Vision Research 49 (2009) 2927–2935

Contents lists available at ScienceDirect

Vision Research

journal homepage: www.elsevier.com/locate/visres

Suppression pathways saturate with contrast for parallel surrounds but not for superimposed cross-oriented masks

Tim S. Meese *, Kirsten L. Challinor, Robert J. Summers, Daniel H. Baker

School of Life and Health Sciences, Aston University, Birmingham B47ET, UK

ARTICLE INFO

Article history:
Received 26 February 2009
Received in revised form 9 September 2009

Keywords:
Human vision
Contrast gain control
Psychophysics
Surround suppression
Crowding
XOM
XOS
Detection

ABSTRACT

Contrast masking from parallel grating surrounds (doughnuts) and superimposed orthogonal masks have different characteristics. However, it is not known whether the saturation of the underlying suppression that has been found for parallel doughnut masks depends on (i) relative mask and target orientation, (ii) stimulus eccentricity or (iii) surround suppression. We measured contrast-masking functions for target patches of grating in the fovea and in the periphery for cross-oriented superimposed and doughnut masks and parallel doughnut masks. When suppression was evident, the factor that determined whether it accelerated or saturated was whether the mask stimulus was crossed or parallel. There are at least two interpretations of the asymptotic behaviour of the parallel surround mask. (1) Suppression arises from pathways that saturate with (mask) contrast. (2) The target is processed by a mechanism that is subject to surround suppression at low target contrasts, but a less sensitive mechanism that is immune from surround suppression 'breaks through' at higher target contrasts. If the mask can be made less potent, then masking functions should shift downwards, and sideways for the two accounts, respectively. We manipulated the potency of the mask by varying the size of the hole in a parallel doughnut mask. The results provided strong evidence for the first account but not the second. On the view that response compression becomes more severe progressing up the visual pathway, our results suggest that superimposed cross-orientation suppression precedes orientation tuned surround suppression. These results also reveal a previously unrecognized similarity between surround suppression and crowding (Pelli, Palomares, & Majaj, 2004).

1. Introduction

Masking is the phenomenon where one stimulus (the mask) makes a second stimulus (the target) more difficult to see. In this paper, we restrict our considerations to the situation where the mask is substantially different from the target in one or more dimensions (i.e., it is not a pedestal). This includes situations where (i) the mask and target are superimposed, but have very different orientations (cross-orientation suppression) and (ii) when the mask surrounds the target (surround suppression) (see Meese, Summers, Holmes, & Wallis, 2007; Smith, Bair, & Movshon, 2006 and Petrov & McKee, 2009 for recent reviews).

Studies from single-cell physiology (Kimura & Ohzawa, 2009; Li, Peterson, Thompson, Duong, & Freeman, 2005; Nolt, Kumbhani, & Palmer, 2007; Smith et al., 2006; Tailby, Solomon, Peirce, & Metha, 2007; Webb, Dhruv, Solomon, Tailby, & Lennie, 2005) and psychophysics (Meese & Hess, 2004; Paffen, van der Smagt, te Pas, & Verstraten, 2005; Petrov, Carandini, & McKee, 2005; Baker, Meese, & Summers, 2007; Cai, Zhou, & Chen, 2008; Cass & Alais, 2006; Meese & Baker, 2009; Petrov & McKee, 2009) have shown that these forms of masking involve multiple processes of suppression. For example, Petrov et al. (2005) performed contrast detection experiments and found that parallel (co-oriented) surround (doughnut) masking was orientation tuned, and diminished when a cross-oriented mask superimposed the doughnut mask. This implies that for their stimuli, cross-orientation suppression asserts its influence earlier in the processing stream than suppression from parallel doughnuts, because the former interferes with the latter. Petrov et al. also found that when a parallel doughnut mask was added to a superimposed cross-oriented mask, the level of masking increased, consistent with a cascade of suppressive influences.

A striking difference between the two forms of suppression above is that on double-log coordinates, superimposed cross-oriented masking accelerates with mask contrast (Foley, 1994; Medina & Mullen, 2009; Meese, 2004; Meese, Challinor, & Summers, 2008; Meese & Holmes, 2002), whereas masking from a parallel

* Corresponding author. Fax: +44 121 333 4220.
E-mail address: t.s.meese@aston.ac.uk (T.S. Meese).

0042-6989/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.visres.2009.09.006

Table 1
Matrix of potential results for Experiment 1 and their interpretations. Bold entries indicate previously established results. Entries in italics indicate the factorial combination of the two likely outcomes for the two novel conditions. The last column shows an interpretation for each of the possible outcomes.

Eccentricity (°)	Superimposed cross-oriented masking	Doughnut cross-oriented masking	Doughnut parallel masking	Interpretation
0	**Accelerates**	**Small or no effect**	**Small or no effect**	n/a
4.5	*Accelerates*	*Accelerates*	**Compresses**	Compression is specific to parallel doughnut masking
4.5	*Accelerates*	*Compresses*	**Compresses**	Compression is specific to doughnut masking
4.5	*Compresses*	*Accelerates*	**Compresses**	Complex interpretation required
4.5	*Compresses*	*Compresses*	**Compresses**	Compression is specific to peripheral masking

doughnut saturates[1] (Petrov et al., 2005; Zenger et al., 2000). These different operating characteristics suggest that fundamentally different processes of suppression are involved. However, (substantial) elevation of psychophysical contrast detection threshold has been found for parallel doughnuts only when the entire stimulus is placed away from the fovea (Petrov et al., 2005; Snowden & Hammett, 1998; see also Xing and Heeger (2000) for contrast-matching). Similarly, masking from cross-oriented surrounds has also been found to be weak or absent in the fovea (Meese et al., 2007; Saarela & Herzog, 2008; though see Meese & Hess, 2004). Thus, it is not clear from previous studies whether the saturating characteristic of suppression is specific to parallel masks, doughnut masks or masking in the periphery. We resolve this issue here by measuring contrast-masking functions for parallel and cross-oriented doughnut masks, and cross-oriented superimposed masks for 1 c/deg patches of target grating in central and peripheral vision.

