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Brief communication

Collinear context (and learning) change the profile of the perceptual filter

Ilmari Kurki [a,b,*], Aapo Hyvärinen [a,b], Pentti Laurinen [b]

[a] Helsinki Institute for Information Technology (HIIT), Department of Computer Science, P.O. Box 68 (Gustaf Hällströmin katu 2b), FIN-00014, University of Helsinki, Finland
[b] Department of Psychology, P.O. Box 9 (Siltavuorenpenger 20 D), FIN-00014, University of Helsinki, Finland

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Abstract

The effect of collinear context on the filter mediating the detection of a Gabor stimulus was investigated by using the classification image method. Classification images were estimated for a 1.5 cpd horizontal Gabor target and the same target flanked by two collinear Gabors horizontally 1.7° displaced from the target. The target was masked by a low-contrast white-noise mask. Obtained classification images were fitted by Gabor functions. The results show that collinear flankers increase the length of the classification image profiles along the collinear axis. At the same time, modest facilitory effects were observed in most subjects. The specificity and the amount of context-induced elongation in the classification images makes it hard to be explained by uncertainty reduction alone. In previous studies, collinear facilitation has been reported to abolish due to perceptual learning. We report a possibly related phenomenon: classification image data was re-analyzed in two parts consisting of the early and the late trials. In the latter trials, differences between the classification images in flankers and no-flankers condition are no longer significant.

Keywords: Classification image; Context; Collinear facilitation; Contrast; Noise

1. Introduction

A classical view of early vision assumes that visual filters act in a spatially localized manner, being driven only by stimuli inside the receptive field. However, it is now widely acknowledged that stimulation of areas nearby the receptive field can substantially modulate the filters' behaviour, typically suppressing the output (see e.g., Cannon & Fullenkamp, 1991; Carandini, Heeger, & Movshon, 1997; Cavanaugh, Bair, & Movshon, 2002; Foley, 1994).

In the lateral masking paradigm, these contextual interactions have been studied by examining the effect of spatially displaced Gabor masks (flankers) on the detectability of a Gabor target. Both suppressive and facilitatory effects have been reported, depending on the configuration and the distance between the flankers and the target (Polat & Sagi, 1993, 1994a). Facilitatory effects have been found in collinear configurations, where the target Gabor and the flanking Gabors lie coaxially to one another. Maximal facilitation has been reported to occur when the distance between the target and the flankers is 2–3 Gabor signal wavelengths, but facilitation is observable even at 12 wavelengths (Polat & Sagi, 1993, 1994a).

Often these lateral interactions have been interpreted in terms of excitatory and inhibitory interactions between the filters sensitive to the target and the flankers (Adini, Sagi, & Tsodyks, 1997; Chen & Tyler, 2001, 2002; Zenger & Sagi, 1996).

As facilitation can be found only in collinear, contour-like configuration, it has been suggested that these excitatory long-range connections could serve in a contour integration mechanism (Polat, 1999; Polat & Sagi, 1993, 1994a). However, there have been failures to show a link between contour integration processes and collinear facilitation or even to

* Corresponding author.
E-mail address: ilmari.kurki@helsinki.fi (I. Kurki).

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show any collinearity effects in suprathreshold stimuli (Hess, Dakin, & Field, 1998; Meese, Hess, & Williams, 2001; Williams & Hess, 1998).

Not all have agreed that this collinear facilitation phenomenon implies the existence of nonclassical excitatory long-range connections and it has been pointed out that (1) flankers may cause substantial higher level uncertainty reduction as the flankers and the target are identical except for their positions (Williams & Hess, 1998; see also Yu, Klein, & Levi, 2002) and (2) flankers may act as a pedestal stimulus to the target. In this case detection would be mediated by nonoptimal perceptual filters that lie between the target and the flanker. These filters would be sensitive to the target while receiving a weak direct excitation from the flankers (Solomon, Watson, & Morgan, 1999).

