Facilitation of Contrast Detection in Near-Peripheral Vision

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Abstract

Foveal detection of a Gabor patch (target) is facilitated by collinear, displaced high-contrast flankers. Polat and Sagi reported that the same phenomenon occurred in the periphery, but no data were presented (Proceedings of the National Academy of Sciences 91 (1994) 1206). Others have found no facilitation in a limited number of conditions tested. To resolve this apparent conflict, we measured lateral facilitation in the near-periphery using a range of stimulus parameters. We found facilitation for a range of target-flanker distances for peripheral eccentricities up to 6°, but the magnitude of the effect was less than found in central vision. Facilitation varied across subjects and with spatial frequency. Flanker contrast had no effect over the range evaluated (10% to 80%). Equal facilitation was found for two global arrangements of the stimulus pattern. Facilitation was found using a temporal, but not a spatial two-alternative forced-choice paradigm, accounting for the different results among previous studies. This finding supports previous indications of the role of attention in altering such facilitation. The value of facilitation from lateral interactions for persons with central vision impairment, who have to shift their attention to a peripheral locus constantly, needs to be examined.
Introduction

Contrast threshold of a target object can be altered by the presence of surrounding objects (Tolhurst & Barfield, 1978; Legge, 1979). Such objects may facilitate (i.e., target object is detected at lower contrast) or suppress (target object is detected only at higher contrast) contrast threshold, hence the common term for co-local objects, masks. An example of this effect is the classic pedestal effect, in which detection of a target is facilitated when superimposed on a low-contrast, co-local pedestal, but suppressed at higher mask contrasts (Legge & Foley, 1980; Foley & Legge, 1981; Zenger & Sagi, 1996). These effects are attributed to the interactions between spatial frequency and orientation tuned channels within the visual system, the sensitivities of which are well characterized by 2-dimensional Gabor functions.

Studies in central vision have demonstrated facilitation of target thresholds when the target and other elements are no longer co-local or concentric, but rather laterally displaced and collinear (“flankers” or “inducers”) (Polat & Sagi, 1993, 1994a; Kapadia, Ito, Gilbert & Westheimer, 1995; Morgan & Dresp, 1995; Yu & Levi, 1997b). Polat and Sagi (1993; 1994a) showed that the contrast threshold for a foveal Gabor patch could be altered by the presence of collinear Gabor flankers when the patterns had similar spatial characteristics (frequency and orientation). They demonstrated maximal contrast facilitation for target-flanker distances of 2 to 3 wavelengths ($\lambda$). The facilitation persisted, though attenuated, with increasing target-flanker distance up to about $12\lambda$. At short target-flanker distances ($\lambda$ or less) suppression was observed. Polat (1999) and others have postulated that these effects are mediated by long-range visuo-cortical connections in area V1. Neurophysiological equivalence has been provided by single-cell recording studies (Polat, Mizobe, Pettet, Kasamatsu & Norcia, 1998). For instance, the
response of cells to stimuli presented within their receptive field can be modulated by stimuli presented to cells outside their receptive field, which when stimulated in isolation, do not alter the cells’ activity. Neuronal facilitation has been observed for collinear patterns presented across receptive fields (Blakemore & Tobin, 1972; Stemmler, Usher & Niebur, 1995), while suppression has been shown for within-field presentation of the same targets (Nelson & Frost, 1985; Sillito, Grieve, Jones, Cudeiro & Davis, 1995; Mizobe, Polat, Kasamatsu & Norcia, 1996).

