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Facilitation of contrast detection in near-peripheral vision

Robert G. Giorgi [a], Grace P. Soong [b], Russell L. Woods [a], Eli Peli [a,*]

[a] The Schepens Eye Research Institute, Harvard Medical School, 20 Staniford Street, Boston, MA 02114-2500, USA
[b] Department of Optometry and Vision Science, The University of Auckland, New Zealand

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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 [Proc. Natl. Acad. Sci. 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 (10–80%). 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.

Keywords: Lateral interactions; Facilitation; Peripheral vision; Contrast sensitivity

1. Introduction

Contrast sensitivity for a target Gabor patch (a sinusoidal grating in a two dimensional Gaussian envelope) changes when the target Gabor patch is flanked by two other Gabor patches (flankers) with matching spatial characteristics (spatial frequency and orientation), as compared to when the target is viewed alone. Polat and Sagi (1993, 1994a) reported that maximal contrast *facilitation* (i.e., lower relative detection threshold) for flanked targets is obtained when the center-to-center distance between the target and each of the two flankers is 2–3 times the wavelength (λ) of the sinusoidal carrier. When the target–flanker distance is about λ or less the detection threshold of the target Gabor is elevated in the presence of flankers as compared to viewed alone (often referred to as *suppression*). The magnitude of relative facilitation or suppression persists over a large range of flanker contrasts (20–80%) (Polat & Sagi, 1993), and varies with spatial frequency (Woods, Nugent, & Peli, 2002), Gabor patch size (bandwidth) (Nugent, Woods, & Peli, 2002) and relative target–flanker orientation, but not on the global orientation of a collinear stimulus pattern (Polat & Sagi, 1994a). Polat (1999) and others have postulated that these lateral interaction effects are mediated by long-range connections in cortical area V1, and this claim has garnered some neurophysiological support over the last decade (Das & Gilbert, 1995; Gilbert, Das, Ito, Kapadia, & Westheimer, 1996; Kapadia, Ito, Gilbert, & Westheimer, 1995; Polat, Mizobe,

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[*] Corresponding author. Tel.: +1 617 912 2597; fax: +1 617 912 0111.
E-mail address: eli@vision.eri.harvard.edu (E. Peli).

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Pettet, Kasamatsu, & Norcia, 1998; Polat & Norcia, 1996).

Although such lateral interaction effects have been well characterized in central vision, we are aware of only limited examinations of these effects in near-peripheral vision. It is of interest to characterize lateral interactions in near-peripheral vision, particularly because persons with bilateral central scotoma (visual field loss) that includes both foveae, often due to macular disease, use an eccentric retinal locus (preferred retinal locus (PRL): Timberlake et al., 1986) to obtain important and detailed information, such as used in letter and face recognition by normally-sighted people (Parish & Sperling, 1991; Peli et al., 1991; Solomon & Pelli, 1994).

Previous reports on the effect of flankers in peripheral vision 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. In their zero pedestal-contrast condition they reported suppression rather than facilitation. It is possible that neither of these two studies that failed to find facilitation used parameters optimal for facilitation in peripheral vision. 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 series of experiments. In Experiment A we varied target eccentricities, in Experiment B we varied spatial frequencies and in Experiment C we varied the flanker contrasts. In Experiment D we compared the effect of flankers for globally horizontal and globally vertical arrangements of the targets and flankers. We found facilitation using stimulus configurations similar to those for which Williams and Hess (1998) and Zenger-Landolt and Koch (2001) reported no facilitation. 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 tested this alternative hypothesis in Experiment E, and we found that this was the important difference.

Here we present evidence that lateral interaction effects occur in near-peripheral vision over a broad range of stimulus parameters when using the temporal paradigm, but not the spatial paradigm.

2. Methods

2.1. Subjects

Subjects were three males and two females aged 18–43 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–E only. All participants read and signed an informed-consent form approved by the Institutional Review Board.

