A ‘first stage’ central performance drop in a Gabor luminance-modulation detection task

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Abstract—In an experiment, 20 participants had to detect a backward masked Gabor luminance-modulation target imposed on a field of uniform luminance at varying eccentricities along the horizontal meridian. Different spatial frequencies were used as target modulations. Results for a 7.0 c/deg target patch showed peak detection performance at the center of the visual field and a steady decrease toward the periphery. For 1.0 c/deg, 0.75 c/deg, and 0.5 c/deg target patches, in contrast, the peak was several degrees off retinal center and decreased steadily toward the center. Findings not only confirmed the familiar sensitivity loss toward peripheral areas for high spatial frequencies, but also indicated a sensitivity loss toward central areas for low spatial frequencies. It is concluded that they further support Gurnsey *et al.*'s (1996) ‘mismatch hypothesis’ extending its scope to also include ‘first-stage’ stimuli.

Keywords: Eccentricity; central performance drop; texture; spatial frequency.

INTRODUCTION

When looking at an image, observers can usually quickly distinguish several, apparently distinct sub-regions within it (referred to as perceptual segregation, visual segmentation). Numerous studies have shown that this also holds for retinal areas outside the fovea centralis — at least when segmentation is caused by some basic image properties such as differences in luminance, texture (i.e. local spatial structure), color, motion, or disparity. However, segmentation performance generally drops with increasing eccentricity. Although there is some debate regarding which drop gradient should be associated with which image property, there seems to be a broad consensus that all proposed gradients *drop* with increasing eccentricity (see, for an overview, Strasburger, 2003). This drop in performance is

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assumed to be caused by some types of sensitivity loss in peripheral vision. It is further assumed that such sensitivity loss might be produced by, for instance, increasing receptive field sizes, achromatic aberration, or receptor spacing. We shall refer to this effect of declining performance with increasing eccentricity as the Peripheral Performance Drop (PPD).

However, the literature shows some exceptions to this general rule (see, for an overview, Poirier and Gurnsey, 2005). Take, for example, a texture boundary composed of line texture elements (texels) of fixed sizes with a difference in orientation along this boundary. When this boundary is moved toward peripheral retinal regions, performance actually *improves* up to a certain peak (Gurnsey *et al.*, 1996, 2004; Joffe and Scialfa, 1995; Kehrner, 1987, 1989; Meinecke and Kehrner, 1994; Morikawa, 2000; Potechin and Gurnsey, 2003; Yeshurun and Carrasco, 1998, 2000). We shall refer to this effect of improving performance with increasing eccentricity as the Central Performance Drop (CPD).

To account for this CPD, Gurnsey *et al.* (1996) proposed the so-called ‘spatial mismatch hypothesis’; that is, the CPD is caused by a spatial mismatch between the scale of the stimuli and the scale of spatial filters. The hypothesis postulates a sensitivity loss for low spatial frequencies within the central visual field *versus* more peripheral areas of the retina. In light of this approach, the CPD might be due to stimuli being too coarse for the center of the retina.

From a theoretical point of view, orientation-contrast stimuli might be referred to as ‘second-stage’ stimuli, because orientation is a stimulus property that always needs a carrier. Unlike, for instance, color or luminance, it cannot exist as such. Frequently used orientation carriers include lines, gratings, or Gabor patches. Accordingly, virtually all recent models of orientation-contrast-induced texture segmentation are based on two successive stages of spatial filtering (e.g. Chubb and Landy, 1991; Landy and Bergen, 1991; Malik and Perona, 1990). A first stage performs a convolution between the input texture and localized spatial filters tuned to defined spatial frequencies and orientations. The output of these filters is then passed on (after rectification or squaring) to a subsequent second stage that performs some kind of spatial pooling and spatial derivative operation to segment between target and background textures.

