on contour interaction appears to be more complicated than predicted from low-level masking. Low-level masking should follow a linear filtering prediction in that only like polarities of target and mask should interact. The actual result is not so clear cut and depends on letter size. For small letters at the resolution limit the simple linear filtering prediction is followed, but for large targets flanks of either polarity produce interference, although differences in the spatial tuning of like- and opposite-polarity flanks have been delineated.

In the present study we investigate the adequacy of the low-level-masking explanation for contour interaction by comparing detection and discrimination measures as a function of the distance between flanks and Landolt C target for stimuli of different polarity and absolute size. The results suggest that the simplest explanation based on low-level masking cannot account for all of the results. The relative contributions of masking and feature integration may vary with the size of the target and the polarity of its flanks.

### 2. MATERIALS AND METHODS

#### A. Stimulus

Stimuli consisted of a Landolt C of variable contrast, flanked by high-contrast bars. They were presented on a NEC XP17 monitor that was controlled by a Cambridge Research Systems VSG2/3 graphics card, which implements a resistor network to sum digital-to-analog converter outputs and allows a pseudo-12-bit representation of gray levels after gamma correction. All stimuli were presented in interlaced mode with a frame rate of 100 Hz such that the low-contrast Landolt C was drawn on a page of video memory different from that of the higher-contrast flanking elements. The display alternated between these two pages at the frame rate and the lookup tables were adjusted accordingly for each page. This allowed us to display the low-contrast Landolt-C target with high-contrast resolution (12 bits) in the presence of high-contrast flanking bars ($\Delta L/L_{\text{background}} = 0.5$). On the other hand, this setup limited the maximum contrast for flanks and target to 0.5.

The Landolt C stimuli (Fig. 1) had a total diameter of 25 mm and a stroke width of 5 mm on the monitor. A 5-mm-wide gap was inserted into the annulus at the top, bottom, left, or right position. The Landolt C was always presented with variable negative contrast, i.e., darker than the mid-gray background ($L = 10 \text{ cd/m}^2$). Flanks consisted of four bars, each 5 mm × 25 mm, positioned at separation (b) of 0, 0.5, 1, 2, and 4 bar width (a). Flanks had either maximal negative contrast (black bars, same polarity as the Landolt C) or positive contrast (white bars, opposite polarity).

After presentation of a fixation target the stimuli were presented foveally for 500 ms at different viewing distances: 1.45, 2.90, and 5.80 m. The diameter of the Landolt C subtended a visual angle of 0.25°, 0.5°, and 1.0°. The resolution limit for this task is $\sim 1.2$ arc min for the gap, i.e., 6 arc min for the C; thus the target was a factor 10, 5.0, and 2.5 times the acuity limit. Smaller stimuli could not be used, because even at maximum contrast it was not possible to discriminate the Landolt C with abutting bars.

#### B. Procedure

Contrast thresholds for detecting the central Landolt C and discriminating the orientation of its gap were mea-
sured in independent runs, because these thresholds were too different to be covered with one set of stimulus contrasts.

The detection task consisted of a 2-alternative temporal forced-choice (AFC) method. The subject had to judge which of two consecutive presentations, both showing the same bars, contained the Landolt C. A single-interval, 4-AFC method was used for the discrimination task. The subject had to judge the orientation of the gap in the Landolt C (i.e., top, bottom, right, left).

Most previous studies on contour interaction have used a percent-correct measure to quantify the effect of flanks. For two reasons, this is not suitable in our study, which compares detection with discrimination. First, the 2-AFC detection task has a 50% guess rate, which differs from the 25% guess rate of the 4-AFC discrimination task. Second, a difference in slope of the psychometric functions for detection and discrimination would further bias a percent-correct measure. Therefore it was necessary to derive contrast thresholds from psychometric functions fitted to the subject’s responses. Contrast thresholds have previously been used successfully in contour interaction for numbers, letters, and Landolt Cs.