In this study, we investigated the mechanisms of contextual collinear interactions by using the classification image technique. The stimuli were masked by low-contrast white noise. The contrast of the target stimulus was adjusted to a detection threshold. In each trial, both the outcome of the trial (correct, incorrect) and the presented two noise masks were recorded. The relationship between each pixel in the stimulus and subjects' response was then analyzed by subtracting the average noise field difference producing the incorrect response from the average noise field difference that produced the correct response (Abbey & Eckstein, 2002; Abbey, Eckstein, & Bochud, 1999). If observer's performance can be modeled by a linear single filter model, the technique provides a direct way to estimate the spatial profile of the filter mediating the detection.

By measuring the classification images for a Gabor target with and without collinear flankers, it is possible to infer how flankers affect the filters used in the detection. If the flankers act by (1) reducing the uncertainty, we should observe diminishing of uncertainty effects in the collinear flankers condition. If the flankers cause (2) a pedestal effect, we should observe elongation of the target filter in the direction of the flankers. We are unable to draw exact predictions for models with long-range connections (Adini et al., 1997; Chen & Tyler, 2001, 2002; Zenger & Sagi, 1996) since they are parametric rather than image driven and thus incapable predicting the performance for our white-noise masked stimuli. These models often employ excitatory connections in long range, which might cause elongation of the classification image profile by a pedestal effect-like mechanism. However, often these models have also inhibitory connections in short range, thus the net effect would depend on the relative strengths of these two.

Furthermore, it has been suggested that collinear context may play a special role in perceptual learning (see e.g., Polat & Sagi, 1994b). We investigated the learning effects from classification images by analyzing the data separately from the early and the late trials.

Preliminary results were presented at the European Conference on Visual Perception in Budapest, Hungary, August 2004.

2. Methods

2.1. Apparatus and stimuli

Stimuli were generated by the Cambridge Research Systems 2/3 graphics board in a Pentium PC and displayed on a calibrated Nokia Multigraph 445 CRT monitor. The mean luminance of the display was 20 cdm^{-2}. The effective resolution of the monitor was 400×300 pixels and display area 38×29 cm. Subjects viewed the stimuli at the distance of 98 cm in a dimly lit room.

The stimuli were horizontal Gabor patches, which were additively masked by white noise. An example of the stimuli is presented in Fig. 1. The center frequency of the Gabors was 1.5 cpd and the width of the circular Gaussian envelope was 0.75° at half height. A rather low frequency was used to minimize the spatial uncertainty effects reported in earlier classification image studies (Ahumada & Beard, 1999). The size of the rectangular noise mask was $2 \times 2°$ with the standard deviation (rms-contrast) of 0.1 linear-contrast units (contrast is expressed here as a fraction relative to the mean luminance-1). Noise consisted of independently drawn Gaussian pseudorandom variables produced by an algorithm with an extra long period (Press, Teukolsky, Vettering, & Flannery, 1992). A new noise sample was generated for every stimulus presentation. The classification images were measured in two conditions: in a *no-flankers* condition for the central target Gabor and in a *flankers* condition for the same target with the presence of two static, high-contrast (0.4 U) flanking Gabors 1.7° (2.5 Gabor wavelengths) horizontally displaced from the target. This distance was selected to get the maximum facilitation, based on a preliminary experiment done with one subject (IK).

2.2. Procedure

A two-interval forced-choice (2IFC) procedure was used. Two consecutive stimulus intervals were presented to the subject, one of them containing the target stimulus. A trial started with the presentation of small, low-contrast central fixation crosshair for 330 ms. The fixation mark disappeared and there was a pause for 330 ms, then the first stimulus was presented for 130 ms, a pause for 330 ms, and finally the second stimulus appeared for 130 ms. The subject's task was to indicate whether the target was in the first or in the second interval by pressing a key.

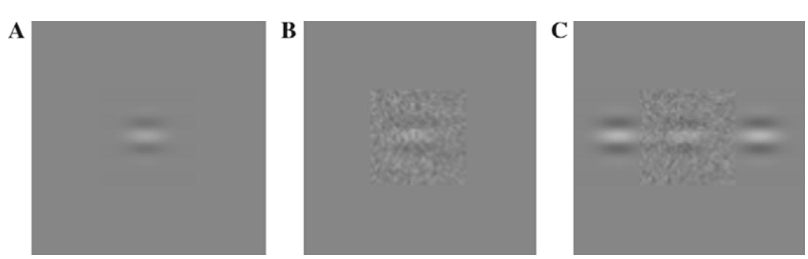

Fig. 1. Stimuli. (A) Target without noise mask. (B) No-flankers condition. (C) Flankers condition. The nominal contrast level of the target is 0.25.