Returning to the spatial mismatch hypothesis, it is necessary to decide *where* to postulate this mismatch: on the first, on the second, or on both stages of spatial filtering. Gurnsey *et al.* (1996) and also Poirier and Gurnsey (2005) favored the second stage of spatial filtering, mainly because of the experimental finding that varying the texel spacing (i.e. varying the distances between texels without modifying the texels as such) had a major impact on the curve of the CPD. Poirier and Gurnsey (2005) argued that “for example *increasing* the distance between texels may *reduce* the salience of a texture edge because the texels of adjacent textures are not sufficiently close to engage the second-layer filter.” (Poirier and Gurnsey, 2005, p. 2441).

Yeshurun and Carrasco (2000) also concluded that the second stage of spatial filtering must elicit the CPD. However, they followed a different line of reasoning: They used oriented Gabor patches (instead of lines) with two different spatial frequencies to gather their data (Experiment 1). As in the experiments using line texels, the feature discriminating between target and background textures was orientation contrast; the spatial frequency of the Gabor patches always remained identical in both target and background areas. Their data revealed a CPD that was unaffected by the spatial frequency of the Gabor patches. They concluded “that the central performance drop was not mediated by the characteristics of the first-order filters” (Yeshurun and Carrasco, 2000, p. 623).

To summarize so far: the literature reveals converging evidence that the CPD observed with textures containing orientation contrasts should be attributed to the second stage of spatial filtering: the segmentation stage or texture-discrimination stage. As a result, one could assume that the CPD would vanish in a task with no need for texture discrimination; namely, in a detection task requiring only first-stage spatial filtering.

However, some experimental findings seem to contradict this assumption: (1) Bryngdahl (1966) reported results from experiments conducted with first-stage stimuli (i.e. spatial sine-wave stimuli) indicating a central sensitivity loss for low spatial frequencies, that is, a CPD (a finding that has never been addressed in the literature). (2) Van der Wildt *et al.*, (1976) also reported evidence for the possible existence of a first-stage CPD, although only inferred indirectly: They projected sinusoidal patterns of increasing width to the central retina of their subjects and found an increasing visibility for these patterns; especially for low spatial frequencies. However, the observed increase in visibility was higher than that to be anticipated through probability summation, based on assuming a homogeneous retina. The authors concluded that “...especially for low spatial frequencies, the most sensitive part of the retina is not the central part of the fovea” (van der Wildt *et al.*, 1976, p. 1052). (3) Finally, a CPD appears in two of the figures (Fig. 4 and Fig. 6) presented in Koenderink *et al.* (1978), although the authors do not comment on this in their text.¹

EXPERIMENTAL

To further test the first stage CPD hypothesis, we imposed Gabor luminance modulations (serving as targets) on a context field of uniform luminance. Bearing Gurnsey *et al.*'s (1996) spatial mismatch hypothesis in mind, we used targets with four different spatial scales, that is, four different spatial frequencies (7.0 c/deg, 1.0 c/deg, 0.75 c/deg, 0.5 c/deg).

To enhance compatibility with earlier findings, we tried to match the experimental conditions as closely as possible to those eliciting a CPD in other studies. Because supra-threshold stimulation might be a prerequisite for the emergence of a CPD (Gurnsey *et al.*, 1996), we set up Gabor targets of supra-threshold luminance

contrast (i.e. 11% Nominal contrast). Strasburger (2003) has reported a detection threshold of 0.5% for Gabor patches of comparable size. The Nominal contrast of a Gabor patch is defined as the Michelson contrast of the sinusoidal grating without the Gaussian envelope. We decided to choose the Nominal contrast as contrast measure, because Peli (1977 [1997 in ref. list]) showed the existence of a good correspondence between the Nominal contrast of a Gabor patch (as a physical measure) and the perceived contrast of this patch as estimated by his subjects (as a psychological measure). The data indicate that this holds for Gabor patches with bandwidths below approximately one octave. As a matter of fact, three of the four Gabor patches as used in our experiments were given a bandwidth (bw) below one octave (spatial frequency 1 (sf1) = 7 c/deg, bw1 = 0.1 octaves; sf2 = 1 c/deg, bw2 = 0.68 octaves; sf3 = 0.75 c/deg, bw3 = 0.92 octaves; sf4 = 0.5 c/deg, bw4 = 1.45 octaves).