In detection and discrimination tasks, the contrast of the central target was adjusted in a staircase procedure. For detection, contrast was reduced by 20% after three correct answers and for discrimination after two correct answers; in both tasks contrast was increased by 25% after every wrong response. The staircase ended after a minimum of 16 staircase reversals for detection and 32 reversals for discrimination. This resulted in at least 70 and 90 presentations, respectively. For each stimulus condition, data were fitted by a Weibull function and the fitting parameter \( \alpha \) was defined as the contrast threshold. This corresponds to 81% correct for detection (50% guess rate) and 72% correct for discrimination (25% guess rate). Data were read into the SPSS 11.0 for analysis and plotting. Analysis of variance for repeat measures (i.e., within subjects) was performed on the data; \( p < 0.05 \) was considered significant.

C. Subjects
Five subjects with normal vision and best-corrected visual acuity of 1.0 or better participated in the study.

3. RESULTS

Discrimination and detection contrast thresholds are plotted as a function of bar separation. Mean data of all five subjects will be presented together with 95% confidence intervals.

Figures 2(a)–2(c) show discrimination and detection thresholds for Landolt Cs of three different sizes (0.25°, 0.5°, and 1.0°) flanked by same-polarity bars. Absolute thresholds for unflanked conditions were roughly doubled when target size was halved. Bringing in the bars did not significantly change the discrimination threshold at 2- and 4-gap separation. Maximum threshold elevation was seen with abutting bars. Detection thresholds did show qualitative differences that depended on the target size. At bar separations of 2× gap or less, flanks did have a significant facilitatory effect of 20%–30% on the detection task for the smallest Landolt C [Fig. 2(a)]. On the other hand, detection of the medium-sized and large targets was not significantly changed by adjacent bars [Figs. 2(b) and 2(c)]. These findings suggest a differential effect of same-polarity flanks on detection and discrimination that is dependent on target size. Thus it is clear that detection and discrimination can be differentially affected, particularly for smaller letter sizes.

To gauge the influence of letter polarity on the relationship between detection and discrimination for contour interaction, we measured contrast thresholds for opposite-polarity flanks [Figs. 2(d)–2(f)]. For all three Landolt sizes, the discrimination curves were qualitatively similar to those with same-polarity bars. However, the overall threshold elevation was less marked when opposite-polarity bars abutted the target. Detection threshold changes were not statistically significant for any stimulus size.

Detection thresholds showed marked differences compared with results for same-polarity bars. At small target sizes [Fig. 2(d)] there was little, if any, facilitation and even a slight threshold elevation with abutting bars. However, these changes were not statistically significant in this group of five subjects. For medium-sized stimuli, facilitation of detection thresholds was nearly significant with opposite-polarity flanks at separations of 0.5 and 1 gap [Fig. 2(e)]. Detection thresholds for large Landolt Cs [Fig. 2(f)] did not show any significant change with opposite-polarity bars. Thus opposite-polarity flanks may be effective at mediating contour interaction for all three letter sizes studied, although their effects on the detectability of the target differ from those of their same-polarity counterparts.

To get a better understanding of the effect of flank polarity and letter size on contour interaction, we replotted the results of Fig. 2 in terms of the total magnitude of the interaction (Fig. 3). The total magnitude of contour interaction was defined as the maximum discrimination threshold elevation, i.e., the ratio of discrimination threshold with abutting bars to discrimination threshold without bars. The overall effect of contour interaction in the fovea was rather small. Same-polarity flanks increased discrimination thresholds by 30%–70% and opposite-polarity flanks only by 10%–45%.

There were no significant differences between the maximum threshold elevation for the small and medium-sized Landolt Cs. However, data for the large stimulus showed less contour interaction (paired \( t \) test for same-polarity bars was \( p = 0.04 \)). The magnitude of contour interaction was consistently smaller for opposite-polarity bars than for same polarity at all target sizes but did not reach statistical significance for any target size (paired \( t \) test) or for the pooled data across all sizes (\( p = 0.06 \)).

Figure 4 summarizes the data displayed in Fig. 2 in terms of the relation between discrimination and detection for (a) same and (b) opposite-polarity bars, each for three different target sizes. We plot the ratio of discrimination threshold to detection threshold as a function of bar separation. Large and medium-sized unflanked Landolt Cs need 40% more contrast for discrimination than for detection (ratio = 1.4); small Landolt Cs need
80% more contrast [Fig. 4(a)]. Same-polarity flanks do affect discrimination and detection of large Landolt Cs equally; thus the threshold ratio does not change (dotted curve, ratio 1.3–1.6). The discrimination of medium and small targets, however, is affected much more by flanks than is detection, and the ratio rises to 2.4 and 3.6, for abutting bars (dashed and solid curve, respectively).