Experiments were conducted in a series of 100 trials of single condition (no-flankers/ flankers). Consecutive series were of different conditions to control the practice effects.

Two subjects (TP and TR) performed the experiments in five separate sessions each containing 1000 trials per condition to assess possible learning effects.

Target contrast was adjusted for 75% correct choices using either method of constant stimulus (MOCS) and preliminary experiments to estimate the threshold (subjects VS, SS, and IK) or an adaptive QUEST Watson and Pelli (1983) method (subjects TP and TR).

Before the main experiment subjects practiced briefly with suprathreshold stimuli without the noise mask. During the first session, auditory feedback was used but after subjects become accustomed to the task, it was turned off. When MOCS was used, slight (0.001–0.002 contrast unit) adjustments of contrast level were done occasionally to keep the detection performance at about 75%. The experiments were conducted during a period of sixteen months.

2.3. Subjects

Five subjects participated in the experiment: IK is one of the authors and highly experienced in psychophysical tasks similar to this, VS and TP were experienced psychophysical subjects while SS and TR were naïve about the purposes of this experiment. All subjects had normal or corrected to normal vision.

2.4. Data analysis

Subjects ran 5000 trials per condition (except IK 4000). Classification images were estimated using the standard weighted sums method (Abbey & Eckstein, 2002). First, the pixelwise difference between the two noise masks presented in each trial was calculated. Then, noise mask differences in trials resulting in correct detection and differences in trials resulting in incorrect detection were averaged separately across the trials. Finally, the average of the incorrects was subtracted from the average of the correct detections.

To quantify the characteristics of the classification image profiles, Gabor functions were fitted to them using the method of least squares. Parameters controlling the amplitude a, horizontal extent σ_x, vertical extent σ_y, wavelength λ, and vertical and horizontal position x_c, y_c were fitted so that the error sum of squares d^2 in

$$d^2 = \sum_{xy} \left(C(x,y) - a\cos(2\pi(y-y_c)/\lambda)\exp\left(-\frac{1}{2}\left(\frac{(x-x_c)^2}{\sigma_x^2} + \frac{(y-y_c)^2}{\sigma_y^2}\right)\right)\right)^2 \tag{1}$$

was minimized. Fitting was done numerically, using the *fminsearch* function of Matlab 6.5 software.

Bootstrap methods (Efron & Tibshirani, 1993) were used for assessing statistical significance. Random picks with replacements were taken from experimentally obtained data so that the number of trials and the distribution of trial types (correct, incorrect) were the same as in the actual experiment. Then, the Gabors were fitted to each sample in the resampled data. Confidence intervals for the fitted parameters were calculated on the basis of 4000 such bootstrap samples in each condition (flankers, no flankers). The statistical significance of the differences in the fitted parameter values (p value) was obtained by the nonparametric ASL_{boot} method. Data sets for both conditions were first merged. Random picks with replacement were taken from this merged data set so that the number and distribution of the trial types matched the actual experiments. After that, Gabor functions were fitted to both of these bootstrap samples and the difference between the parameters analyzed on the basis of 10,000 pairs.

Absolute efficiencies were calculated by comparing the observed detectability indexes d'_{o} with ideal observer's d'_{i} (i.e., standard signal-to-noise-ratio of the stimulus) (see eg. Green & Swets, 1974; Tanner & Birdsall, 1958).

$$F = (d'_{\text{o}}/d'_{\text{i}})^2. \tag{2}$$

Finally, we re-analyzed the data to find out whether there were perceptual learning effects. The data for the classification images was re-analyzed in two chunks, the first consisting the first 2000 trials (two sessions) and the latter the last 3000 trials. This aggregation of data was done to reduce the noise.