Methods

Participants. Twenty participants (ten in each of the two experimental parts) were paid to participate in the experiment. All had normal or fully corrected visual acuity.

Apparatus. A Macintosh PowerBook G4 controlled the experiment, and stimuli were presented on a LaCie electron 22 blue4 CRT at 120 Hz frame rate. The three color channels of the display were hardware-calibrated using a LaCie blue eye 2 vision Calibrator to ensure strictly achromatic stimuli at each of the 256 possible levels of luminance. The computer was controlled by a MATLAB program extended by the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997). The Psychophysics Toolbox was also used to perform a Gamma correction of the display leading to a linear relationship between input voltage and output luminance. Luminance was measured with a Minolta Luminance Meter LS-110.

Participants sat at a table with their heads in a head- and chin-rest. The display monitor was positioned at an observation distance of 60 cm with the direction of gaze inclined slightly downward. Participants responded to the stimuli by pressing one of two mouse keys with the index fingers of either hand.

Stimuli. The stimuli contained three different areas: (a) the screen area (1024×786 pixels = $37.0^\circ \times 29.5^\circ$ of visual angle; homogeneous luminance = 8.2 cd/m^2); (b) the context area, centered within the screen area (861×357 pixels = $31.0^\circ \times 13.7^\circ$ of visual angle; homogeneous luminance = 50.6 cd/m^2); and (c) the cosine-modulated Gabor target patch, stripes oriented horizontally, standard deviation of the isotropic Gaussian envelope = 0.81° , integrated luminance = 50.6 cd/m^2 for three of the four Gabor targets. The 0.5 c/deg Gabor shows a slightly enhanced integrated luminance (0.3% of its maximum) because of a dc-component caused by its large bandwidth (i.e. few cycles under its envelope). The Nominal luminance contrast of the target peaked at 56.13 cd/m^2 .

The position of the target patch within the context area was varied along the horizontal meridian. To conduct a d' analysis, trials were blocked by location. Within each block, the target patch could appear in only two locations $\pm x^\circ$ from fixation. These locations were $\pm 0.76^\circ$, $\pm 2.27^\circ$, $\pm 3.78^\circ$, $\pm 5.29^\circ$, $\pm 6.81^\circ$, and $\pm 8.32^\circ$. The experiment was conducted in two parts: part one: 7.0 c/deg and 0.5 c/deg Gabor patches; part two: 1.0 c/deg and 0.75 c/deg Gabor patches.

Mask. The mask, which appeared after stimulus presentation, was the same size as the context area (i.e. $31.0^\circ \times 13.7^\circ$ of visual angle) and had a homogeneous luminance of 53.4 cd/m². We selected a mask luminance slightly above the context luminance (50.6 cd/m²) because, in a first approach, we wanted to start with identical target contrasts in all conditions. The mask luminance turned out to be the best way to ensure a medium level of performance (i.e. to avoid bottom or ceiling effects), because varying presentation time proved to be unacceptably coarse as it was restricted to whole display frame steps (8.3 ms in the present case; see below).

Figure 1 shows the two stimuli with the highest and lowest target spatial frequencies (context area containing a target patch in the leftmost position; i.e. -8.32°). Figure 1a shows the 7.0 c/deg Gabor-patch; Fig. 1b, the 0.5 c/deg Gabor patch. To convey the spatial structure of the stimuli in this figure, the target contrast is more enhanced than that used in the actual experiment.

Procedure. Conditions and target locations were blocked. A target location block consisted of 104 trials — 52 positive trials with a target presented within the context area either to the left or right side of fixation (26 times left and 26 times right in random sequence), and 52 negative trials with no target (i.e. context only). The sequence of positive and negative trials within a target location block and the sequence of target location blocks were also randomized.

