

Contour interaction in fovea and periphery

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It has been known for some time that both foveal and peripheral visual acuity are higher for single letters than for letters in a row. Early work showed that this was due to the destructive interaction of adjacent contours (termed contour interaction). It has been assumed to have a neural basis, and a number of competing explanations have been advanced that implicate either high-level or low-level stages of visual processing. Our previous results for foveal vision suggested a much simpler explanation, one determined primarily by the physics of the stimulus rather than the physiology of the visual system. We show that, under conditions of contour interaction or crowding, the most relevant physical spatial-frequency band of the letter is displaced to higher spatial frequencies and that foveal vision tracks this change in spatial scale. In the periphery, however, beyond 5°, the physical explanation is not sufficient. Here we show that there are genuine physiological lateral spatial interactions, which are due to changes in the spatial scale of analysis. © 2000 Optical Society of America [S0740-3232(00)01708-7]

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1. INTRODUCTION

It is well known that the best acuity is obtained with single letters.¹⁻⁴ This is true for the fovea² and the periphery.^{2,5} The detrimental effect of the proximity of nearby letters or contours³ is referred to as contour interaction in the visual literature. A number of authors have speculated that it is due to either limitations at a low level of visual processing^{2,6-9} or attentional influences at a high level of visual processing.^{4,10} The former can be thought of as either the lateral inhibition within a single detector or inhibitory influences from distant neurones, an interpretation for which there is anatomical¹¹ and physiological¹² support. Recently, we¹³ have shown that there is a much simpler explanation for foveal vision, one based primarily on the physics of the stimulus, not the physiology of the visual system. Here we ask whether this simple physical explanation also holds for peripheral vision. Since Flom and colleagues² showed that a similar form of interaction occurs in fovea and periphery, there is every reason to believe that it might hold. On the other hand, a number of studies^{3,4,14} have highlighted differences in contour interaction between fovea and periphery that might suggest that a common explanation would not suffice.

2. METHODS

A. Apparatus

An Apple Macintosh computer controlled stimulus presentation and recorded subjects' responses. Programs for running the experiment were written in the MATLAB programming environment (MathWorks Ltd.) with Psychtoolbox code.¹⁵ Stimuli were displayed on a 21-in. Nanao FlexScan monochrome monitor, with a frame refresh rate of 75 Hz. Pseudo 12-bit contrast accuracy was achieved by electronically combining the red-green-blue outputs from the computer with a video attenuator.¹⁶

B. Stimuli

Landolt C stimuli were based on an annulus with a stroke width of 30 pixels and a total diameter of 150 pixels. A 30-pixel-wide gap was inserted into the annulus at the top, bottom, left, or right position on the annulus. Outline edges of the figure were not antialiased. In the flanked conditions, two horizontal (150 × 30 pixel) bars were positioned above and below the C, and two vertical (30 × 150 pixel) bars were positioned to its left and right. Flank distance was defined as the distance from the edge of the bar closest to the C to the outer edge of the annulus defining the C. The standard stimulus appeared on a midgray (45 cd/m²) background. Flanks appeared either black (same contrast polarity condition) or white (90 cd/m²; opposite contrast polarity condition). Figure 1 shows a subset of the stimuli used.

In the filtering condition, patterns were spatially band limited by being filtered (after they were positioned centrally within a 256-pixel-square window) with an isotropic Laplacian-of-Gaussian filter:

$$\nabla^2 G(\sigma) = \left(1 - \frac{x^2 + y^2}{2\sigma^2}\right) \exp\left(-\frac{x^2 + y^2}{2\sigma^2}\right). \quad (1)$$

Images were normalized, to maximize Michelson contrast, before presentation. The range of filtering tested was $\sigma = 4.78$ to 18 pixels. At the foveal viewing distance, one pixel subtended 7.8 for subject RFH, 6.2 for subject NK, and 5.5 for subject MT.

The above filter defined a spatial-frequency region where local phase components were allowed to pass unaltered. Outside this specified passband, phase components were scrambled (thus the filter was stochastic). Scrambling was achieved by randomizing the phase component of the image (while maintaining local power) at certain spatial frequencies. We did this by forward Fourier transforming the stimulus into the familiar complex representation of phase and amplitude. We then defined a hard-windowed annulus whose center was aligned with

the middle of the Fourier plane (i.e., the dc term at 0 cycles per image). Values falling within the range of spatial frequencies defined by the annulus were not altered. Values falling outside the annulus had their phase component replaced with a random value from 0° – 360° while retaining local amplitude. (Note: The Fourier description of a real image with no imaginary component will have the property of Hermitian symmetry.¹⁷ Our randomization procedure maintained Hermitian symmetry so that the result, when back transformed, would contain no imaginary components.) Finally, the Fourier description was back transformed. The resulting image has the same global amplitude spectrum as the original; only the phase structure has been altered. An example of such filtering is seen in Fig. 2 for an unflanked Landolt C.

C. Procedure

Subjects—three of the authors who had extensive practice on the task—performed a single-interval four-alternative forced-choice task. Summary results were also obtained on two other subjects. They were presented with a Landolt C stimulus for 500 ms and were required to judge whether the gap was in the top, bottom, left, or right position. Subjects were trained to maintain fixation during peripheral presentations. Eye movements were not monitored in subsequent experiments. We first measured subjects' ability to perform this task with unflanked C's at a variety of viewing distances in order to determine the minimum angle of resolution (mar) of the gap for each subject for this task. The viewing distance that produced 85–95% correct gap-position discrimination was then used for foveal testing (this performance range was selected to avoid ceiling and floor effects). For subject RFH the viewing distance used was 8.6 m, for subject NK it was 10.8 m, and for subject MT it was 13.1 m. This corresponds to a minimum angle of resolution (i.e., gap width) of 0.024° for RFH, 0.019° for NK, and 0.017° for MT. Eccentricity (the nasal field) and viewing distance

covaried so that performance for the unflanked letter remained approximately constant.