3. Results

3.1. Detection performance

Detection performance is shown in Fig. 2. Performance is expressed by absolute efficiency (F) rather than threshold

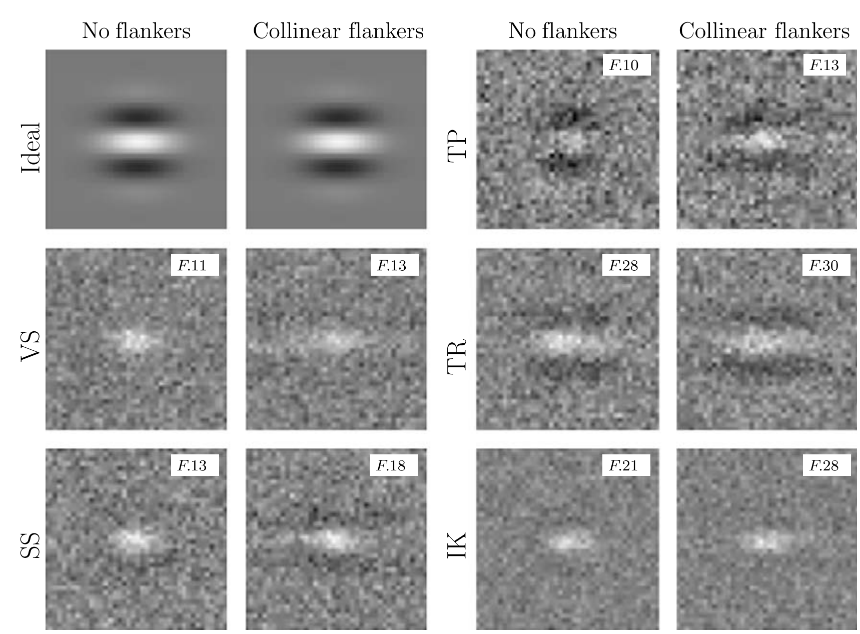

Fig. 2. The classification images for five subjects and the filter of an ideal observer. F is the absolute efficiency (see text).

contrast, because for some subjects, proportion of correct choices varied between the conditions. Results show that absolute detection efficiency is 7% (TR) to 30% (IK) better with collinear flankers (see Fig. 2).

3.2. Classification images

The classification images are presented in Fig. 2. The parameters and statistics of the Gabor fits are presented in Table 1. In all conditions and subjects, the profiles of classification images clearly resemble a single Gabor-filter. In the no-flankers condition, the profiles of the classification images are smaller than the filter of the ideal observer (or size of the target stimulus) except for subject TR.

The profiles in classification images in the flankers condition are horizontally elongated compared to the no-flankers condition. The horizontal extent estimated from the fits (σ_x) grows from 22% (TR) to 143% (VS) when compared to the no-flankers profile. In other parameters, changes are less pronounced. Seemingly significant lowering of amplitude in no-flankers condition in some subjects vanish if the norms of the filters are taken into account.

3.3. Learning effects

The time course of the experiment for horizontal extent σ_x is shown in Fig. 3. The differences in horizontal extent parameter are only evident at the beginning of

Table 1
Best-fitting parameters (a, amplitude; σ_x, horizontal extent; σ_y, vertical extent; x,y, horizontal and vertical position)