Each stimulus presentation was preceded by a small circle (diameter = 10 pixels) displayed at screen center. This informed the participant that the computer was ready, and that he or she could summon the first or next stimulus display by pressing both mouse keys simultaneously. The computer then replaced the circle by a fixation point (1 pixel) followed automatically by the stimulus after 800 ms. The ready circle and the fixation dot were displayed with a luminance of 0.1 cd/m² on the screen area with a homogeneous luminance of 8.2 cd/m². The stimuli (either pure context or context + target) were displayed within four display frames (i.e. for 33.3 ms), before being replaced by the mask. The mask remained on the screen until the participant responded by pressing either the left (target absent) or right key (target present). One short acoustic click informed the participant that a response was correct; a short double click, that it was false. After that, the mask was deleted and the circle reappeared on the screen, indicating that a new trial could be initiated. Each target location block started with a sequence of 10 ‘warm-up’ trials with exposure durations of nine display frames (i.e. 75 ms).

Figure 1. Stimuli. (a) Condition 7.0 c/deg. (b) Condition 0.5 c/deg. The horizontal position of the target patch (presented with a probability of $p = 0.5$ within the context area) was varied along the horizontal meridian.

Participants were instructed to focus on the fixation point as closely as possible and respond as quickly as they could while avoiding false alarms. Four sessions were administered, each lasting about 45 min. Session 1 was excluded from the data analysis. The sequence of the two conditions within each part of the experiment was altered and balanced across participants and was changed for each participant from session to session.

Results

For each participant, trials in which the reaction time exceeded the block mean by three standard deviations were dropped from the analysis.

Figures 2 and 3 present the percentage of hits, the percentage of false alarms (Fig. 2), the d' values, and the reaction times (Fig. 3) as functions of the eccentricity of the target. The d' values were calculated by averaging individual d' s across

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Figure 2. Experimental results. Hits and false alarms (%), plotted against retinal eccentricity of the target (degrees of visual angle) for Condition 7.0 c/deg (filled circles), Condition 1.0 c/deg (open circles), Condition 0.75 (open squares), and Condition 0.5 c/deg (filled squares). Error bars give $\pm$ s.e. for each condition end each eccentricity.

subjects. A trend analysis (Keppel and Wickens, 2004) was used to test the statistical significance of the apparent decrease (Cond. 7.0 c/deg) and increase (Conds. 1.0 c/deg, 0.75 c/deg, 0.5 c/deg) in mean d' values (see Fig. 3). This revealed a significant linear trend for all conditions (Cond. 7.0 c/deg: $F(1, 9) = 33.56$, $p < 0.001$; Cond. 1.0 c/deg: ($F(1, 9) = 8.20$, $p < 0.05$; Cond. 0.75 c/deg: $F(1, 9) = 13.09$, $p < 0.01$; Cond. 0.5 c/deg: $F(1, 9) = 73.92$, $p < 0.001$).² Thus, it can be stated that d' values (i.e. sensitivity) decrease with increasing eccentricity

Figure 3. Experimental results. d' values (calculated by averaging individual d' values across subjects) and reaction times (ms) (averaged across subjects), plotted against retinal eccentricity of the target (degrees of visual angle) for Condition 7.0 c/deg (filled circles), Condition 1.0 c/deg (open circles), Condition 0.75 (open squares), and Condition 0.5 c/deg (filled squares). Error bars give $\pm$ s.e. for each condition and each eccentricity. The RT curves show reaction times for hits (i.e. correct yes-responses).

in Cond. 7.0 c/deg and increase with increasing eccentricity in Conds. 1.0 c/deg, 0.75 c/deg, and 0.5 c/deg.

A speed-accuracy trade-off could be ruled out because the mean d' values and the mean RT values related inversely (high d' values corresponded with low RT values; see Fig. 3).