Runs consisted of 100 trials, but breaks were taken within runs to alleviate the effects of fatigue. Graphs show percent correct performance. Typical error bars (denoting two standard deviations) are shown in frame A of each composite figure. We collected responses for the correct identification of the position of the gap (up, down, right, or left) as well as for the correct orientation (horizontal or vertical). A comparison of these two allows one to estimate the importance of positional uncertainty in the task.

D. Modeling

The procedure for predicting the spatial frequency used to perform the task is based on the idea that performing the position discrimination task involves two subtasks. First, one determines the orientation of the gap (either horizontal or vertical) and then one determines its position (either left/right or above/below). The first stage is assumed to be the point at which spatial-frequency selection takes place. If that is true, Bondarko and Danilova,¹⁸ reasoned, then the most sensible spatial frequency for subjects to use when performing the position discrimination task is one that maximizes the difference in Fourier power at horizontal and vertical orientations. This can be determined by simply computing the discrete Fourier power spectrum of a stimulus, plotting the absolute difference between the horizontal and the vertical components (as a function of spatial frequency), and selecting the frequency that maximizes this function. In so doing we assume that the visual system has access to a single spatial-frequency band and that summation across scales does not underlie this task.

3. RESULTS

Before entertaining the previous neural proposals for the contour interaction effect, Hess *et al.*¹³ considered a much simpler explanation, one based on the physics of the stimulus. According to their explanation, visual performance should be degraded because nearby contours move the frequency band that is most relevant to detection to higher spatial frequencies for which the fovea has reduced sensitivity. They used the classical method for investigating the effects of adjacent contours, namely, that originally used by Flom and colleagues.² Subjects are asked to identify the orientation of a Landolt C in a four-alternative forced-choice task (up, down, right, or left) in

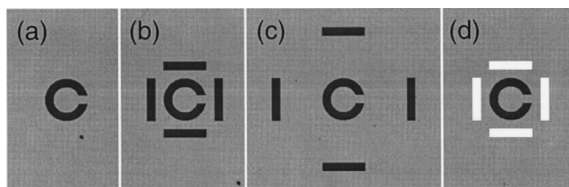


Fig. 1. Subset of the stimuli used in the contour interaction task.

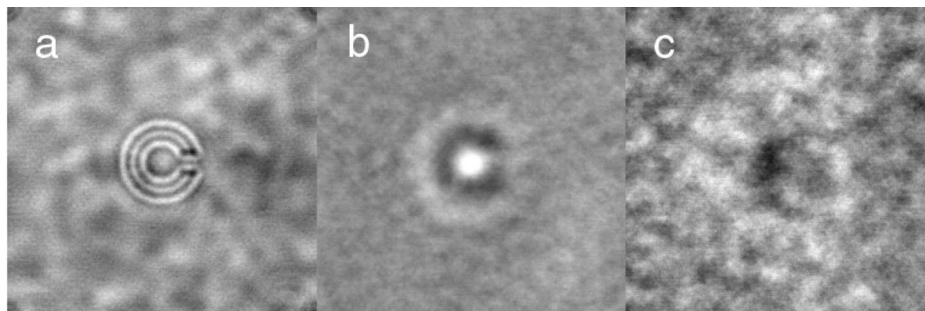


Fig. 2. Illustration of the effects of bandpass filtering of an unflanked Landolt C at (c) 0.7, (b) 1.6, and (a) 5.6 c/lett.

