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Gratings that induce perceptual distortions mask superimposed targets

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Abstract. Masking is known to depend upon the relationship between the spatial-frequency content of target and mask. This relationship has been held constant in three experiments in order to investigate the separate contribution of the spatial parameters of the mask, in this case a grating with square-wave luminance profile. Thresholds for the detection of a probe target were highest when the background grating upon which the probe was superimposed had a spatial frequency of about 4 cycles deg^{-1} (experiment 1) and a duty cycle of 50% (experiment 3). In experiment 2, the thresholds were strongly affected by the size of the background grating even though the size of the target was small in proportion to the grating and remained constant. The increase in threshold was linearly related to the area of visual cortex to which the grating projected. The spatial parameters of gratings that maximise masking are therefore the same as those that have been shown to be optimal for the induction of perceptual distortions, suggesting a possible physiological mechanism for both the masking and the distortions.

1 Introduction

When a target is optically superimposed upon a patterned background it may become more difficult to see. For example, if the target is a low-contrast grating, it becomes more difficult to see when the background is another grating of similar spatial frequency and orientation (DeValois and DeValois 1990). The spatial-frequency components of the target and the background interact. The following study addressed the question of whether some backgrounds are more likely to mask stimuli than others *irrespective* of the interaction between the spatial-frequency components of target and mask. The relationship between the spatial-frequency components of target and mask were held as constant as possible in order to investigate the effects of various parameters of the background grating.

When certain gratings are observed, illusions of colour, form, and motion are often reported (Wilkins et al 1984). The illusions were probably first reported by Purkinje (1823, cited in Wade 1977), and are somewhat similar in nature to the 'jazzy' effect obtained in some op art paintings (Wade 1978). In this paper we shall refer to them as grating-induced perceptual distortions, or perceptual distortions for short. Subjective reports of perceptual distortions are influenced by the following parameters of square-wave gratings: (i) spatial frequency (maximum distortions at about 4 cycles deg^{-1}); (ii) size (distortions increase linearly with the area of the cortex to which the pattern projects); and (iii) duty cycle (maximum distortions at 50% duty cycle) (see Wilkins et al 1984; Wilkins 1986, 1987, 1995).

Georgeson (1976) employed a modular model of the visual cortex to explain the perceptual distortions seen in gratings. He suggested that grating stimuli would excite a narrow range of cortical neurons (those tuned to the particular spatial frequency and orientation of the grating), and demonstrated how this focal excitation could give rise to disinhibition of distant neurons, and hence to illusory effects of orientation, colour, and spatial frequency. Wilkins et al (1984, page 1015), on the basis of electroencephalographic studies of patients with photosensitive epilepsy, argued that the induction of perceptual distortions may depend on the *intensity* of focal excitation: "Sensory stimulation that induces intense cortical excitation ... may cause a breakdown of inhibitory mechanisms that either remains localized or spreads. If the discharge remains localized within the visual cortex, neurons may nevertheless be inappropriately excited so as to produce anomalous visual effects". Because of the long-range excitatory connections that exist between cortical columns of similar orientation preference (Ts'o et al 1986; Gilbert 1994), it is possible that sufficiently intense focal excitation is especially likely when all the elements of the stimulus are identically oriented (as in a grating).

Sillito (1975, 1979) and many others since (see Berman et al 1992) have shown that the receptive-field properties of cortical cells are strongly dependent on intact intracortical inhibitory mechanisms. Given that perceptual distortions may have their origin in a local, temporary, disruption of cortical inhibition, an obvious question arises as to whether the gratings that induce perceptual distortions may also impair the perception of a superimposed target.

In the experiments to be reported in this paper therefore we examined the effects of varying three grating parameters (fundamental spatial frequency, size, and duty cycle) on the thresholds for detection of a superimposed target. In order to overcome the confounding effect of differential spatial-frequency masking of the target by gratings of different fundamental spatial frequencies, careful selection of the targets was necessary. Solomon and Pelli (1994) have demonstrated that the spatial-frequency band necessary for the identification of letters remains constant, regardless of letter size, if the spatial frequencies are measured with respect to character size, rather than the more usual visual angle. Targets in experiments 1 and 2 were thus letters, scaled in size to the background grating so that the number of cycles of the grating per character width remained constant. It was thought that the effect of spatial-frequency masking of the target letter should therefore remain constant across all grating–letter pairs, and any additional impairment of target perception could be attributable to the disruption of inhibition induced by the grating.