Although these effects have been well characterized in central vision, we are aware of only limited examinations of these effects in near-peripheral vision, and those reports are contradictory. Polat and Sagi (1994b) stated in a footnote that facilitation occurred in the periphery at 3° eccentricity with the “same pattern of enhancement” as in central vision, but no data were presented. Williams and Hess (1998) also tested at 3° eccentricity. They reported that there was no facilitation at 3λ target-flanker separation. With a target-flanker separation of 6λ, one of their three subjects did show weak, but statistically significant, facilitation. Zenger-Landolt and Koch (2001) tested at 4° eccentricity and a target-flanker distance of 4λ. For their zero pedestal-contrast condition, that has the same configuration as the Polat and Sagi paradigm, they reported suppression. It is possible that neither of these two studies that failed to find facilitation used parameters optimal for an effect in peripheral vision. In central vision, Woods, Nugent and Peli (2002) found that these lateral interaction effects changed with spatial frequency, target-flanker distance and Gabor patch size (bandwidth). Consequently, a failure to find facilitation with one or two conditions could have been simply a failure to sufficiently explore the parameter domain. We test this hypothesis in Experiments A and B. Another difference between Polat and Sagi (1994b), who reported facilitation, and the two studies that did not (Williams & Hess, 1998; Zenger-Landolt & Koch, 2001), was the use of a spatial two-
alternative forced choice (2AFC) paradigm, by the latter two studies, rather than the temporal 2AFC paradigm used by Polat and Sagi (1994b). We test this alternative hypothesis in Experiment E, and we found that this was the important difference.

It is of interest to characterize lateral interactions in near-peripheral vision, particularly because persons with central field loss (central scotoma: “hole in vision), often due to macular disease, use an eccentric retinal locus (preferred retinal locus (PRL): Timberlake, Mainster, Peli, Augliere, Essock & Arend, 1986) to obtain important and detailed information, such as used in letter and face recognition by normally-sighted people (Parish & Sperling, 1991; Peli, Goldstein, Young, Trempe & Buzney, 1991; Solomon & Pelli, 1994). Since the facilitation by lateral interactions is presumed to aid in contour integration and spatial vision it is interesting to find if and how it functions in near-peripheral vision.

Here we examined lateral interactions in peripheral vision using a broader set of spatial conditions than has been previously reported. We sought to determine whether contrast detection of a target Gabor could be facilitated by the presence of flanking Gabor patches when the target Gabor was presented to the near-periphery of normally-sighted subjects. We found that it did so over a wide range of stimuli parameters using the temporal 2AFC paradigm, but not when using the spatial 2AFC paradigm.

**Methods**

**Subjects**

Subjects were three males and two females aged 18 to 43 years with normal or corrected-to-normal vision. Three of the subjects (3, 4 and 5) were privy to the purpose of the experiments and had experience in psychophysical experiments. Two of the subjects (1 and 2) were naïve to
the purpose of the experiments and had no prior experience in measures of contrast sensitivity. Subject 4 participated in Experiment A only, and subject 5 participated in Experiments B, C, D and E only. All participants read and signed an IRB approved informed consent form.

Apparatus

Stimuli were presented as grey-level modulations using a VisionWorks™ computer (Vision Research Graphics, Durham, NH), software version DOS 3.2.2, and were presented on a Nanao™ Flex-Scan FX E7 color monitor. A screen display of 1024 x 600 pixels was used which subtended a view of 21.8°x 13.2° at a distance of 1 meter. The video format was 122.6 Hz non-interlaced. A Cambridge Research Systems™ VSG2/4© card was used to drive the monitor, its three outputs passed first through a secondary passive resistor network to achieve 15-bit grey-level representation after gamma correction (Pelli & Zhang, 1991; Swift, Panish & Hippensteel, 1997). The mean luminance was 40 cd/m² in an otherwise dark room.

Stimuli

Stimuli were presented as vertical or horizontal collinear (i.e. the same local orientation and global orientation as the target patch: Polat & Sagi, 1994a) arrangements of Gabor patches for all experiments (e.g., figure 1a). The equation delineating the luminance distribution of each Gabor patch was of the form:

\[
L(x, y, \theta) = L_0 \left\{ 1 + C \cos \left( \frac{2\pi}{\lambda} \left[ (x - x_0) \cos \theta + (y - y_0) \sin \theta \right] \right) \right\} e^{-\frac{(x-x_0)^2 + (y-y_0)^2}{\sigma_x^2 + \sigma_y^2}}
\]
where $x$ was the value of the horizontal axis, $y$ of the vertical axis, $(x_0, y_0)$ was the center of a Gabor patch, $L_0$ was the mean luminance, $\theta$ was the orientation of the carrier, $\sigma$ was the standard deviation of the Gaussian envelope, and $\lambda$ was the wavelength of the sinusoid. Note that $\sigma_x$ is not the standard deviation of the Gaussian (Peli, Arend, Young & Goldstein, 1993). We used $\sigma_x = 0.5\lambda$ and $\sigma_y = \lambda$ for flanker size in all experiments, except experiment D, where $\sigma_x = \lambda$ and $\sigma_y = 0.5\lambda$. Patch contrast, $C$, ranged between 0 and 1. The stimulus for all experiments consisted of a central target patch (when present), either flanked (flanked condition) or not flanked (standard condition) by equidistantly placed Gabor patches. Both the target and flanking patches were vertically aligned (local orientation, $\theta_{\text{local}} = 0^\circ$) except in experiment D, where all patches were horizontally aligned ($\theta_{\text{local}} = 90^\circ$). Global orientation (i.e., the orientation of the line passing through the centers of the patches) was vertical for all experiments, except the horizontal condition in Experiment D. Target-flanker separation for all experiments was defined as the center-to-center distance between target and flanking patches in units of $\lambda$. Because our display system did not allow overlapping stimuli to be drawn to a single page of video memory (specifically when the target-flanker separations were less then $4\lambda$), target and flanking patches were usually written to separate pages of memory and presented in a frame-flipping arrangement (stereo mode: Yu & Levi, 1997a; Williams & Hess, 1998). In this arrangement, stimuli appear in every other frame, and hence the actual contrast is half that reported by the software. When greater contrasts were required (Experiment A, $12^\circ$ eccentricity condition; Experiment B, $8\text{cyc/deg}$ condition; Experiment C, $80\%$ contrast flankers), the patches were presented in every frame. All absolute contrasts were also corrected for an undocumented VisionWorks software feature that alters the actual displayed contrast of the target without reporting that alteration properly in the output file. This occurs when the parameter "contrast relative to crest and trough"
for the target object(s) (located in the stimulus sub-menu of the objects sub-menu of StimulusMaker) is set to a value less than 1 (e.g. parameter value = 0.40). This parameter value is multiplied by the value set by whichever staircase one uses (specified in the MethodMaker menu) to create the displayed contrast. Itself, this is not a problem, and was implemented with good reason for some applications, in particular for stimuli composed of multiple sinusoids. However, the reported contrast in the output file is the contrast set by the staircase (e.g. 0.25) and not the displayed contrast, which is the contrast set by the staircase multiplied by the parameter value (e.g., reported result = 0.25, whereas displayed contrast = 0.10). For relative contrast thresholds, as reported mainly here, this had no effect at all, but it was important to correct when reporting absolute target contrasts.

Because of potential non-linearities in the response of the graphics monitor when few pixels are used to express a sinusoid, we ensured that one wavelength consisted of no fewer than about 20 pixels (Klein, Hu & Carney, 1996; García-Pérez & Peli, 2001; Woods et al., 2002); different spatial frequencies (λ⁻¹) were achieved by changing viewing distance (except 1 cyc/deg. in Experiment B). Different viewing eccentricities were accomplished by having subjects fixate a low-contrast (with respect to background luminance) fixation cross of 0.5° that appeared to the right (all experiments except when it was above in the horizontal condition in Experiment D and between the stimulus patterns in the spatial-2AFC condition in Experiment E). For eccentricities that were greater than the screen width, a laser pointer was projected onto a white board placed parallel to and to the right of the screen and served as the fixation point.

Procedure

A temporal 2AFC was used, except in Experiment E. For each trial, subjects were instructed to maintain fixation on the fixation point. Each temporal 2AFC trial consisted of two 98 ms
Lateral Interactions in Peripheral Vision

intervals separated by an 867 ms inter-stimulus interval during which the background and fixation point remained displayed. Temporal onset-offset of the stimuli was a rectangular pulse. For flanker trials, each interval contained the laterally displaced flanker pair, but only one of the two intervals contained the target patch. For non-flanked (standard) trials there were no flankers, only the target patch was presented, and only in one interval. The subject’s task was to indicate, by keyboard press, which of the two temporal intervals contained the target. Each spatial 2AFC trial (Experiment E only) consisted of a single 98 ms interval. For flanker trials, two vertically aligned flanker pairs were presented equidistantly to the left and right of a central fixation cross (see fig.5) and the target patch was presented between either the left or the right flanker pair. For non-flanked (standard) trials, only the target patch was presented. The subject indicated whether the target patch appeared to the left or right of fixation. Incorrect responses were followed by audible feedback. Subjects were permitted to repeat a trial only if they blinked or failed to fixate the fixation point.