Subject	No-flankers		Collinear flankers		p value
	Best fit	95% Confidence interval	Best fit	95% Confidence interval	
Ideal					
σ_x	**5.66**		**5.66**		
σ_y	**5.66**		**5.66**		
f	**12**		**12**		
VS					
a	**2.92**	2.58 to 3.33	**1.67**	1.32 to 2.26	<.001
σ_x	**3.29**	2.84 to 3.79	**8.01**	5.06 to 11.45	<.001
σ_y	**2.24**	1.63 to 2.85	**3.38**	2.39 to 4.19	.07
f	**19.83**	15.4 to 7192.00[a]	**14.48**	12.85 to 16.71	.27
x_c	**−0.50**	−0.93 to 0.07	**−1.35**	−2.70 to 0.15	.09
y_c	**−0.18**	−0.41 to 0.06	**−0.04**	−0.30 to 0.22	.41
SS					
a	**2.74**	2.35 to 3.16	**2.42**	1.87 to 3.00	.32
σ_x	**3.22**	2.80 to 3.76	**5.08**	3.76 to 7.23	.02
σ_y	**3.54**	2.89 to 4.25	**4.03**	3.51 to 4.76	.16
f	**14.54**	13.06 to 16.23	**11.36**	10.66 to 12.05	.34
x_c	**−0.52**	−0.97 to 0.25	**−0.51**	−1.70 to 0.24	.24
y_c	**−0.37**	−0.60 to 0.11	**−0.37**	−0.50 to 0.17	.47
TP					
a	**1.65**	1.39 to 1.95	**1.43**	1.28 to 1.90	.29
σ_x	**3.66**	3.06 to 4.48	**7.15**	4.84 to 8.23	<.001
σ_y	**6.65**	5.96 to 7.57	**5.56**	4.77 to 6.28	.06
f	**10.72**	10.22 to 11.26	**10.42**	9.88 to 10.91	.40
x_c	**0.12**	−0.71 to 0.51	**0.45**	−2.37 to 0.52	.68
y_c	**−0.20**	−0.39 to 0.01	**−0.30**	−0.54 to 0.17	.49
TR					
a	**2.11**	1.90 to 2.37	**1.80**	1.62 to 1.99	.03
σ_x	**6.52**	5.83 to 7.23	**7.95**	7.12 to 8.91	.01
σ_y	**5.37**	4.75 to 6.12	**5.90**	5.35 to 6.52	.25
f	**12.77**	12.27 to 13.31	**12.07**	11.66 to 12.50	.04
x_c	**0.35**	−0.39 to 1.08	**−0.31**	−1.32 to 0.21	.15
y_c	**0.23**	0.08 to 0.39	**0.13**	−0.03 to 0.26	.32
IK					
a	**3.48**	3.11 to 3.95	**3.49**	3.12 to 4.00	.98
σ_x	**3.23**	2.89 to 3.59	**3.97**	3.31 to 4.60	.03
σ_y	**3.07**	2.52 to 3.58	**2.63**	2.28 to 3.07	.21
f	**13.09**	12.00 to 14.28	**12.54**	11.58 to 13.81	.49
x_c	**−0.01**	−0.40 to 0.47	**0.00**	−0.87 to 0.09	.94
y_c	**0.00**	−0.03 to 0.34	**−0.01**	−0.15 to 0.18	.96

Confidence intervals and p values were obtained by bootstrap estimation.
[a] Upper bound of the confidence interval could not be estimated reliably.

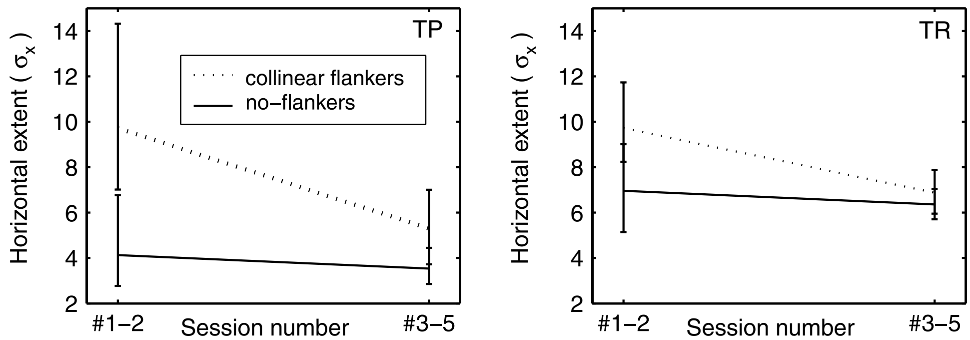

Fig. 3. The effect of practice (TP,TS). Best fits for the horizontal extent (σ_x) of the estimated filter as a function of trial number. Data is analyzed in the independent chunks of 2000 and 3000 trials (see text). Solid lines: flankers condition. Dashed lines: no-flankers condition. Error bars represent 95% confidence interval. Data in other subjects (not shown) are comparable. The difference between the early and the late session is statistically nonsignificant ($p > .1$) in no-flankers condition but significant ($p < .03$) in collinear flankers condition for both subjects. p values were estimated by bootstrap methods.

the experiments. Practice seems to cause retuning of the profile of the classification images so that the best fitting filters converge during learning, in a time period of about two sessions.