Table 1 summarises the established outcomes from previous studies in bold, the likely possibilities for the unknown outcomes in italics, and their various interpretations in the right hand column. The results of our first experiment are consistent with those in the second row. We present two hypotheses for the cause of the saturating masking functions and test these with a second experiment in which we manipulated the size of the hole in a doughnut mask. The results support the hypothesis that the pathway mediating surround suppression saturates with contrast. They do not support the competing hypothesis in which performance is mediated by dual mechanisms, one very sensitive and subject to surround suppression, the other less sensitive but immune from surround suppression.

The results from Experiment 1 were first presented in abstract form by Challinor, Meese, and Summers (2007).

2. Methods

2.1. Equipment

Stimuli were displayed on a 120 Hz EIZO FlexScan 6600-M 19 in., Gamma corrected greyscale monitor with the use of a VSG 2/5 stimulus generator (Cambridge Research Systems) controlled by a PC and operating in pseudo-15 bit mode. The display had a mean luminance of 40.7 cd/m^2. Mask and target frames were temporally interleaved giving an image refresh rate of 60 Hz. The mask and target contrasts were controlled using look-up tables. A chin and headrest was used to help observers hold fixation at a viewing distance of 70 cm.

2.2. Stimuli and conditions: Experiment 1

All stimuli were 1 c/deg sine-wave gratings modulated by one of two spatial windows and had a duration of 100 ms. The target was a circular patch of horizontal grating in sine-phase with the centre of the display, ensuring that it contained no mean luminance increment. It had a full-width at half-height (FWHH) of 1.26° (36 pixels) (Fig. 1a). The blurring around the edge was done with a raised sine-function with a half-cycle width of 0.28° (8 pixels), giving a central unmodulated target plateau of 1 cycle (28 pixels) and a full target width of 1.54° (44 pixels). The cross-oriented superimposed mask was a vertical grating modulated by the same window as the target (Fig 1b). The doughnut window used for the surround-masks had an outer diameter of 7.7° (FWHH). The central hole had a diameter of 1.96° (FWHH) and used the same blurring as above. The cross-oriented and parallel doughnut masks are shown surrounding the target in Fig. 1c and d, respectively.

We used a 2 (field position) × 3 (mask configuration) × 8 (mask contrast) factorial experimental design. Stimuli were always rendered in the centre of the monitor and were viewed either centrally

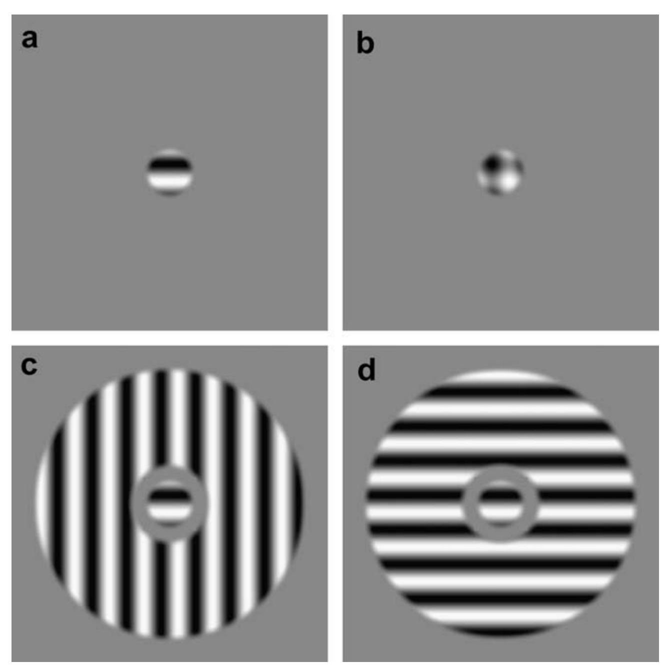

Fig. 1. High-contrast examples of target, and mask plus target stimuli used in Experiment 1. The target was always a small patch of horizontal grating (a), the mask was either a small patch of cross-oriented grating (b), a surrounding doughnut of cross-oriented grating (c), or a surrounding doughnut of parallel grating (d).

[1] As pointed out by a reviewer, Petrov et al.'s masking function is non-monotonic (i.e., it declines a little after reaching a maximum level at a contrast of 10%). However, this effect is small and it is unclear whether it was found for all four of their observers (only the average is shown). Zenger, Braun, and Koch (2000) found a similar effect for just one of their four observers. For simplicity, we refer to this type of masking function as asymptotic and/or saturating since this terminology captures the primary characteristic of the effect. The non-monotinicity – if real – appears to be a fairly minor, secondary effect (for detection thresholds at least) and is not of direct interest here. Furthermore, whether this is related to non-monotonic effects that have been found in contrast discrimination (Kingdom & Whittle, 1996; Zenger-Landolt & Heeger, 2003; Zenger-Landolt & Koch, 2001) is also unclear.