2 General method

2.1 *Apparatus*

The apparatus used to present stimuli in experiments 1 and 2 is represented in figure 1. The background and target fields, viewed at 0.53 m, were similarly illuminated by means of circular fluorescent tubes (Philips TL E 32W/29) driven by a high-frequency (32 kHz) AC supply, giving an effectively steady light (CCT 2900K). The resultant space-averaged luminance of the background gratings was approximately

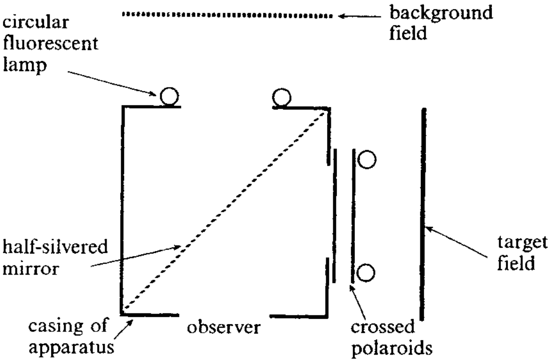

Figure 1. Plan of the apparatus used to superimpose the target letter on the background grating (experiments 1 and 2).

60 cd m^{-2}, measured by a Minolta LS-100 spot photometer. Modulation of the target-letter luminance was achieved by two circular sheets of polariser, one mounted so that it could be rotated about its centre.

The background grating stimuli had a square-wave luminance profile, duty cycle of 50%, and Michelson contrast of 0.86, and were mounted with the bars of the grating oriented at 45° to the vertical. Six letters (E, F, H, I, L, or T) were used as targets. The width of each letter was the same as its height, except for the letter I which consisted of a single vertical stroke. The letters were laser printed in white on a black background, so that increasing the luminance of the target field would not substantially alter the apparent luminance of the grating surrounding the letter, nor reduce its contrast. The letters were aligned so that, in each case, the centre of the letter was superimposed upon the centre of the circular background. Cathode-ray-tube displays were not used because the flicker inherent in such displays is known to affect ocular motor control (Wilkins 1986; Kennedy and Murray 1991) and may conceivably also affect masking.

In experiment 3, a different apparatus was used. A printed background grating, mounted on a black background such that the bars of the grating were horizontal, was evenly illuminated by two tungsten projector lamps, giving a space-averaged luminance of approximately 50 cd m^{-2}. The target was front-projected onto the grating by means of a third projector, and its luminance controlled by means of a calibrated crossed-polarizer system similar to that used in experiments 1 and 2. The grey levels of the bright and dark bars of the background grating were adjusted, by using drawing software, in such a way that changing its duty cycle would not alter the space-averaged reflectance. Gratings were circular, and their radii subtended 2.5 deg of visual angle, viewed at 1.55 m. The fundamental spatial frequency of the grating with 50% duty cycle (ie the square-wave grating) was 3.0 cycles deg^{-1}.

As the spatial-frequency composition of a grating is altered by changing its duty cycle, it was not possible to employ letters as targets in experiment 3. Instead, left-oblique and right-oblique bars were used, so that the spatial-frequency components of the target would be oriented at 45° away from those of the horizontal background grating, thus minimising spatial-frequency masking while still enabling a simple two-alternative forced-choice method to be used. The width of the target bars subtended 0.17 deg and their length was equal to the diameter of the background grating.

3 Experiment 1

3.1 *Subjects*

Twenty-four female and two male subjects participated in this study. Their age range was 29–66 years and all had normal or corrected vision. Verbal informed consent was obtained from each person before the commencement of the experimental session.

3.2 *Procedure*

Trials were conducted in two blocks. In the first block, the radius of the background grating was held constant at 10.2 deg, and its fundamental spatial frequency took one of the following values: 0.8, 1.6, 3.2, 6.4, or 12.7 cycles deg^{-1}. The width of the target letter equalled 3.5 cycles of the background grating; letter width therefore decreased in absolute size with increasing spatial frequency of the grating.

In the second block, the relative letter width was increased to 17.5 cycles of the grating. The gratings remained unchanged, except that limitations of the size of the apparatus meant that it was not possible to use the 0.8 cycle deg^{-1} grating.

For each trial, the target-letter luminance was set to its minimum, and the threshold luminance required for correct identification of the letter target determined by an ascending method of limits. Subjects undertook two practice trials at the outset.

For both blocks of trials, a measurement of threshold contrast was taken three times at each background spatial frequency, each time with a target letter selected pseudorandomly (without repetition) from the set of six. Background-grating spatial frequency also varied pseudorandomly (without repetition).

It was possible, with this procedure, that the variation of letter size would itself affect letter detectability. The thresholds for identification of each of the target letters against a uniform grey background with a space-averaged luminance equal to the grating backgrounds were therefore determined for one subject (EC), by using a closely similar method to that described above.