4. Discussion

Our results show that collinear masks change the profile of the classification images: adding the flankers elongates the perceptual filter towards the flankers. This elongation was significant ($p < .05$) for every subject. The elongation in classification image profiles is likely to be linked to the facilitation reported in earlier studies without the noise masks. In fact, flankers slightly increased the absolute efficiency.

The perceptual learning causes significant retuning in the horizontal axis of the classification image profile. After 2000 trials of practice, the difference in the horizontal axis is not apparent any more. Practice in the lateral masking paradigm at a single flanker distance (without the noise masks) is known to destroy the collinear facilitation (Polat & Sagi, 1994b). It seems that after enough training, observers adopt a common strategy in both conditions. This suggests that contextual information is not used in an optimized detection strategy. Learning effects here seem to operate mostly by retuning of the filter towards the ideal profile, in line with earlier studies (Gold, Sekuler, & Bennet, 2004; Li, Levi, & Klein, 2004).

Earlier classification image studies have shown that using a high-frequency Gabor-target leads to a featureless classification image, likely to be explained by the uncertainty of phase or location of the target (Ahumada & Beard, 1999). For the low-frequency target we used here, classification images in the no-flankers condition are generally smaller than the filter of the ideal observer, especially on horizontal axis, and have broader orientation (and on most subjects, frequency) tuning. This suggests uncertainty about the spatial frequency and orientation of the target stimulus.

Might the elongation caused by collinear flankers be explained by uncertainty reduction? A simulation[1] was done to examine the issue. The task and the stimuli were identical to that of the experiment. We simulated a model observer having both orientation and spatial uncertainty. The observer's response was based on the maximum of outputs of a filter bank having the parameters of the ideal filter but differing in orientation and spatial location.

Simulations show that orientation uncertainty causes the classification images to underestimate the horizontal width of the receptive area. However, the effect is quite modest. Only in the maximum values, effects comparable to the empirical data (up to 140%) was seen. Orientation uncertainty does not explain why classification images are in some cases more elongated than the ideal profile (although this is significant just in TP; VS $p = .07$, TP $p > .1$). Spatial uncertainty along the horizontal axis could explain this, but again only in the extreme values. As the research on this subject has barely begun, we cannot ascertain how plausible such an assumption is. In an initial study by Murray, Bennet, and Sekuler (2005), spatial uncertainty could not explain the uncertainty effects in the classification images. Thus, although an uncertainty based explanation is not impossible, it requires rather specific and ill-founded assumptions. Furthermore, the classification images in the collinear-flankers condition are not necessarily more ideally tuned than in no-flankers condition: we estimated the net effect of parameter changes to the sampling efficiency (ρ^2) of a linear single filter observer having the best fitting templates by calculating the squared dot product between the fitted profile W_f and the ideal profile W_i (see also Li et al., 2004):

$$\rho^2 = \left(\sum_{x,y} W_f(x,y) W_i(x,y) \right)^2. \quad (3)$$

Results show that there is a notable increase just in two subjects (SS,VS).

[1] Details are available on request.

We think that the pattern of results here is to be explained more fruitfully in terms of sensitivity changes in the low-level filters. Perhaps the simplest such explanation—an analogue to the model suggested by Solomon et al. (1999)—is that the flankers act like pedestal stimulus to the filters between the target and the flankers. If the outputs of the filters are thresholded, the net effect of the target and the external noise in the stimulus will occasionally cause excitation exceeding the threshold in these filters (see also Blackwell, 1998), which could explain the elongation in the classification images. Our results do not rule out the possibility of more complex interactions if these act by increasing (rather selectively) the sensitivity of the filters situated near to the ends of the target.

To conclude, using classification images we have shown that collinear flankers change the profile of the perceptual filter, making it more elongated. The amount and the specificity of the change makes the hypothesis of uncertainty reduction on a higher level problematic and suggests that the observed changes in the classification images reflect at least partially an increase of the sensitivity of low-level filters. During the data acquisition, differences between the profiles greatly diminish and observers seem to adopt a common detection strategy in both conditions. This may be related to disappearance of the collinear facilitation in contrast threshold studies (Polat & Sagi, 1994b). It suggests that the optimized detection strategy is the same in both conditions. Furthermore, it can be taken as further evidence that perceptual learning operates by retuning of the perceptual filters.

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