2.2. 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 × 600 pixels was used which subtended a view of 21.8° × 13.2° at a distance of 1 m. 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 pseudo 15-bit grey-level representation after gamma correction (Pelli & Zhang, 1991; Swift, Panish, & Hippensteel, 1997). The mean luminance was 40 cd/m^2 in an otherwise dark room.

2.3. 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., Fig. 1a). The equation delineating the luminance distribution of each Gabor patch was of the form:

$$L(x,y,\theta) = L_0\left\{1 + C\cos\left(\frac{2\pi}{\lambda}[(x-x_0)\cos\theta + (y-y_0)\sin\theta]\right)\mathrm{e}^{-\left[\frac{(x-x_0)^2}{\sigma_x^2}+\frac{(y-y_0)^2}{\sigma_y^2}\right]}\right\}$$

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, θ was the orientation of the carrier, and C was the patch contrast. λ was the wavelength of the carrier and was the unit used throughout the text to indicate target–flanker separations. σ_x and σ_y were the horizontal and vertical space constants, respectively. Note that we used $\sigma_x = 0.5\lambda$ and $\sigma_y = \lambda$ for

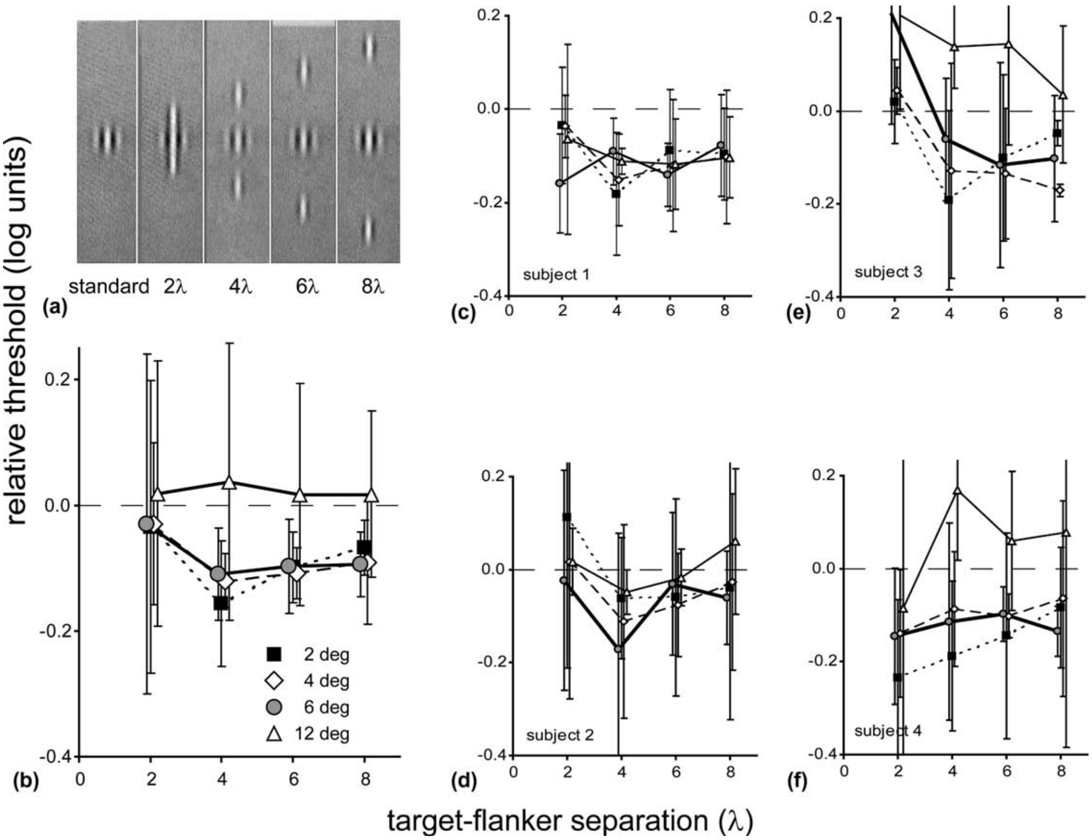

Fig. 1. Experiment A examined the effects of flanker–target distance and stimulus eccentricity on contrast thresholds. (a) Stimuli used in Experiment A. The panels from left to right show the non-flanked target (standard) and the four target–flanker separations examined (2λ to 8λ). Subjects fixated a 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 between-subject 95% confidence intervals. (c)–(f) Individual subject data revealing the substantial between-subject variability. Error bars are within-subject 95% confidence intervals based on means of 3–6 sessions per condition.

flanker size in all experiments, except Experiment D, where $\sigma_x = \lambda$ and $\sigma_y = 0.5\lambda$ for the horizontal condition. Our choice of different vertical and horizontal space constants was based on a finding by Nugent et al. (2002) that wide bandwidth flankers (across the sinusoidal grating) enhanced facilitation in central vision.

The stimulus for all experiments consisted of a central target patch (when present), either flanked (flanked condition) or not flanked (standard condition) by two equidistantly placed Gabor patches (see Fig. 1a). Both the target and flanking patches were vertically aligned (local orientation, $\theta_{\text{local}} = 0°$) except in Experiment D, where all patches were horizontally aligned ($\theta_{\text{local}} = 90°$) for the horizontal condition. 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. Flanker contrast for all experiments was 40% unless otherwise noted.

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 4λ), target and flanking patches were usually written to separate pages of memory and presented in a frame-flipping arrangement (stereo mode: Williams & Hess, 1998; Yu & Levi, 1997). In this arrangement, stimuli appear in every other frame, and hence the actual contrast is half that reported by the software [1].