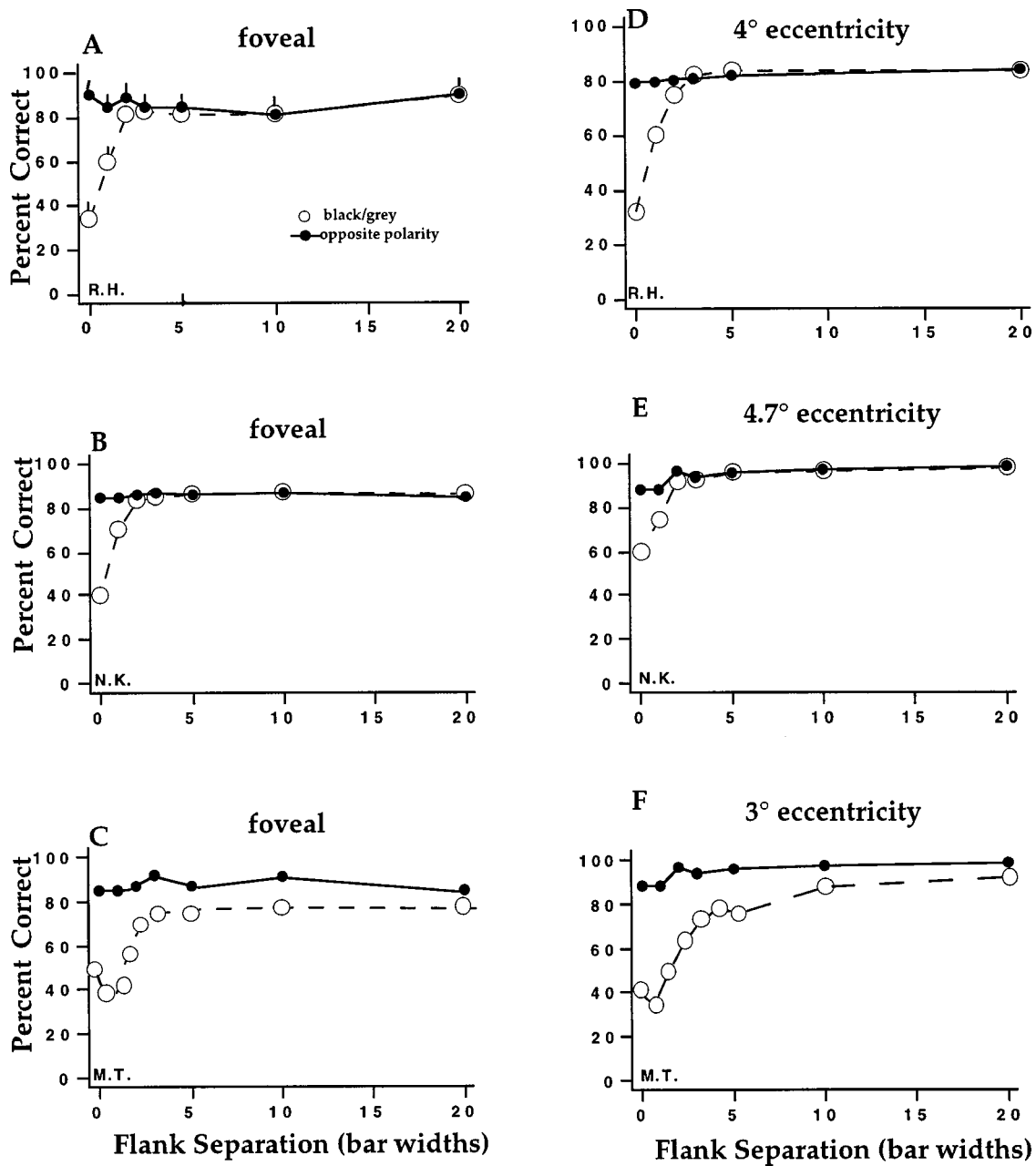


Fig. 3. Percent correct for the identification of the position (up, down, left, right) of a gap in a Landolt C is plotted as a function of the distance of lateral contours (see Fig. 1). Results are displayed for foveal and near periphery and for same (open symbols) and reverse contrast polarity flanking contours (solid symbols). Typical error bars [2 standard deviations (SD)] are displayed in frame A.

the presence of adjacent contour bars [see Figs. 1(b) and 1(c)] at various separations. They showed that for stimuli modulated about a mean light level, as shown in Figs. 3(a), 3(b), and 3(c) by open symbols; performance starts to deteriorate when the adjacent contours are two times the gap size (or barwidth) of the C, usually reaching a trough when abutting. Previous studies (see Ref. 2 for review) used black-on-white stimuli and have shown even stronger effects with a partial release from interaction in the abutting condition. Modulating the stimuli about a mean light level (i.e., black on gray, see Fig. 1) affords one the opportunity of having the letter and adjacent flanking contours of opposite contrast polarity [see Fig. 1(d)]. Performance under these conditions [solid symbols in Figs.

3(a), 3(b), and 3(c)] is very different: There is no longer any adverse effect of the adjacent contour; that is, the foveal contour interaction effect is abolished.

A previous study¹⁸ showed that from a physical standpoint the most relevant spatial-frequency band for detecting the orientation of an unflanked Landolt C [i.e., Fig. 1(a)] is approximately 1.15–1.30 cycles per letter (c/lett), a factor of two lower than that corresponding to the size of the gap itself (whose fundamental spatial frequency is at 2.5 c/lett). Hess *et al.*¹³ wondered whether this would change in the flanking condition normally associated with contour interaction [i.e., Fig. 1(b)]. Their results showed that the difference in the Fourier spectrum for orientations aligned and orthogonal to the gap in the C was lo-

cated at approximately 1.25 c/lett,¹⁸ which corresponds to 9.36 cycles per degree (c/deg) for RFH, 11.7 c/deg for NK, and 14.08 c/deg for M.T. When the flanks are one bar-width or one gap size away, the relevant spatial-frequency band shifts higher by half an octave to 1.75 c/lett, which corresponds to 12.5 c/deg for RFH, 15.6 c/deg for NK, and 18.7 c/deg for MT. Furthermore, they showed that when the flanks are of opposite polarity no such shift occurs in the difference spectrum.