Each experimental block contained a standard (non-flanked) condition and at least one flanked condition. Order of the non-flanked and flanked conditions was randomized within a block. A staircase procedure was used in which the contrast of the target patch was reduced by 0.30 log units (about 50%) following three consecutive correct responses and increased by 0.405 log units (about 254%) for each incorrect response. For each experimental session, two practice reversals were followed by 40 experimental reversals. Contrast threshold for the target Gabor patch was taken to be the geometric mean of those 40 experimental reversals of the staircase. These staircases were expected to converge towards 83% correct (García-Pérez, 1998). Subjects completed between three and six staircases for each experimental condition. Facilitation (or inhibition) is reported as the difference in the logarithm of the average contrast detection
threshold for the flanked and non-flanked conditions. We used 95% confidence limits (t-distribution) as the measure of variability.

**Results**

**Experiment A: The effect of retinal eccentricity and target-flanker distance**

To test for facilitation in peripheral vision, we chose a range of eccentricities and target-flanker distances that contained, but extended the spatial parameter set used in previous studies. Contrast detection thresholds were measured on four subjects at four retinal eccentricities (2, 4, 6, and 12°), each at four target-flanker distances (2, 4, 6 and 8λ). Fig. 1a illustrates from left to right the target alone (non-flanked) and the four target-flanker (flanked) conditions. We chose a spatial frequency of 2cyc/deg for both target and flankers since peak contrast sensitivity moves to lower spatial frequencies with increasing eccentricity (Rovamo, Virsu & Nasanen, 1978). Note that we and Polat and Sagi (1994b) used a temporal 2AFC paradigm in this experiment (and Experiments B, C and D), while Williams and Hess (1998) and Zenger-Landolt and Koch (2001) used spatial 2AFC paradigm. That difference is evaluated in Experiment E.

As shown in Fig. 1b, on average, significant facilitation was found for target-flanker distances of 4, 6 and 8λ for eccentricities up to 6° (except 4cyc/deg, 8λ: t₃=3.0, p=0.06). No facilitation was observed for target-flanker distances of 2λ at any eccentricity in the averaged data; however, one of our four subjects (subject 4) did show significant facilitation at this target-flanker distance for eccentricities up to 6° (Fig. 1f: t₃≥3.22, p≤0.05). No facilitation was seen at 12° eccentricity for any target-flanker distance in the averaged data, though one subject (subject 1, fig. 1c) did show facilitation at target-flanker distances of 4 to 8λ even at this eccentricity (t₃≥3.80, p≤0.03). As can be seen by comparing averaged and individual data, there was
substantial between-subject variability, but such variability in this task has been reported even in central vision (Polat & Sagi, 1993; Woods et al., 2002). In general, however, we found facilitation where others (Williams & Hess, 1998; Zenger-Landolt & Koch, 2001) had not.

To ensure that the outcome of our experiment was not confounded by subjects’ eye movements encroaching towards the target (i.e., “peeking”), we performed a control experiment to examine the steadiness of our subjects’ fixation upon the fixation point. We used an eye tracking system (ISCAN®, ISCAN, Inc., Burlington, MA) to record the subject’s point of regard while performing the experiment. Two subjects (3 and 5) completed trials with- and without-eye tracking: spatial frequency 2cyc/deg, viewing eccentricity 4°, and for the flanker trials, a target-flanker distance of 4λ. Both the on-screen fixation point and subject’s point of regard were recorded to video allowing determination of eye movements during each stimulus presentation. Neither subject’s fixation during any trial encroached towards the stimuli pattern by more than 1°, which is the nominal resolution of the ISCAN system. Facilitation for each subject was similar for the with- and the without-eye movement recording sessions.