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[1] All absolute contrasts were 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.

When greater contrasts were required (Experiment A, 12° eccentricity condition; Experiment B, 8 cyc/deg condition; Experiment C, 80% contrast flankers), the patches, both flankers and target, were presented in every frame.

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 22 pixels (García-Pérez & Peli, 2001; Klein, Hu, & Carney, 1996; Woods et al., 2002); different spatial frequencies (λ^{-1}) were achieved by changing viewing distance, which allowed us to leave constant the distance from the targets to the edge of the screen (except 1 cyc/deg. in Experiment B). Different viewing eccentricities were accomplished by having subjects fixate a low-contrast 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.

2.4. Procedure

A temporal-2AFC was used, except for the spatial-2AFC condition 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 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, and was applied to both the target and the flankers (when present) so that their presentation was synchronous. 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. Each staircase consisted of two practice reversals 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 suppression) is reported as the difference in the logarithm of the average contrast detection threshold for the flanked and non-flanked conditions. Using García-Pérez's (1998) simulation technique, our staircase setup, and psychometric function parameters found in a related experiment, we computed that the standard error of the contrast threshold estimator to be about 0.030 log contrast units. Hence, with four subjects, we could detect a relative contrast threshold difference (i.e. between flanked and non-flanked conditions) of about 0.045 log contrast units ($\alpha = 0.05$, $\beta = 0.2$). We used 95% confidence limits (t-distribution) as the measure of variability. These values are based on group means for any particular experimental condition and hence reflect between-subject variance (except as noted for Fig. 1c–f).

3. Results

3.1. 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 sets 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). Flanker contrast was always 40%. 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 2 cyc/deg for both target and flankers since peak contrast sensitivity moves to lower spatial frequencies with increasing eccentricity (Pointer & Hess, 1989; Rovamo, Virsu, & Nasanen, 1978). Note that we (like Polat & Sagi, 1994b) used a temporal-2AFC paradigm in this experiment (and Experiments B–D), while Williams and Hess (1998) and Zenger-Landolt and Koch (2001) used a spatial-2AFC paradigm. That difference was evaluated in Experiment E.