3.3 *Results*

Figure 2 shows thresholds for identification of the letter targets both with grating and with uniform backgrounds. With a uniform background, the 17.5 cycles per character letters were identified at very similar contrasts regardless of letter size. With grating backgrounds, thresholds for the same letters were dependent on the grating spatial frequency: intermediate spatial frequencies gave rise to higher thresholds. This pattern of data was similar for the 3.5 cycles per character letters, except that the thresholds for identification against a uniform background were raised for the smallest letters. In consequence, the reduction in threshold contrast with background gratings of high spatial frequency was less marked. At each spatial frequency, slightly higher contrast was required to identify the 3.5 cycles per character letters, as compared with the 17.5 cycles per character letters.

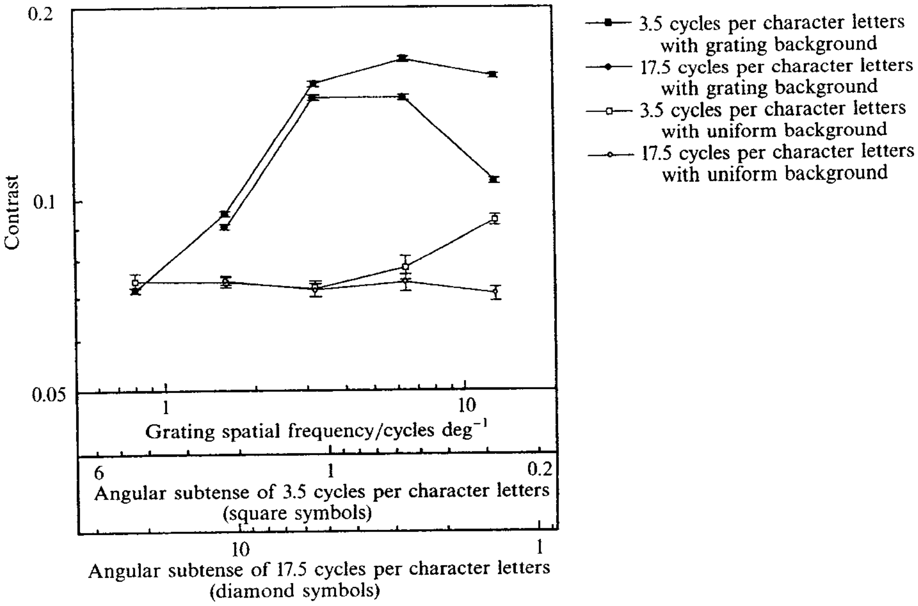

Figure 2. Contrast thresholds for letter detection. Filled symbols denote thresholds with grating background (pooled data from twenty-six subjects); open symbols, thresholds with a uniform background (one subject). Error bars represent the standard error associated with each mean. The three abscissae give the spatial frequency of the background grating, and the angular subtenses of each type of letter (3.5 and 17.5 cycles per character). The ordinate shows contrast, defined in this and all subsequent figures as

$$\frac{L_{(\mathrm{target+mask})} - L_{(\mathrm{mask})}}{L_{(\mathrm{target+mask})}} .$$

4 Experiment 2

4.1 *Subjects*

Subjects were those who participated in experiment 1.

4.2 *Procedure*

The experimental method was similar to that of experiment 1, except that two blocks of trials were conducted with letter sizes of 2.5 and 12.5 cycles respectively (the two letter sizes used were reduced in order that background gratings with small radii would still be sufficiently large to cover the target letters). The spatial frequency of the background grating was held constant at 3.2 cycles deg^{-1}, but the radius of the background grating varied, taking one of the following values: 1.4, 2.8, 5.5, or 10.2 deg.

4.3 *Results*

Figure 3 shows the relationship between threshold contrast and Drasdo's (1977) estimate, Q, of the percentage of visual cortex stimulated by the background grating, given by:

$$Q = 100(1 - \mathrm{e}^{-0.0574\phi}),$$

where ϕ is the angular radius of a circular region, the centre of which is foveally fixated.

Although the relationship between visual performance and cortical topography has been shown to vary considerably with the nature of the psychophysical task (Rovamo et al 1992), the choice of Drasdo's original equation can be justified by its ability to predict other psychophysical and electrophysiological effects of gratings (Wilkins et al 1984).

It may be seen from figure 3 that there is a linear relationship between Q and threshold contrast, for both letter sizes ($R^2 = 0.99$ for the 2.5 cycles per character letters and $R^2 = 0.98$ for the 12.5 cycles per character letters). In addition, the gradients of these lines were similar (1.28×10^{-3} and 1.31×10^{-3}, respectively, for the regression of identification threshold on Q). The increase in contrast required to identify the 2.5 cycles per character letters, as compared with the 12.5 cycles per character letters, was near constant at each value of Q.