These results led to the following questions. First, in the unflanked condition [Fig. 1(a)] does foveal vision operates at the scale that the difference spectrum suggests is most pertinent? Second, in the flanking condition [Fig. 1(b)] in which contour interaction is evident [Figs. 3(a), 3(b), and 3(c)], does the visual system shift its scale of analysis to the more relevant higher frequencies as indicated in the difference spectrum? Third, in the flanking condition with opposite polarity bars [Fig. 1(d)], does the scale of analysis shift back to that seen in the unflanked

condition? All of these predictions follow from an analysis of the power spectra alone. To answer these questions, we measured performance for the same task but this time under conditions in which subjects could use only a subset of the available spatial-frequency information contained in the stimuli. This was achieved by filtering the stimulus such that the spatial phases of all spatial frequencies on either side of a specified passband were randomized (see Fig. 2 for examples). By moving the peak position of the bandpass filter, we were able to gauge the influence of specified spatial-frequency bands in our letter acuity task, with the aim of determining what letter spatial-frequency band underlay performance for different flanking conditions. These results are shown in Fig. 4 for three subjects. In these panels, spatial-frequency tuning functions are shown for each subject for the unflanked condition [Figs. 4(a), 4(e), and 4(i)], for flanks at five-barwidth separation [Figs. 4(b), 4(f), and 4(j)], for flanks at 1-barwidth separation [Figs. 4(c), 4(g), and 4(k)], and for flanks at

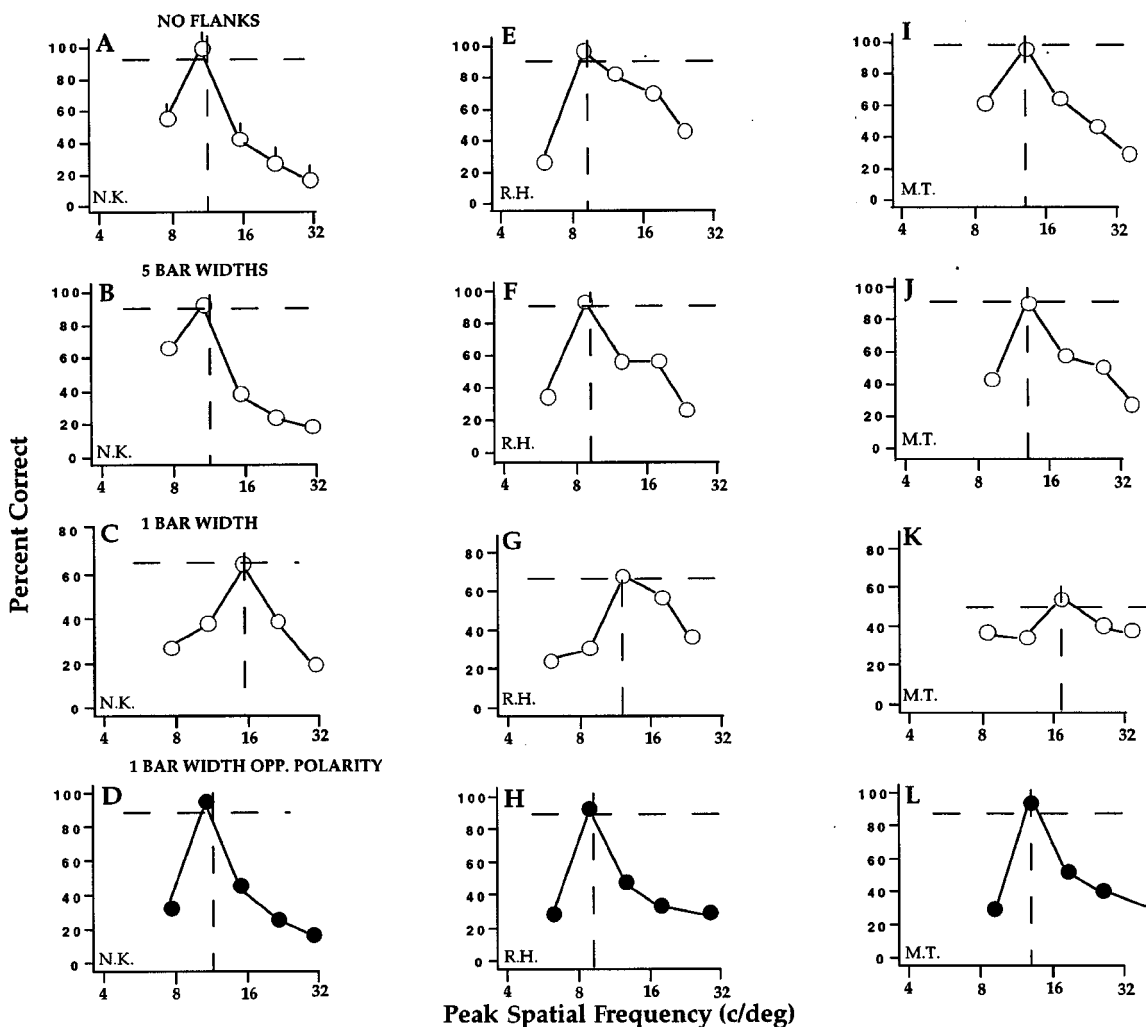


Fig. 4. Foveal bandpass-filter filtering functions for Landolt C identification for three subjects (open circles) for unflanked [(a), (e), and (i)], same polarity flanks at five-barwidth separation [(b), (f), and (j)] and same [(c), (g), and (k)] and opposite polarity [(d), (h), and (l)] flanks at one-barwidth separation. Percent correct is plotted against the peak spatial frequency of the passband in cycles per degree. The horizontal dashed line gives the unfiltered performance, whereas the vertical dashed lines give the predictions for the peak filtering location based solely on the difference spectra (see text). The predictions when converted from cycles per letter to cycles per degree differ slightly for each subject because their absolute acuity is not the same. The physical predictions (vertical lines) match the peak locations in the filtering functions. The minimum angle of resolution in the unflanked case was 0.024° for RFH, 0.019° for NK, and 0.017° for MT. Typical error bars (2 SD) are displayed in frame A.