For opposite-polarity flanks the picture looks somewhat different [Fig. 4(b)]. The sharp rise in discrimination-to-detection ratio with bars close to the target is missing. This reflects the smaller elevation in discrimination threshold and especially the elevation of detection thresholds by opposite-polarity flanks [Fig. 2(d)]. For the medium-sized Landolt C the dashed ratio curve in Fig. 4(b) shows a sharp rise near 0.5 and 1 gap separation that is caused by the facilitation of detection thresholds present at that separation [Fig. 2(e)]. Again the large Landolt C has the lowest discrimination-to-detection ratios of all three stimulus sizes.

4. DISCUSSION

We measured foveal contrast thresholds for detection and discrimination of Landolt Cs of different sizes flanked by bars of different polarities. We found only slight quantitative differences in discrimination thresholds between these conditions. However, detection did show a greater dependence on stimulus size and flank polarity. This resulted in differences between detection and discrimination performance, which in turn has implications for the mechanisms underlying contour interaction. The main findings can be summarized as follows:
1. For large targets, there is only a small contour interaction effect, and it affects detection and discrimination equally and does not depend critically on the relative polarity of the target and flanks.

2. For smaller letters, with same-polarity flanks the closer the flank, the more discrimination is differentially affected compared with detection.

3. For opposite-polarity flanks, discrimination is also differentially affected compared with detection but to a lesser degree.

These results show that detection and discrimination of the same target within a contour interaction paradigm are not always affected equally, and hence their interrelationship is complex, depending as it does on both letter size and flank polarity (relative to that of the target). To that extent, one of the simplest low-level-masking models of contour interaction based on the detectability of the target can be ruled out. To this extent our conclusions, especially for small-sized targets, mirror those of Solomon and Morgan. Although the discrimination of large Landolt Cs can be predicted from a knowledge of their detectability in accordance with the results of Levi et al., the associated dependency on flank polarity is not what one would expect from lateral spatial masking. For smaller targets, the way in which target discrimination is affected bears no simple relationship to its detectability. This rules out the simplest model of low-level masking in which the reduction in target discriminability due to adjacent flanks follows simply from its poorer detectability. It does not rule out more complex models of low-level masking where either the mechanisms or the information underlying detection and discrimination differ. It does suggest that the mechanisms responsible for detection and discrimination of broadband, sharp-edged stimuli may not be the same.

A. Magnitude of Foveal Contour Interaction

Our present results show that stimulus size and relative polarity of the flanks seem not to affect greatly the overall amount of threshold elevation seen in foveal contour interaction. Although we found a significant difference between small and medium-sized Landolt Cs of 30% (Fig. 3), there was no difference between our medium and large targets. Other studies have reported threshold elevations for targets at the acuity limit, i.e., much smaller than our stimuli. Contrast threshold elevation has been used in some more recent studies as a measure of contour interaction for larger targets. In this study we found a 70% mean threshold elevation for discrimination for small and medium-sized Landolt Cs flanked by same-polarity bars. This corroborates data of previous studies where the elevation has been 50% for 0.5° Landolt C. Strasburger et al. were the first to use contrast thresholds to quantify crowding. With foveal presentation, they did not find a significant change of threshold with character sizes 0.06°–1.0° when flanking elements were brought in. However, with eccentric viewing (4°) a
100% threshold elevation was present. Chung et al.\textsuperscript{6} used filtered letters of size 0.32° to test foveal contour interaction. They found a maximal contrast threshold elevation by flanking filtered letters of 70%–100% for some spatial frequencies.