In summary, we found small but significant facilitation in peripheral vision within a range of eccentricities and target-flanker distances. The magnitude of facilitation we found at near-peripheral loci was about 0.1 log units, or about half that reported by us and others examining these lateral interactions in central vision (Polat & Sagi, 1993; Woods et al., 2002). Also, whereas maximal facilitation occurred at target-flanker distances of 2 to 3λ in central vision, we found maximal facilitation in near-peripheral vision for target-flanker distances of about 4 to 6λ. Next, we examined how peripheral lateral interactions vary with spatial frequency, since the two studies that failed to find facilitation (Williams & Hess, 1998; Zenger-Landolt & Koch, 2001) used (about) 4 cyc/deg stimuli, whereas we had used 2 cyc/deg stimuli.
Experiment B: Effect of spatial frequency

Lateral interactions in central vision vary with spatial frequency, with greater facilitation for higher spatial frequencies (8 and 13.3 cyc/deg) than lower spatial frequencies (2 and 4 cyc/deg) (Woods et al., 2002). We suspected that the lateral interactions in peripheral vision might be different. Specifically, because in the near-periphery higher spatial frequencies are not detected, or require higher contrasts for detection, we expected an attenuation of facilitation with increasing frequency, or at least, for higher spatial frequencies. Pointer and Hess (1989) showed that the peripheral contrast sensitivity function scales down with eccentricity and spatial frequency as compared to the foveal contrast sensitivity function.

To investigate the effect of spatial frequency in peripheral vision, four subjects viewed spatial frequencies of 1, 2, 4, 6 and 8 cyc/deg. As the facilitation found in Experiment A was greatest at a target-flanker distance of about $4\lambda$, we chose this separation, and used a single eccentricity of $4^\circ$ as this was in our region of interest, as related to people with central vision loss. To achieve the various spatial frequencies, viewing distance was varied from 100 to 400 cm, except for the 1-cyc/deg stimuli, for which stimulus size was doubled and presented at 100 cm (rather than 50 cm, at which accommodation demands would have been greater).

On average, significant facilitation was found for spatial frequencies of 1 to 6 cyc/deg (Fig. 2). There was no significant difference in facilitation between spatial frequencies of 1 to 6 cyc/deg ($F_3=1.04$, $p=0.42$). For 8 cyc/deg, on average, there was no significant facilitation, but, one of the four subjects demonstrated facilitation even at this (relatively) high spatial frequency (subject 1, $t_3=3.9$, $p=0.03$). There appeared to be less between-subject variability at the lower spatial frequencies (1 and 2 cyc/deg).
Facilitation was significant over the low- to mid-spatial frequency range (1 to 6 cyc/deg) that we tested. The reduction in facilitation at the higher spatial frequency, 8 cyc/deg, was expected. We hypothesized that it was related to the reduced high spatial frequency contrast sensitivity in mid-peripheral vision (Pointer & Hess, 1989) that is typically ascribed to decreased optical resolution (Jennings & Charman, 1981), larger cone spacing, and increased ganglion cell receptive field summation at peripheral loci (Wiesel, 1960).

**Experiment C: Effect of flanker contrast**

In central vision, lateral interactions have been shown to be independent of flanker contrasts, for contrasts of 20 to 80% for spatial frequencies of 2 to 13.3 cyc/deg (Polat & Sagi, 1993; Woods et al., 2002). To test how flanker contrast alters facilitation in the near-periphery, four subjects viewed flankers with contrasts of 10%, 20%, 40% and 80%. Target-flanker distance was again 4λ, eccentricity was 4° and spatial frequency of both the target and flankers was 2 cyc/deg.

Over the range of flanker contrasts tested, significant facilitation was found at all contrasts, 10% to 80% and there was no significant difference in the facilitation produced by the flankers of those four contrasts (Fig.3: F\textsubscript{3}=0.30, p=0.82). Our lowest (10%) contrast flankers were still well above the target detection thresholds of our subjects (1.4 to 2.0%), thus we did not see the decrease in facilitation with decreasing flanker contrast when contrast is reduced to near threshold, that has been shown in studies in central vision (Woods et al., 2002). Recently, Varadharajan and Foley (2003) reported that in peripheral vision flankers produced a “dipper-shaped” function of target detection threshold with increasing flanker contrast, but the range of contrasts and other parameter details used in their study were not made explicit in the published abstract. We did not see that type of function with the flanker contrasts we used. In general, we found significant facilitation that was resilient to supra-threshold flanker contrast.
Lateral Interactions in Peripheral Vision