Discussion

We can now return to the question whether ‘first-stage’ stimuli might be capable of eliciting a CPD. Our results show a marked dependence of sensitivity on spatial frequency when a Gabor luminance-modulation target has to be detected within a homogeneous context (i.e. a field of uniform luminance) at different eccentricities along the horizontal meridian. For low-frequency targets (i.e. 1.0 c/deg, 0.75 c/deg, and 0.5 c/deg), we find a reduced sensitivity (operationalized as d' values) in the central visual field compared with more peripheral retinal areas (i.e. a CPD emerges). For the high-frequency target (i.e. 7.0 c/deg), sensitivity peaks in the central visual field followed by a steady decrease toward more peripheral areas (i.e. a PPD appears).

Our results agree with Gurnsey *et al.*'s (1996) mismatch hypothesis: Under the given experimental conditions (supra-threshold stimulation, short presentation times with subsequent backward masking), the visual system seems to be band pass with respect to Gabor modulations of different spatial frequencies. Outside central retinal areas, we find a high-frequency attenuation: Sensitivity for the high-frequency target drops with increasing eccentricity. However, within central retinal areas, we find a low-frequency attenuation: Sensitivity for low-frequency targets drops with decreasing eccentricity.

These results indicate that the potential emergence of a CPD is not restricted to the processing of second-stage stimuli (e.g. texture segregation by orientation contrasts), but can be anticipated under conditions of first-stage stimulus processing as well (e.g. Gabor luminance-modulation detection; at least under conditions as reported here).

This leads us to ask why Yeshurun and Carrasco (2000) found no impact of the frequencies of the Gabor patches comprising their target- and background textures on the course of performance curves (i.e. hit rates). We see two possible reasons for this: (1) These authors used two spatial frequencies, namely 2 c/deg and 6 c/deg. However, the present findings seem to indicate that the CPD elicited by first-stage Gabor modulation is restricted to lower frequencies (actually, the emergence of the CPD in our Cond. 1 c/deg appears to be rather weak; see Fig. 3).³ Thus, Yeshurun and Carrasco's (2000) two Gabor frequencies might have produced very similar levels of performance on the first stage of processing, probably both with a trend to central peak performance. (2) If a CPD is to be expected on the first as well as the second stage of visual processing, we cannot rule out the possibility that in tasks activating both stages, a (large) CPD on one stage might ‘mask’ a (small) CPD on the other. This may well be what happened in Yeshurun and Carrasco's (2000) study.

CONCLUSIONS

In summary, the emergence of a ‘first-stage’ CPD in our experiments extends the scope of the mismatch hypothesis by indicating that this mismatch is not restricted to

the processing of ‘second-stage’ stimuli. However, it is necessary to bridge the gap between our results and studies reporting a decreasing performance with increasing eccentricity (PPD studies; e.g. Rovamo *et al.*, 1978). Several factors might be responsible for these conflicting results, such as stimulus contrast, presentation time, or the use of a backward mask (see Gurnsey *et al.*, 1996). A careful variation of these stimulus factors might help to clarify their impact in eliciting either a CPD or a PPD. This might also promote the formulation of computational models dealing with CPD and related phenomena, which, in turn, might give more insight into the underlying processes.

There has been some debate on whether such models require a temporal component or whether it might be sufficient to formulate them in strictly spatial terms (see, for a review of different approaches, Gurnsey *et al.*, 1996). The temporal approach focuses mainly on the potentially disruptive effects of a backward mask in tasks with short SOAs. However, the data presented in this paper further support the strictly spatial approach for the following reason. If central retinal areas were to be linked to lower processing (and/or transmission) speed (as proposed by Morikawa, 2000), performance should always suffer from a central (compared with a more peripheral) presentation. However, this is not supported by our data: we found both a CPD and a PPD under identical SOA conditions.

Finally, Gurnsey *et al.*’s (1996) ‘spatial mismatch hypothesis’ seems to provide the most parsimonious account of the data presented here.

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NOTES

1. We thank an anonymous reviewer for drawing our attention to this reference.
2. Whether higher-order trends (i.e., some form of curvature) could be helpful in describing the relationship between sensitivity and eccentricity cannot be considered yet given the present state of the discussion.
3. Further research is needed to clarify whether this might be due to some sort of ceiling effect.

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