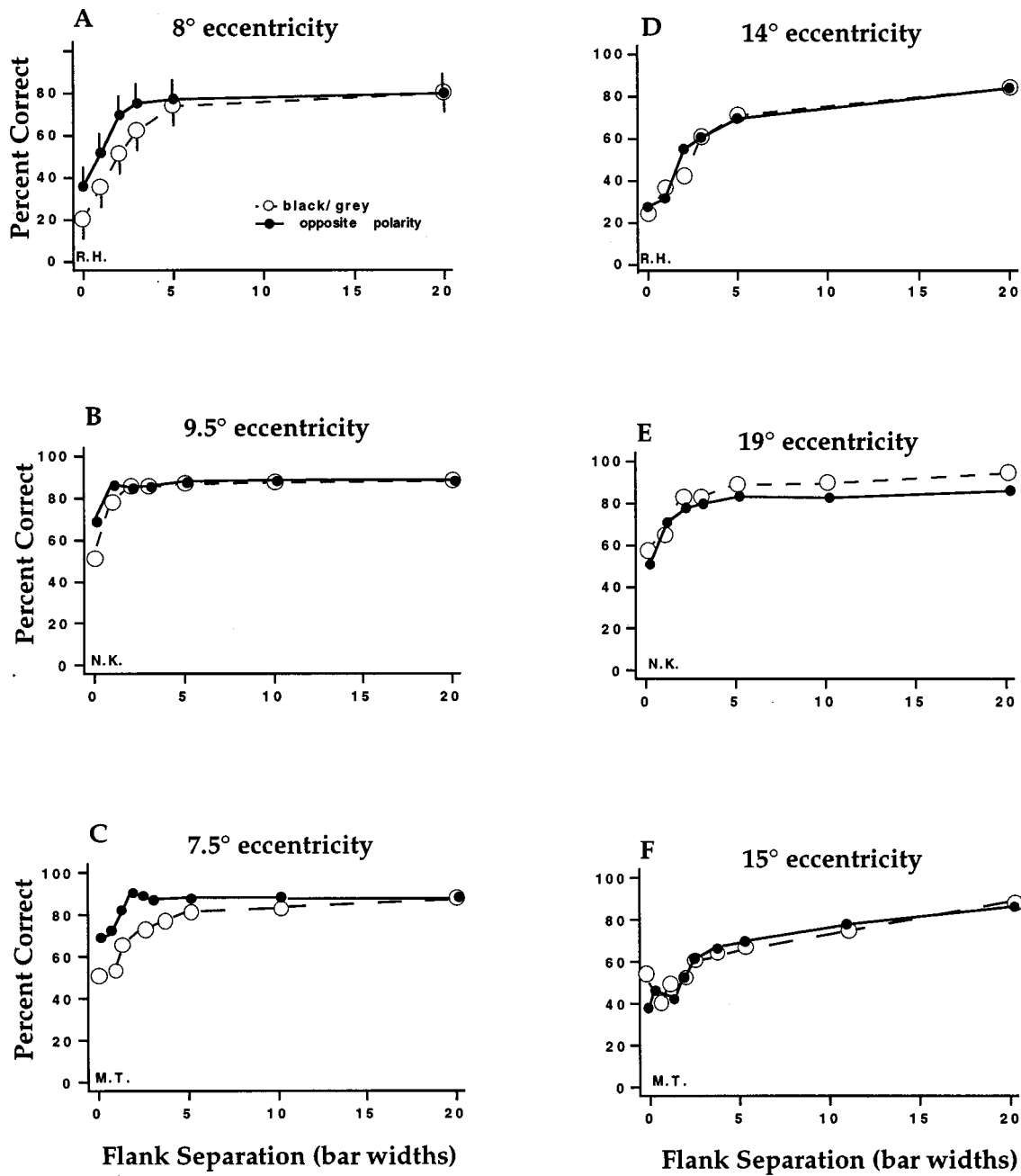


Fig. 5. Percent correct for the identification of the position (up, down, left, right) of a gap in a Landolt C is plotted as a function of the distance of lateral contours (see Fig. 1). Results are displayed for midperiphery and for same (open symbols) and reverse-contrast polarity flanking contours (solid symbols). Typical error bars (2 SD) are displayed in frame A.

one-bar-width separation for opposite polarity bars [Figs. 4(d), 4(h), and 4(l)]. The horizontal dashed line depicts performance levels for unfiltered stimuli, and the vertical dashed line is the predicted position of the peak from the difference spectra. The difference-spectra prediction is in cycles per letter, but when it is converted into cycles per degree it will depend on the acuity level of the particular subject or the peripheral part of the visual field used because, for different subjects, different viewing distances were used to obtain criterion level of performance in the unflanked case. These results demonstrated first that in the unflanked condition the peak of the filtering function is positioned at spatial frequencies that closely

match the peak in the difference spectrum [dashed vertical lines in Figs. 4(a), 4(e), and 4(i)], which is ~ 1.25 c/lett. This provides the first proof that the peak in the difference spectrum, first identified by Bondarko and Danilova,¹⁸ is actually used by human vision. Second, this situation is unchanged for adjacent contours at five-bar-width separation [Figs. 4(b), 4(f), and 4(j)]. Third, it can be seen that when the adjacent contours are one bar-width away, performance utilizes higher stimulus spatial frequencies [Figs. 4(c) and 4(g)]. The shift is approximately half an octave, matching that previously seen in the difference spectrum. This shift in the spatial scale subserving detection does not occur when the adjacent

contours are of opposite contrast polarity [Figs. 4(d), 4(h), and 4(l)], which also parallels that seen in the difference spectrum.