**Experiment D: Effect of stimulus global orientation**

Studies in central vision have explored lateral interactions for different local and global orientations of the target and flanking Gabor patches (Polat & Sagi, 1994a). Stimuli are considered collinear when each patches’ local orientation is aligned with the global orientation of the stimulus, i.e. $\theta_{\text{local}} = \theta_{\text{global}}$. Polat and Sagi (1994a) demonstrated that maximal facilitation occurred for collinear arrangements of Gabor signals, regardless of the global orientation examined: $\theta_{\text{global}} = 0, 45$ or 90° (with respect to vertical). The dependence of facilitation on stimulus orientations for these lateral interactions has been argued to play a role in tasks such as illusory contours and gap-filling (Mitchison & Crick, 1982; Polat & Sagi, 1993).

Insensitivity to global orientation has not been demonstrated in peripheral vision. This is of particular interest to us, as we are interested in the vision of people with central field loss. When central vision is lost, most people adopt a PRL. These PRLs are usually near the edge of the scotoma and located (in the visual field) mainly below, right and left of the former fovea. For a person with a right or left PRL our typical vertical stimuli will not usually fall into the scotoma, but for a person with a below PRL the upper flanker would probably fall into the scotoma. However, for a person with a below PRL, usually neither flanker would fall into the scotoma if the global orientation were horizontal. To test the effect of global orientation, four subjects viewed vertically- and horizontally-aligned stimuli (Fig. 4), with a 4λ target-flanker distance, an eccentricity of 4°, and a spatial frequency of 2cyc/deg.

Significant facilitation was observed for both stimulus conditions (Fig. 4). Moreover, no difference was found between the vertical and the horizontal conditions ($t_3 = 0.91$, $p = 0.42$). Between-subject variation appeared to be greater for the horizontal condition than the vertical condition. Apparently greater within-subject variability was observed for the horizontal
condition (data not shown), that could be due in part to a practice effect, subjects having performed all other experiments in the study with vertically-oriented stimuli, or to difficulty maintaining fixation above as compared to right (not tested). Thus, when testing people with a central scotoma and a below PRL, horizontally-orientated stimuli are expected to produce lateral interactions comparable to vertically-oriented stimuli viewed by people with left and right PRLs. If there is greater between-subject variability for horizontally-oriented stimuli, larger sample sizes will be required to show effects of interest.

**Experiment E: Temporal versus spatial 2AFC**

In Experiments A to D, we found small, yet significant, facilitation for lateral interactions in the near-periphery using a range of stimulus parameters that included the parameters employed by other groups that did not find facilitation (Williams & Hess, 1998; Zenger-Landolt & Koch, 2001). Since the restricted parameter range of those two studies could not explain the apparent discrepancy, that left our other hypothesis: that differences in the psychophysical task between those who have reported facilitation (us and Polat & Sagi, 1994b) and those who have not (Williams & Hess, 1998; Zenger-Landolt & Koch, 2001) could explain the apparent conflict. Those two studies that failed to find facilitation used conditions at which we found facilitation, but they used a spatial 2AFC, rather than a temporal 2AFC. To test our hypothesis, four subjects performed the contrast detection task, using both a temporal 2AFC and a spatial 2AFC paradigm, with the same spatial parameters. The spatial parameters (spatial frequency 4 cyc/deg, target-flanker distance 4λ, eccentricity 4°) were chosen to be similar to those employed by the two studies that failed to find facilitation. Fig. 5 illustrates the stimuli used for the spatial 2AFC.

As before, we found facilitation with the temporal 2AFC paradigm, and like Williams and Hess (1998) and Zenger-Landolt and Koch (2001), we did not find significant facilitation
with the spatial 2AFC paradigm (Fig. 6: \( t_3 = 2.1, p = 0.12 \)). The difference between the two psychophysical paradigms was statistically significant (\( t_3 = 3.88, p = 0.03 \)). Therefore, this appears to be the explanation of the failure of those two studies to find facilitation in near-peripheral vision. We are not aware of another report of a difference between a vision function when measured using a spatial 2AFC paradigm compared to the results for what is apparently the same measurement conducted using a temporal 2AFC. Recently, Freeman Sagi and Driver (2001) demonstrated that facilitation, in this Polat and Sagi (1993) paradigm, depends on attention to the flankers, suggesting that attention may alter the grouping of image features, in a task typically ascribed to low-level vision. It is possible that the need for an observer to attend to “competing” stimulus configurations, as is required in the spatial 2AFC paradigm, precludes or reduces any small facilitation effect.