As shown in Fig. 1b, on average, statistically significant facilitation was found for target–flanker distances of 4, 6 and 8λ for eccentricities up to 6° (except 4°, 8λ: $t_3 = 3.0$, $p = 0.06$). No significant 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: $t_3 \geqslant 3.22$, $p \leqslant 0.05$). No significant 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 ($t_3 \geqslant 3.80$, $p \leqslant 0.03$). 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 2 cyc/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 (data not shown).

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 4–6λ. 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.

3.2. 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). For near-peripheral vision, Tailby, Cubells, and Metha (2001) proposed that relative receptive field sizes may be smaller for higher than lower spatial frequencies in near-peripheral vision, in which case facilitation might be less for higher than lower spatial frequencies.

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 4λ, we chose this separation, and used a single eccentricity of 4° as this was in our region of interest, related to people with central vision loss. Flanker contrast was 40%. 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 1–6 cyc/deg (Fig. 2). There was no significant difference in facilitation between spatial frequencies of 1–6 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).

The reduction in facilitation at the highest spatial frequency tested (8 cyc/deg) differs from central vision where greater facilitation has been reported at higher than lower spatial frequencies (Woods et al., 2002). The proposal by Tailby et al. (2001) of spatial-frequency dependent receptive field sizes was based on their examination of contrast thresholds for strings of three Gabor patches viewed eccentrically (4.8°). It is not clear whether the results for such a detection task (string of patches) is related to the lateral interactions between supra-threshold flankers and a single target patch. For central vision, Woods et al. (2002) reported that facilitation reduced once the flankers were near detection threshold. Contrast sensitivity is reduced for higher spatial frequencies in near-peripheral vision (Rovamo et al., 1978; Pointer & Hess, 1989). It is possible that when detection threshold approaches maximum contrast, that there might be an impact on facilitation, though we know of no evidence of this. The 8 cyc/deg stimuli were visible to our subjects as their detection thresholds ranged from 24.6% to 26.3%.

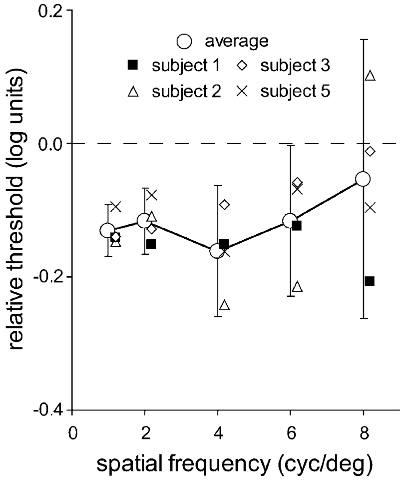

Fig. 2. Experiment B examined the effect of spatial frequency, with a target–flanker distance of 4λ and eccentricity of 4°. Average data for four subjects is shown (large circles) along with individual data. Facilitation was found for frequencies of 1–6 cyc/deg, but not 8 cyc/deg. No difference was found between facilitation at frequencies 1–6 cyc/deg. For clarity, individual data are shown horizontally offset from average data. Error bars are between-subject 95% confidence intervals.

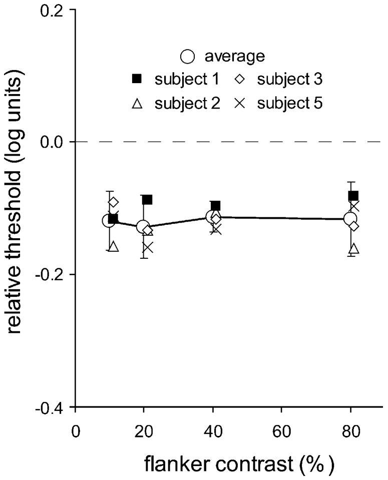

Fig. 3. Experiment C examined the effect of flanker contrast, with a spatial frequency of 2 cyc/deg, a target–flanker distance of 4λ and eccentricity of 4°. Average data for four subjects is shown (large circles) along with individual data. Facilitation was observed for all four flanker contrasts tested, 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 between-subject 95% confidence intervals.