Results of the effects of adjacent contours for a range of retinal eccentricities are shown in Figs. 3(d), 3(e), and 3(f) and Fig. 5. Similar effects of changing the contrast polarity of the flanking bars are seen for the near periphery [3° – 4.7° in Figs. 3(d), 3(e), and 3(f)] but not for the mid or far periphery (7.5° – 19° in Fig. 5). In the former case, no contour interaction takes place for bars of opposite polarity, whereas in the latter case contour interaction takes

place regardless of the polarity of the flanking bars. This suggests that the interactions that are occurring at the larger eccentricities are not explicable in terms of the physical explanation that was advanced by Hess *et al.*¹³ to explain the foveal results. Such an explanation would predict no interaction in the opposite-polarity case.

To investigate this further, we measured the spatial-frequency filtering functions at each eccentricity for all of our stimulus conditions. The results for the perifovea (3° – 4°) are shown in Fig. 6, and those at the larger eccentricities ($\sim 14^\circ$) are shown in Fig. 7. In each figure, as be-

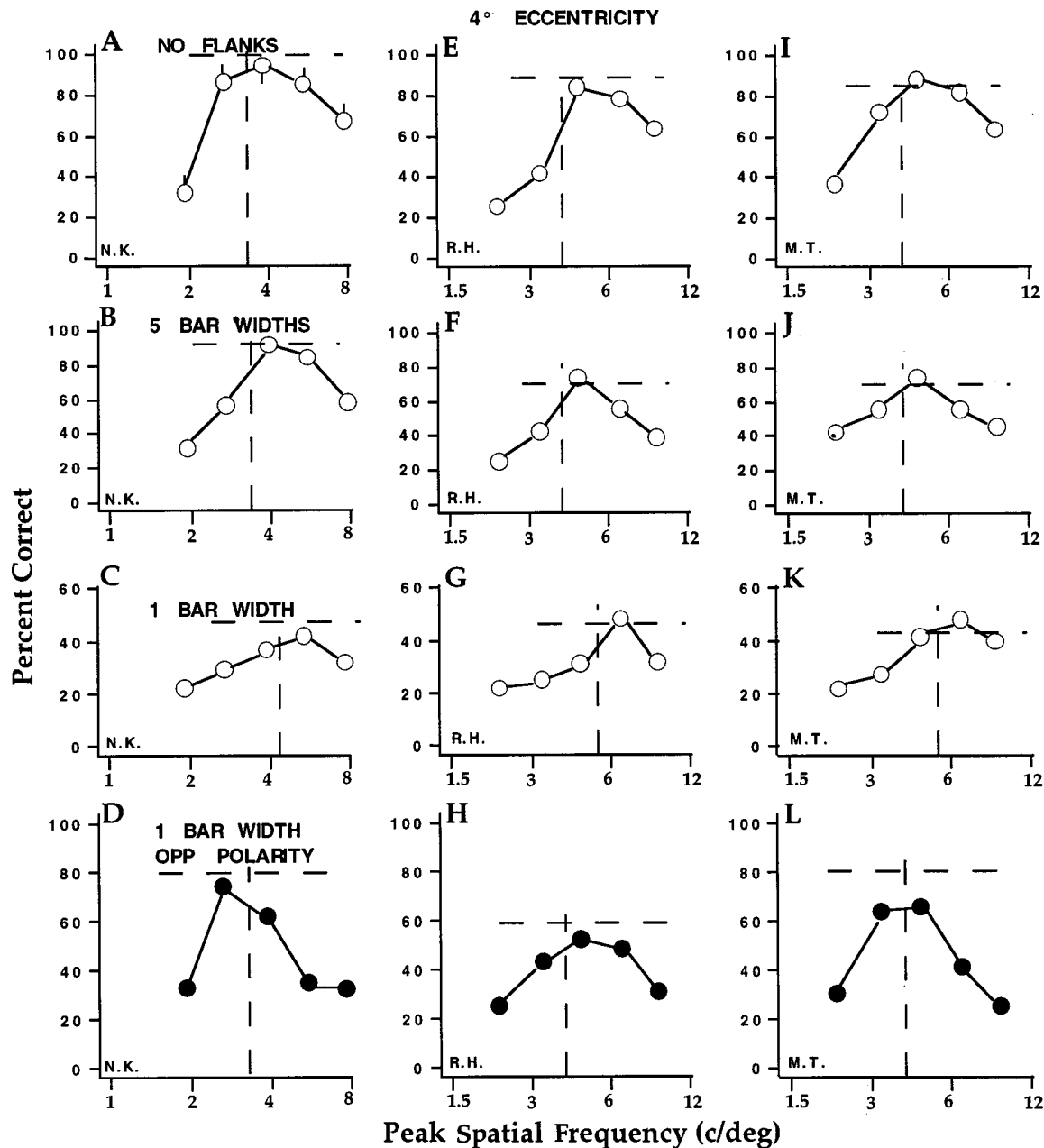


Fig. 6. Near-peripheral bandpass-filter filtering functions for Landolt-C identification for three subjects (open circles) for unflanked [(a), (e), and (i)], same polarity flanks at five-barwidth separation [(b), (f), and (j)] and same [(c), (g), and (k)] and opposite polarity [(d), (h), and (l)] flanks at one barwidth separation. Percent correct is plotted against the peak spatial frequency of the passband in cycles per degree. The horizontal dashed line gives the unfiltered performance, whereas the vertical dashed lines give the predictions for the peak filtering location based solely on the difference spectra (see text). The predictions when converted from cycles per letter to cycles per degree differ slightly for each subject because their absolute acuity is not the same. The physical predictions (vertical lines) roughly match the peak locations in the filtering functions. Typical error bars (2 SD) are displayed in frame A.