**Discussion**

We have found clear evidence for facilitation in the Polat and Sagi (1994b) paradigm in the near periphery for a wide range of stimulus parameters. The magnitude of the facilitation found in the periphery was only about half that found foveally for similar configurations but, nevertheless, significant and meaningful. The finding of facilitation is in agreement with the original report of Polat and Sagi (1994b) but in apparent conflict with the reports of Williams and Hess (1998) and Zenger-Landolt & Koch (2001). Those studies, however, investigated the effect using a spatial 2AFC procedure with the flanker stimuli on both sides of the fovea, while we used the temporal 2AFC procedure used by Polat and Sagi (1994b) in which the stimuli are displayed only to one side of the fovea. When we used a spatial 2AFC procedure with the same display and subjects, we also failed to find significant facilitation. Thus it appears that the difference is technically
reconciled. This difference, however, raises a number of questions regarding the nature of the effect and the role of attention in this facilitation.

It has been suggested that the facilitation of contrast detection by collinear flankers is a low level function resulting from long-range neuronal connectivity in primary visual cortex (Polat, 1999; Freeman et al., 2001). It is frequently pointed out that these facilitations appear to be low-level functions as they depend on spatial frequency, local orientation, global orientation and spatial separation. This low-level vision nature of the phenomenon was also supported by the finding of facilitation of the single cell contrast-response by collinear flankers presented outside the classical receptive field, in recordings from adult cat striate cortex (Polat et al., 1998).

If such facilitation through lateral interactions is purely a simple, low-level function, traditionally, it was not expected to be affected by the spatial organization or the presumed effect of divided attention, as we found here. Recently, Freeman et al (2001) demonstrated a dependence of facilitation on attention. Their subjects detected a target placed between two pairs of flankers (either collinear or with an orthogonal global orientation). Subjects attended only one of the flanker pairs in a secondary task. They found that only the attended flankers affected contrast threshold. Unattended flankers, even when in the same location (i.e. collinear), failed to lower the contrast threshold. It could be argued that in their case the attention was to a specific global orientation. In our spatial 2AFC procedure both targets had the same global orientation and thus our subjects attended to the correct global orientation and yet did not demonstrate facilitation. Thus the attention to global orientation alone is not sufficient, divided attention between two locations even with the same global orientations reduces the facilitation as well, further demonstrating a higher-level alteration of this local effect.
Helmholtz observed that acquisition of peripheral visual information could be enhanced by shift of attention (von Helmholtz, 1962). Grindley and Townsend (1968), who measured peripheral visual acuity with and without attention, confirmed Helmholtz’s observations. Thus, directed peripheral attention of the type required in the temporal 2AFC can improve visual acuity or letter recognition, not just the detection of targets. Generally, it has been assumed that visual functions measured using a spatial 2AFC are the same as those measured using a temporal 2AFC. We are not aware of other reports of such a difference. If this difference between the two psychometric methods was found to generalize to other visual functions, it would have implications for the interpretation of results measured using different psychometric methods. Such a difference would imply that attention is a more significant factor than previously believed, particularly if this effect was found with other “low-level” visual functions.