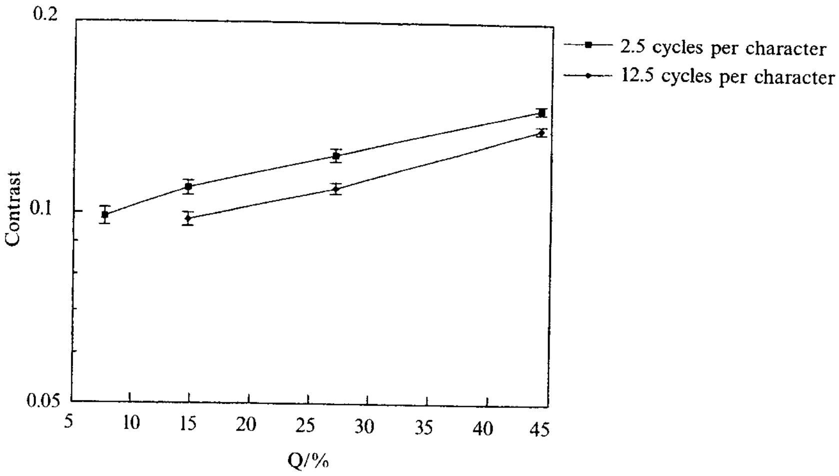

Figure 3. Contrast thresholds for letter detection as a function of Q, an estimate of the percentage of visual cortex stimulated by the grating background. Pooled data from twenty-six subjects are shown; bars give standard errors.

5 Experiment 3

5.1 *Subjects*

Three women and one man participated in this experiment (age range 18–47 years). They wore refractive corrections where appropriate. All gave written informed consent.

5.2 *Procedure*

The experimental procedure was similar to that in the previous experiments, except that left-oblique and right-oblique bars were used as targets instead of letters. Each subject was required to report the orientation (left oblique or right oblique) of the target five times against each grating. Eleven horizontal background gratings with equal space-average reflectance were presented, with duty cycles of 8%, 17%, 25%, 33%, 42% 50%, 58%, 67%, 75%, 83%, and 92%. The order of presentation of gratings was pseudorandom (without repetition). In each trial, target luminance was initially set at a random subthreshold level, then the threshold for orientation identification was determined by means of an ascending method of limits. The threshold was defined as the lowest luminance step in the first series of four correctly reported orientations. Subjects underwent five practice trials before the experimental session.

5.3 *Results*

Pooled data from the four subjects are represented in figure 4. There is an inverted-U-shaped relationship between duty cycle and contrast threshold for correct identification of the orientation of the target.

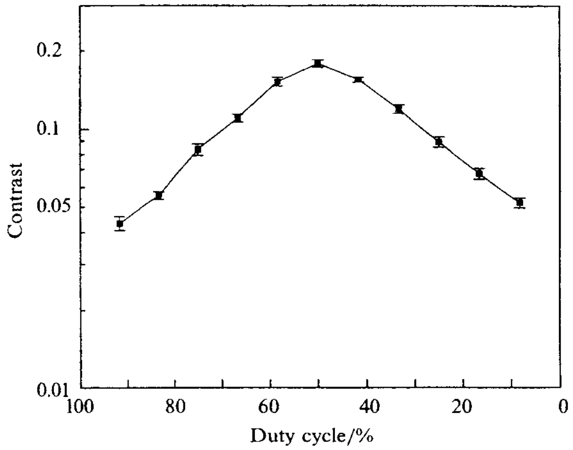

Figure 4. Contrast thresholds for target detection as a function of the duty cycle of the background grating. Pooled data from four subjects are shown; bars give standard errors.

6 Discussion

The extent to which a square-wave grating masked a superimposed target was investigated in three experiments in which the effects of the spatial frequency, size, and duty cycle of the grating were studied. In every case, the masking functions were similar to those that determine the propensity of a square-wave grating to elicit perceptual distortions.

It is unlikely that the effects of the grating parameters are due simply to spatial-frequency masking: first, letter size covaried with grating spatial frequency in such a way that the spatial frequencies of the grating were in a constant relationship to the spatial-frequency band required for identification of the letter (Solomon and Pelli 1994). Second, the contrast required for identification of the letters against a uniform background was not affected by their size (with one exception), indicating that the variation in letter size (and hence spatial-frequency composition) cannot account for the results. Third, the only variation in experiment 2 was the radius of the background grating; the letter targets and grating spatial frequency remained identical. It is therefore difficult to explain the linear relationship between Q and identification threshold on the basis of spatial-frequency masking alone.