3.3. Experiment C: effect of flanker contrast

In central vision, lateral interactions have been shown to be independent of flanker contrasts, for contrasts of 20–80% for spatial frequencies of 2–13.3 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, 10–80% and there was no significant difference in the facilitation produced by the flankers of those four contrasts (Fig. 3: $F_3 = 0.30$, $p = 0.82$). Our lowest (10%) contrast flankers were still well above the target detection thresholds of our subjects (1.4–2.0%), 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.

3.4. Experiment D: effect of stimulus global orientation

Studies in central vision have explored lateral interactions for different global orientations of the stimulus pattern (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).

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 a central scotoma (visual field loss) that includes the fovea. When central vision is lost in both eyes 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 vertically-oriented 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. Because we wish to extend these studies to people with central scotoma, it was important to determine if facilitation by flankers occurs for horizontal global orientations of the stimulus pattern, since it would be necessary to present horizontally-oriented stimuli to some individuals. We therefore performed an experiment in which four subjects viewed vertically- and horizontally-oriented stimuli (Fig. 4 insets), and compared facilitation for the two conditions. Stimuli were identical for the two conditions, except for global orientation: Target–flanker distance was 4λ, eccentricity was 4° and spatial frequency of both the target and flankers was 2 cyc/deg. Flanker contrasts were 40%.

Significant facilitation was observed for both stimulus conditions (Fig. 4). 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.

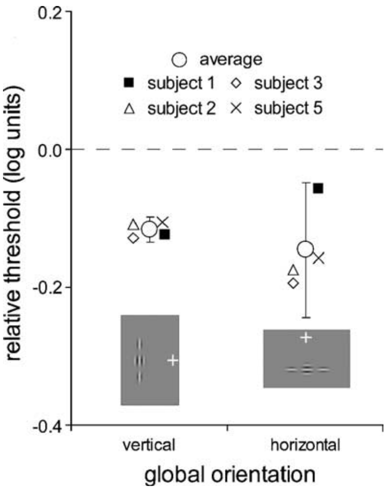

Fig. 4. Experiment D examined the effect of global orientation, with a spatial frequency of 2 cyc/deg, target–flanker distance of 4λ and eccentricity of 4°. Insets below the plotted data show the flanked-condition stimuli for the vertical and horizontal orientations. For clarity the fixation crosses 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 between-subject 95% confidence intervals.

3.5. Experiment E: temporal versus spatial-2AFC

In Experiments A–D, we found small, yet statistically 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 (this report, 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 stimulus 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°, flanker contrasts 40%) were chosen to be similar to those employed by the two studies that failed to find facilitation. Flanker contrast was always 40%. Fig. 5 illustrates the stimuli used for the spatial-2AFC.

As before, we found facilitation with the temporal-2AFC paradigm, but, 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.

Fig. 5. An illustration of the stimulus used for the spatial-2AFC condition of Experiment E, showing the flanked condition. Subjects fixated the central fixation cross (shown enlarged for clarity). 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.

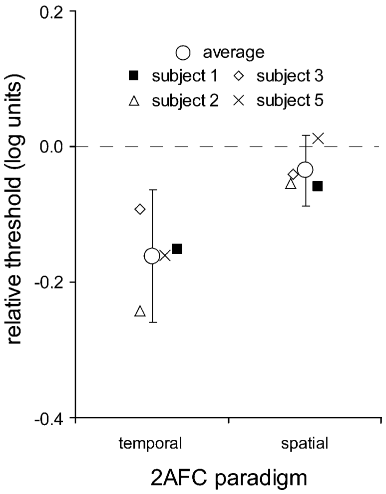

Fig. 6. Experiment E examined the effect of psychophysical (2AFC) paradigm, using a spatial frequency of 4 cyc/deg, a target–flanker separation of 4λ and eccentricity of 4°. For the temporal 2AFC condition, the target (and flankers in flanked trials) appeared to the left of the fixation cross (left inset Fig. 4). For the spatial-2AFC condition, the target appeared randomly to the left or the right of the fixation cross (between one of the pairs of flankers for flanked trials) (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 between-subject 95% confidence intervals.