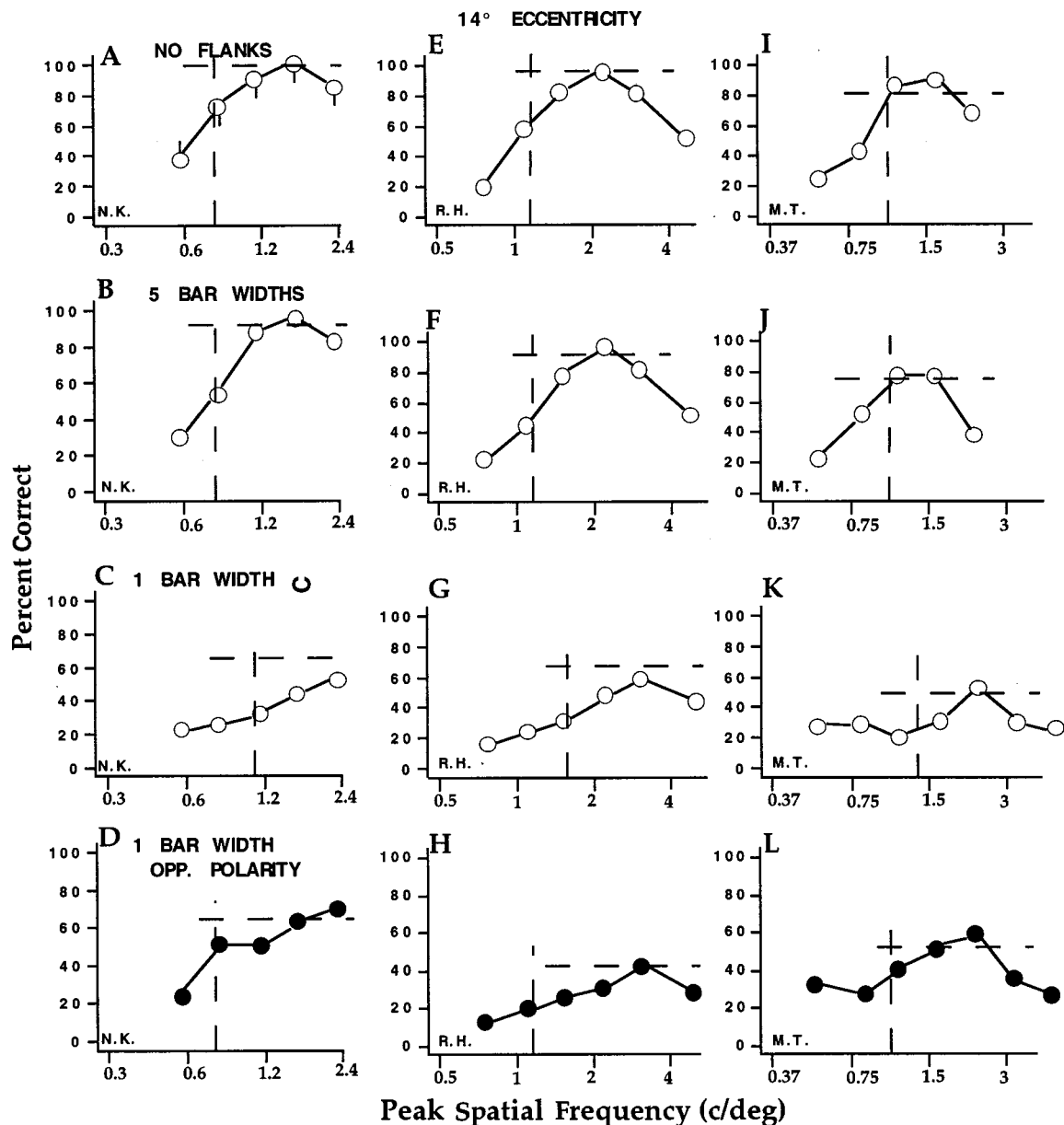


Fig. 7. Peripheral bandpass-filter filtering functions for Landolt C identification for three subjects (open circles) for unflanked [(a), (e), and (i)], same polarity flanks at five-barwidth separation [(b), (f), and (j)] and same [(c), (g), and (k)] and opposite polarity [(d), (h), and (l)] flanks at one barwidth separation. Percent correct is plotted against the peak spatial frequency of the passband in cycles per degree. The horizontal dashed line gives the unfiltered performance, whereas the vertical dashed lines give the predictions for the peak filtering location based solely on the difference spectra (see text). The predictions when converted from cycles per letter to cycles per degree differ slightly for each subject because their absolute acuity is not the same. The physical predictions (vertical lines) do not match the peak locations in the filtering functions. Typical error bars (2 SD) are displayed in frame A.

fore, the horizontal dashed line indicates the performance level for the unmasked stimulus and the vertical dashed line indicates the physical prediction based on the difference spectra.¹⁸ The physical predictions are still reflected in the filtering data for the near eccentricities (Fig. 6) in that at one-barwidth separation the peak of the filtering function shifts higher by half an octave, although the predicted locations of the peaks are not predicted as well as they were for the foveal results. Although there is a significant shift of the peak filtering to higher spatial frequencies for the population results ($t = 1.909$, $p = 0.0413$; one sample, one-tailed t test), the magnitude of the shift is small (average = 0.09 octave).