The effects of changing the size of the target letter, in experiments 1 and 2 are, however, explainable in terms of straightforward spatial-frequency masking. The near-constant increase in contrast required to identify the 3.5 and 2.5 cycles per character letters, as compared with the 17.5 and 12.5 cycles per character letters, respectively (see figures 2 and 3), is consistent with the findings of Solomon and Pelli (1994). The fundamental frequency of the grating was within the spatial-frequency band required for letter identification for the smaller letters, but outside it for the larger letters; the increase in contrast required to identify the smaller letters was therefore likely to have been a reflection of greater spatial-frequency masking.

We would argue that some additional mechanism must be invoked to account for the effects of changing the grating parameters, effects which were over and above those expected solely on the basis of the spatial-frequency composition of target and background. The extra masking provided by certain gratings may be explained in terms of the disruption of cortical inhibition thought to be responsible for perceptual distortions (Wilkins 1995). The gratings that induce such distortions are similar in many respects to those that evoke seizures in patients with photosensitive epilepsy (Wilkins et al 1984). In these patients it is thought that a minimal, diffuse failure of GABAergic inhibition renders the cortex sensitive to any sensory stimulus that elicits a strong physiological excitation (Meldrum and Wilkins 1984). In normal subjects, the excitatory input caused by appropriate gratings fails to be modulated quite sufficiently by cortical inhibition, giving rise to a spread of excitation sufficient to provoke perceptual distortions but not seizures. According to this view, the masking effects we have demonstrated occur because of the inappropriate excitation of neurons that would otherwise have been involved in the detection of the target stimulus.

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References

Berman N J, Douglas R J, Martin K A C, 1992 "GABA-mediated inhibition in the neural networks of visual cortex" *Progress in Brain Research* **90** 443–476

DeValois R L, DeValois K K, 1990 *Spatial Vision* (Oxford: Oxford University Press)

Drasdo N, 1977 "The neural representation of visual space" *Nature (London)* **266** 554–556

Georgeson M A, 1976 "Psychophysical hallucinations of orientation and spatial frequency" *Perception* **5** 99–111

Gilbert C D, 1994 "Circuitry, architecture and functional dynamics of visual cortex" *Ciba Foundation Symposium* **184** 35–62

Kennedy A, Murray W S, 1991 "The effects of flicker on eye movement control" *Quarterly Journal of Experimental Psychology* **43A** 79–99

Meldrum B S, Wilkins A J, 1984 "Photosensitive epilepsy in man and the baboon: integration of pharmacological and psychophysical evidence", in *Electrophysiology and Epilepsy* Eds P Schwartzkroin, H V Wheal (London: Academic Press) pp 51–77

Rovamo J, Mäkelä P, Whitaker D, 1992 "Models of the visual cortex on the basis of psychophysical observations", in *Functional Organisation of the Human Visual Cortex* Eds B Gulyas, D Ottoson, P E Roland (Oxford: Pergamon Press) pp 241–254

Sillito A M, 1975 "The contribution of inhibitory mechanisms to the receptive field properties of neurones in the striate cortex of the cat" *Journal of Physiology (London)* **250** 305–329

Sillito A M, 1979 "Inhibitory mechanisms influencing complex cell orientation selectivity and their modification at high resting discharge levels" *Journal of Physiology (London)* **289** 33–53

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

T'so D Y, Gilbert C D, Wiesel T N, 1986 "Relationships between horizontal interactions and functional architecture in cat striate cortex as revealed by cross-correlation analysis" *Journal of Neuroscience* **6** 1160 – 1170

Wade N J, 1977 "Distortions and disappearances of geometrical patterns" *Perception* **6** 407 – 433

Wade N J, 1978 "Op art and visual perception" *Perception* **7** 21 – 46

Wilkins A J, 1986 "What is visual discomfort?" *Trends in Neurosciences* **9** 343 – 346

Wilkins A J, 1987 "Visual sensitivity and hyperexcitability in epilepsy and migraine", in *Migraine and Epilepsy* Eds F Andermann, E Lugaresi (Newton, MA: Butterworths) pp 339 – 365

Wilkins A J, 1995 *Visual Stress* (Oxford: Oxford University Press)

Wilkins A, Nimmo-Smith I, Tait A, McManus C, Della Sala S, Tilley A, Arnold K, Barrie M, Scott S, 1984 "A neurological basis for visual discomfort" *Brain* **107** 989 – 1017