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.

4. Discussion

We have found clear evidence for facilitation in the Polat and Sagi (1993) 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, statistically significant and meaningful (similar in magnitude to binocular enhancement of contrast sensitivity: Campbell & Green, 1965). 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 and 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 (Freeman et al., 2001; Polat, 1999). 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, it is 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 (1962) observed that acquisition of peripheral visual information could be enhanced by shift of attention. 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.

In Experiment E we compared two 2AFC paradigms to resolve the apparent conflict between earlier reports. As we replicated those reported paradigms, our comparison confounded spatial location of the stimuli with attention, in that 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. However, in the temporal-2AFC procedure our subjects (and apparently also Polat & Sagi's, 1994b 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). It is possible to remove the confounding of attention and spatial location in the 2AFC paradigm (e.g. Solomon & Morgan, 2003), and this is matter should be addressed.

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 our temporal-2AFC procedure the normally-sighted 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, 1998). Westheimer (1998) 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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References

Campbell, F. W., & Green, D. G. (1965). Monocular versus binocular visual acuity. *Nature, 208*, 191–192.

Das, A., & Gilbert, C. D. (1995). Long-range horizontal connections and their role in cortical reorganization revealed by optical-recording of cat primary visual-cortex. *Nature, 375*, 780–784.

Freeman, E., Sagi, D., & Driver, J. (2001). Lateral interactions between targets and flankers in low-level vision depend on attention to the flankers. *Nature Neuroscience, 4*, 1032–1036.

García-Pérez, M. A. (1998). Forced-choice staircases with fixed step sizes: asymptotic and small-sample properties. *Vision Research, 38*, 1861–1881.

García-Pérez, M. A., & Peli, E. (2001). Luminance artifacts of cathode-ray tube displays for vision research. *Spatial Vision, 14*, 201–215.

Gilbert, C. D., Das, A., Ito, M., Kapadia, M., & Westheimer, G. (1996). Spatial integration and cortical dynamics. *Proceedings of the National Academy of Sciences of the United States of America, 93*, 615–622.

Grindley, G. C., & Townsend, V. (1968). Voluntary attention in peripheral vision and its effect on acuity and differential thresholds. *Quarterly Journal of Experimental Psychology, 20*, 11–19.

Helmholtz, H. (1962). In J. P. C. Southall (Ed.), *Handbuch der Physiologischen Optik*. New York: Dover (Transl. German ed.).

Kapadia, M. K., Ito, M., Gilbert, C. D., & Westheimer, G. (1995). Improvement in visual sensitivity by changes in local context—parallel studies in human observers and in V1 of alert monkeys. *Neuron, 15*, 843–856.

Klein, S. A., Hu, Q. J., & Carney, T. (1996). The adjacent pixel nonlinearity: problems and solutions. *Vision Research, 36*, 3167–3181.

Nugent, A. K., Woods, R. L., & Peli, E. (2002). Flanker size affects visual lateral interactions (abstract). In *Association of Research Vision Ophthamology 2002 annual meeting, CD-ROM: 4718*.

Parish, D. H., & Sperling, G. (1991). Object spatial-frequencies, retinal spatial-frequencies, noise, and the efficiency of letter discrimination. *Vision Research, 31*, 1399–1415.

Peli, E., Goldstein, R. B., Young, G. M., Trempe, C. L., & Buzney, S. M. (1991). Image-enhancement for the visually-impaired—simulations and experimental results. *Investigative Ophthalmology and Visual Science, 32*, 2337–2350.

Pelli, D. G., & Zhang, L. (1991). Accurate control of contrast on microcomputer displays. *Vision Research, 31*, 1337–1350.