The issue of peripheral attention and its role in spatial facilitation is of particular interest in relation to the visual function of patients with central visual field loss, that is often due to macular disease. These patients lose their foveal vision and have to use peripheral retina for the type of spatial vision tasks normally performed by the fovea. Patients with bilateral macular disease develop a PRL that takes on the visual motor and sensory function of the fovea (Timberlake et al., 1986). It seems likely that the development of a PRL requires a shift of attention to the peripheral retina. It is interesting and important to know whether these patients can direct their attention to the PRL in the way that attention is directed to the fovea. In the spatial 2AFC procedure our subjects had to split their attention between the two peripheral target locations, presumably, resulting in reduced or eliminated facilitation. In the temporal 2AFC procedure our subjects (and apparently also Polat and Sagi (1994b)’s subjects) had to shift their attention from the fovea to a single peripheral target location and were able to do so, to some
extent, as they did demonstrate facilitation (though only about half the level of facilitation seen at the fovea). In this procedure the subjects had to suppress the natural tendency to direct attention to the fovea. This tendency is very strong and suppression of it seems to be possible only under static conditions. During eye movements or on any other transient the foveation reflex usually takes over in normally-sighted subjects (Zeevi & Peli, 1979; Zeevi, Peli & Stark, 1979). It is assumed that patients with bilateral central visual field loss eventually lose their foveation tendency and thus they may be able to shift attention more completely (or uniquely) to the PRL. If this is the case, these patients might show more facilitation than normally-sighted observers using a peripheral target at the same eccentricity. Such increased facilitation could account for the earlier reports of improved spatial vision in the near-periphery with training (reviewed by Westheimer, 2001). Westheimer (2001) found no long-term learning effect for resolution threshold or Landolt-C acuity, while noting that other tasks that, presumably, required higher-level processing do demonstrate long-term learning. Polat and Sagi (1994b) reported increased facilitation from lateral interactions with training (learning) in central vision. We plan to examine this question by testing for facilitation at the PRL of patients with unilateral and bilateral central visual field loss.
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Figures

Figure 1
Fig. 1. (A) Stimuli used in experiment A. From left to right, are the non-flanked (standard) and the four target-flanker separations examined. Subjects fixated a point to the right of stimuli (not shown). Stimuli had a spatial frequency of 2 cyc/deg. (B) Averaged data for four subjects at four eccentricities (2, 4, 6 and 12°). Facilitation (lower relative contrast threshold) was found at target-flanker separations of 4 to 8λ at eccentricities up to 6°. No facilitation was observed for the target-flanker distance of 2λ at any eccentricity. No facilitation was observed at an eccentricity of 12° for any target-flanker distance. For clarity, some data are shown horizontally offset. Error bars are 95% confidence intervals. (C-F) Individual subject data revealing the substantial between-subject variability.
Fig. 2. Experiment B examined the effect of spatial frequency, with a target-flanker distance of $4\lambda$ and eccentricity of $4^\circ$. Average data for four subjects is shown (large circles) along with individual data. Facilitation was found for frequencies of 1 to 6 cyc/deg, but not 8 cyc/deg. No difference was found between facilitation at frequencies 1 to 6 cyc/deg. For clarity, individual data are shown horizontally offset from average data. Error bars are 95% confidence intervals.
Fig. 3. Experiment C examined the effect of flanker contrast, with a spatial frequency of 2 cyc/deg, a target-flanker distance of 4λ and eccentricity of 4°. Average data for four subjects is shown (large circles) along with individual data. Facilitation was observed for all four flanker contrasts tested, and no difference in facilitation was found between the four flanker contrasts. All flanker contrasts were well above the contrast threshold of the target patch. For clarity, individual data are shown horizontally offset from average data. Error bars are 95% confidence intervals.
Fig. 4. Experiment D examined the effect of global orientation, with a spatial frequency of 2 cyc/deg, target-flanker distance of $4\lambda$ and eccentricity of $4^\circ$. Insets above the plotted data show the flanked-condition stimuli for the vertical and horizontal orientations. For clarity the fixation crosses are shown larger than used in the experiment. Average data for four subjects is shown (large circles) along with individual data. Facilitation was found for both global orientations, and no difference in facilitation was found between the two orientations. For clarity, individual data are shown horizontally offset from average data. Error bars are 95% confidence intervals.
Fig. 5. An illustration of the stimulus used for the spatial 2AFC experiment, showing the flanked condition. Subjects fixated the central fixation cross. A trial consisted of a single 98 ms presentation in which the target was either 4° to the left or right of fixation. The subjects’ task was to indicate on which side the target appeared.
Fig. 6. Experiment E examined the effect of psychophysical (2AFC) paradigm, using a spatial frequency of 4 cyc/deg, a target-flanker separation of 4λ and eccentricity of 4°. A target appeared between one of the pairs for each trial (Fig. 5). Average data for four subjects is shown (large circles) along with individual data. Significant facilitation was found for the temporal, but not the spatial 2AFC paradigm. For clarity, individual data are shown horizontally offset from average data. Error bars are 95% confidence intervals.
References