Changes in foveal visual resolution due to crowding are small for high-contrast stimuli. Jacobs\textsuperscript{16} found a 0.18 log MAR, Flom\textsuperscript{1} a 0.12–0.2 log MAR decrease in visual acuity with flanked Landolt Cs, and Simmers\textsuperscript{17} a 0.12 log MAR decrease with letters flanked by bars. To compare these threshold data and percent-correct data, the slope of the psychometric function has to be taken into account. A drop in performance from 80% to 20% correct was seen by Flom et al.\textsuperscript{1} at the visual acuity limit with bars at the critical distance. Considering a typical Weibull function with a slope of 4.0 ($\beta = 4.0$) this percent-correct change would translate to an elevation of resolution threshold of 0.2 log MAR. Hess et al.\textsuperscript{19} measured percent correct for foveal contour interaction with low-contrast Landolt Cs that had 0.6° diameter and reported a drop from 92% to 45% correct with abutting bars, which translates to a 40% drop in contrast threshold if a slope of 4.0 was considered.

So in summary, most studies agree that the magnitude of foveal contour interaction is rather small (less than a factor of 2) and is present only with flanks very close to the target.

B. Detection versus Discrimination
Mere detection of an object (e.g., letter) does not allow identification of that object. Several features of the object have to be first detected and then integrated in subsequent processing to allow discrimination or identification.\textsuperscript{24}

1. Unflanked Landolt C
We found that discrimination thresholds for unflanked Landolt Cs were 1.4 times the detection threshold for large and medium-sized targets. The contrast for the discrimination of the small Landolt C had to be 1.8 times higher than for detection. This may reflect the fact that higher spatial frequencies are required for discriminating the orientation of the gap compared with detecting the lower spatial frequencies representing the Landolt C as a whole.

In an unpublished pilot study we looked at the contrast sensitivity function for detection and discrimination of Landolt C of different sizes in normal subjects. At high spatial frequencies, thresholds were equal or only up to 30% higher for discrimination. However, at lower spatial frequencies, i.e., less than 1 cycle per Landolt C, thresholds for detection did not drop as they did for discrimination. Thus detection is subserved by a much broader spatial-frequency range.

The diameter of the Landolt C (0.25°) corresponds to the peak of the contrast sensitivity function ($\approx 2$ c/deg). Finer features (i.e., gap size 0.05°) correspond to higher spatial frequencies for which our contrast sensitivity is reduced. Thus contrast must be relatively higher to allow discrimination of the gap of a small Landolt C in comparison with that of a larger Landolt C for which the gap spatial frequencies are closer to the peak of the contrast sensitivity function.

Most previous studies that have compared detection with discrimination have used grating stimuli.\textsuperscript{24–26} Coarse discrimination of spatial frequency and orientation is possible at detection threshold, but for fine discrimination, contrast has to be higher than for detection threshold. Data comparing detection and identification thresholds for complex stimuli such as letters or Landolt Cs are scarce. Higgins et al.\textsuperscript{22} found that discrimination thresholds for small letters (13 arc min) was 2.5–4 times detection threshold for the same stimuli, thus higher than for our small Landolt C (15 arc min).

2. Flanked Landolt C
In the flanked situations, discrimination thresholds showed small quantitative differences but no significant qualitative difference for different target sizes and flank polarities. On the other hand, detection thresholds exhibited a great deal of variation. We found facilitation for small targets flanked by same-polarity bars [Fig. 2(a)] and medium targets flanked by opposite-polarity bars [Fig. 2(c)]. Furthermore, large targets flanked by same-polarity bars [Fig. 2(e)] and small targets flanked by opposite-polarity bars [Fig. 2(d)] exhibited inhibition.

In a lateral masking experiment with Gabors, Polat and Sagi\textsuperscript{19} found inhibition and facilitation for detection of the central Gabor depending on the distance between the target and its two flanking masks. At separations less than twice the wavelength of the grating, contrast thresholds for detecting the central element were increased up to 0.4 log unit. At larger separation up to 6–12 wavelengths, detection thresholds were reduced by up to 0.3 log unit. A recent result for detection within a contour interaction paradigm\textsuperscript{15} also suggests that facilitation occurs at large flank–test separations. This finding does not generalize to Landolt-C targets because we show here that facilitation is confined to small targets at close flank–target separations. The low-level lateral masking effect previously demonstrated with Gabors has also shown to be polarity specific.\textsuperscript{11,12} Although the contour interaction dependencies are different for same- and opposite-polarity flanks, both polarities produce sizable contour interaction, arguing against any simple low-level-masking prediction based on what we know of lateral spatial masking.