In the midperiphery ($\sim 14^\circ$), the situation is very different in terms of the filtering functions (Fig. 7). In the unflanked case, the spatial-frequency band that is being used (peak filtering) is significantly higher than where the peak in the difference spectrum predicts (vertical dashed line). In the one-barwidth case, the peak is displaced to higher spatial frequencies by more than half an octave, but reversing the polarity of the flanks does not shift the peak back to its original position as the physics of the stimulus would predict. The physical predictions and the positions of peak filtering are different by almost an octave. It is clear that the physical predictions are violated here, and one has to conclude that the underlying

effects are physiological and involve shifts to a higher scale of analysis.

4. DISCUSSION

Flom *et al.*² in their original study of contour interaction suggested that contour interaction was due to a neural interaction that was essentially the same in fovea and periphery of normal vision. Our results replicate theirs in that we, too, show that the relationship between percent correct performance and the separation of same-sign flanking bars is similar in fovea and periphery. However, we go on to show that the underlying explanations are different. Previously, we¹³ had demonstrated that the classical contour interaction effect for foveal vision is explicable in terms of the physics of the stimulus. It is not the result of inhibitory neural interactions within low- or high-level stages of visual processing as previously thought.^{2-4,6-9,19} These changes in the spatial scale utilized by the visual system are wholly predicted by the stimulus power spectra and are contingent on conditions of contour interaction. This suggests that the physics of the stimulus forces the visual system to use a spatial scale that, while containing the most relevant information for the task, is too high to support optimum performance.²⁰

We now show that the same explanation holds for the near periphery in the case in which reversing the contrast of adjacent contours significantly reduced or abolished contour interaction. A similar though less dramatic effect has been reported for peripheral vision.¹⁹ The filtering functions show that the physical predictions are still correct. In the midperiphery, however, the situation changes and the physical explanation cannot be sustained. Reversing the contrast polarity of the adjacent contours does not diminish the lateral interaction, and the physical predictions are no longer accurate in predicting where peak filtering occurs under our various stimulus conditions. The filtering functions reveal that a band of spatial frequencies corresponding to the gap in the *C* are being used in the unflanked case and that adjacent contours at one barwidth forces the visual system to use even higher frequencies. The finding that the scale shift is to higher rather than lower spatial frequencies rules out the possibility that contour interaction is due to inappropriate feature linking,⁹ at least for our stimulus, as this would predict a change in scale to lower spatial frequencies. This scale shift may be the result of poorer shape discrimination in the periphery making the lower spatial frequencies corresponding to the physical prediction unusable, though our recent results on circularity detection in peripheral vision do not support this interpretation (results reported by Actmann, Hess, and Wang are available from R. Hess at the address on the title page). On the other hand, a finer scale of analysis may be necessitated because of a deficit in segregating the target from the flanking distractors. The finding that reversing the contrast polarity of the adjacent contours has no influence argues that it involves cortical cells² that do not distinguish between polarity changes (e.g., complex cells).

A. Underlying Physiology

If the shift to a finer scale of analysis is due to deficient shape discrimination, then this may be the result of a greater cortical magnification in V4, the putative shape-processing area, compared with V1. On the other hand, if the underlying problem is one of segregation, then it implicates a deficiency in the analysis of the outputs of different filters in the periphery. Such a problem may be due either to a reduced range of filters in the periphery²¹ or to a less complete analysis of the filters' outputs.²²

B. Role of Positional Uncertainty

Our prime assumption has been that performance on our task is limited by the output of orientational tuned mechanisms. We thereby assume that once the orientation (horizontal versus vertical) of the gap has been detected, there will be no additional loss of performance due to positional coding (up versus down, right versus left). Although this is a reasonable assumption in the fovea, can it be sustained for the periphery? To determine the answer, we collected in all conditions percent correct for the location of the gap (four-alternative forced-choice) and for the orientation of the gap (two-alternative forced-choice). When these two measures were appropriately scaled for the difference in ranges, we found no significant difference between them, thus confirming our initial assumption that positional uncertainty did not have a significant influence on our results even at the largest eccentricities. A simple calculation confirms this. Given the acuity values of our stimulus, the levels of positional uncertainty measured at any of the tested eccentric loci²³ are about four times less than that needed to affect this task.

We anticipate that the extent of the interactions in peripheral vision may depend on the type of stimulus used to investigate it. For example, it is known that in peripheral vision a more pronounced interaction occurs when larger or more complex flanking elements are used.^{3,19} Such interactions are reduced but not abolished by reversing the contrast polarity of the flanking elements.¹⁹ Also, the detection of a Landolt *C* does not require elaborate feature linking in the way that recognizing an alphanumeric character would. We expect that under these conditions the regional extent and form of any neural interactions may change. The fact that we find similar results in the fovea and near periphery (<5°) may be a consequence of our stimulus or task. Leat and Epp¹⁴ showed that for different stimuli, contour interaction was different in fovea and 2°. It is difficult to know whether different stimuli merely magnify the effect or whether they reflect different underlying processes. In this regard it would be interesting to know whether similar spatial scale changes occur for these different stimuli.

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