Pointer, J. S., & Hess, R. F. (1989). The contrast sensitivity gradient across the human visual-field—with emphasis on the low spatial-frequency range. *Vision Research, 29*, 1133–1151.

Polat, U. (1999). Functional architecture of long-range perceptual interactions. *Spatial Vision, 12*, 143–162.

Polat, U., Mizobe, K., Pettet, M. W., Kasamatsu, T., & Norcia, A. M. (1998). Collinear stimuli regulate visual responses depending on cell's contrast threshold. *Nature, 391*, 580–584.

Polat, U., & Norcia, A. M. (1996). Neurophysiological evidence for contrast dependent long-range facilitation and suppression in the human visual cortex. *Vision Research, 36*, 2099–2109.

Polat, U., & Sagi, D. (1993). Lateral Interactions between spatial channels—suppression and facilitation revealed by lateral masking experiments. *Vision Research, 33*, 993–999.

Polat, U., & Sagi, D. (1994a). The architecture of perceptual spatial interactions. *Vision Research, 34*, 73–78.

Polat, U., & Sagi, D. (1994b). Spatial interactions in human vision: from near to far via experience-dependent cascades of connections. *Proceedings of the National Academy of Sciences of the United States of America, 91*, 1206–1209.

Rovamo, J., Virsu, V., & Nasanen, R. (1978). Cortical magnification factor predicts photopic contrast sensitivity of peripheral vision. *Nature, 271*, 54–56.

Solomon, J. A., & Morgan, M. J. (2003). Flanked targets: easier to see, harder to identify. *Perception: ECVP 2003 abstracts* Available: http://www.perceptionweb.com/perception/ecvp03/0743.html.

Solomon, J. A., & Pelli, D. G. (1994). The visual filter mediating letter identification. *Nature, 369*, 395–397.

Swift, D., Panish, S., & Hippensteel, B. (1997). The use of VisionWorks (TM) in visual psychophysics research. *Spatial Vision, 10*, 471–477.

Tailby, C., Cubells, O., & Metha, A. (2001). Enhanced sensitivity for peripherally-presented collinearly-aligned stimulus elements: contour detection or spatial summation. *Clinical and Experimental Optometry, 84*, 354–360.

Timberlake, G. T., Mainster, M. A., Peli, E., Augliere, R. A., Essock, E. A., & Arend, L. E. (1986). Reading with a macular scotoma I. Retinal location of scotoma and fixation area. *Investigative Ophthalmology and Visual Science, 27*, 1137–1147.

Varadharajan, S. L., & Foley, J. M. (2003). Effects of flanking patterns on contrast detection and contrast discrimination. In *Vision Science Society Third Annual Meeting*, Abstract # SA5 (p. 102).

Westheimer, G. (1998). Is peripheral visual acuity susceptible to perceptual learning in the adult? *Vision Research, 41*, 47–52.

Williams, C. B., & Hess, R. F. (1998). Relationship between facilitation at threshold and suprathreshold contour integration. *Journal of the Optical Society of America A—Optics Image Science and Vision, 15*, 2046–2051.

Woods, R. L., Nugent, A. K., & Peli, E. (2002). Lateral interactions: size does matter. *Vision Research, 42*, 733–745.

Yu, C., & Levi, D. M. (1997). End stopping and length tuning in psychophysical spatial filters. *Journal of the Optical Society of America A—Optics Image Science and Vision, 14*, 2346–2354.

Zeevi, Y., & Peli, E. (1979). Multiple visual feedback loops in fixation tasks. In *XII International Conference on Medical and Biological Engineering* (pp. 55–56).

Zeevi, Y. Y., Peli, E., & Stark, L. (1979). A study of eccentric fixation with secondary visual feedback. *Journal of the Optical Society of America, 69*, 669–675.

Zenger-Landolt, B., & Koch, C. (2001). Flanker effects in peripheral contrast discrimination—psychophysics and modeling. *Vision Research, 41*, 3663–3675.