C. Low-Level-Detection Processes
Our aim in this study was to reveal to what extent low-level-detection processes contribute to, and offer a suitable explanation for, foveal contour interaction. This bears on one of the simplest explanations of contour interaction: At the lowest level of visual processing (i.e., simple detection), oriented spatial frequency components in the adjacent high-contrast flanks mask the detection of comparable components in the target; it is this effect alone that renders the identification and discrimination of the target difficult. This explanation would be based on the assumption that there is a unitary mechanism for detection and discrimination and that lateral spatial masking is solely responsible. The contour interaction that we
measured for the larger letter showed the strongest support for a unitary underlying mechanism because detection and discrimination were affected equally, consistent with a masking explanation. However the interaction did not exhibit a strong polarity dependence, as one would have expected if masking were the correct explanation.

One problem in comparing masking and contour interaction in the literature is that different stimuli are used in these two situations. Letters and Landolt Cs are the traditional stimuli for contour interaction experiments, whereas gratings are preferred for investigations of masking. Levi et al. tried to bridge those two fields and designed a stimulus that combined aspects of both approaches. The strokes of a tumbling “E” and four flanking bars were made of five collinear Gabor patches each. Detection of a single Gabor flanked by two Gabors showed similar flank contrast properties and the same dependence on flank separation as orientation discrimination of the E. Levi concluded that “foveal crowding is simple contrast masking.” This result is consistent with our findings for large Landolt Cs (the smallest target used by Levi et al. corresponded to the largest one used in the present study) for which discrimination thresholds (contour interaction) parallel detection thresholds (masking) when flanks are presented close to the central target.

D. Higher-Level-Discrimination Processes

Our results for smaller Landolt Cs are not compatible with the simplest explanation based on low-level masking of a unitary underlying mechanism. In this case, the relationship between detection and flank distance is of a form very different from that found for discrimination. At the same flank distance, detection can be facilitated and discrimination inhibited. The lack of a simple relationship between detection and discrimination suggests that the mechanism responsible for detecting the stimulus is different from that underlying its discrimination. This does not in itself allow rejection of the masking explanation, but it does make it difficult to evaluate the masking explanation by simply comparing detection and discrimination functions.

These conclusions for smaller stimuli are supported by a number of previous studies. Chung et al. investigated the spatial-frequency and contrast properties of crowding in the fovea and at 5° eccentricity in order to evaluate a masking explanation. They found broader tuning curves than expected from simple masking, and, more significantly, differences were found between the spatial extent of crowding and that of masking. The spatial extent was much larger than expected from masking and did not scale with the spatial frequency of the stimulus, as expected from lateral masking experiments. Flank contrast, too, had an effect different from that expected from simple masking; no facilitation was seen at low contrasts in crowding, and there was less dependence of threshold elevation on flank contrast. Chung and co-workers concluded that crowding and masking share qualitatively different aspects but differ in some important quantitative aspects.

Another study that looked at the effect of flank contrast on target thresholds was that of Palomares and co-workers. They, too, found a function different from that expected on the basis of simple masking: sigmoidal rather than the expected linear masking function. In addition the spatial extent of crowding was ten times larger than that of masking by noise at an eccentricity of 4°.

The size of the letters in both of these previous studies was similar to our small Landolt C (0.25°): 0.32° for Chung’s foveal letters and 0.25° in the Palomares study. Their conclusions agree with ours for small stimuli: Contour interaction is unlike masking. It would be interesting to know whether their results are dependent on stimulus size as ours are.

Our study suggests that the explanation for foveal contour interaction cannot be due simply to the reduced detectability of the target in all cases. Target size is an important consideration. The detectability explanation is stronger for large compared with small targets. However even for large targets, an explanation based on reduced detectability due to simple masking may not be the whole story, because flank–target interaction is still present for flanks of opposite polarity. To go beyond this rather simple detectability model and evaluate the adequacy of a low-level-masking explanation in general will require a detailed knowledge not only of what information is needed to accomplish these discriminations but also of what underlying mechanisms are responsible.

Finally, some of the present discrepancies in the literature concerning the applicability of simple masking to contour interaction and crowding may be reconciled by taking into account the different-sized targets used in these studies.

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