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Binocular functional architecture for detection of contrast-modulated gratings

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ABSTRACT

Combination of signals from the two eyes is the gateway to stereo vision. To gain insight into binocular signal processing, we studied binocular summation for luminance-modulated gratings (L or LM) and contrast-modulated gratings (CM). We measured 2AFC detection thresholds for a signal grating (0.75 c/deg, 216 ms) shown to one eye, both eyes, or both eyes out-of-phase. For LM and CM, the carrier noise was in both eyes, even when the signal was monocular. Mean binocular thresholds for luminance gratings (L) were 5.4 dB better than monocular thresholds – close to perfect linear summation (6 dB). For LM and CM the binocular advantage was again 5–6 dB, even when the carrier noise was uncorrelated, anti-correlated, or at orthogonal orientations in the two eyes. Binocular combination for CM probably arises from summation of envelope responses, and not from summation of these conflicting carrier patterns. Antiphase signals produced no binocular advantage, but thresholds were about 1–3 dB higher than monocular ones. This is not consistent with simple linear summation, which should give complete cancellation and unmeasurably high thresholds. We propose a three-channel model in which noisy *monocular* responses to the envelope are binocularly combined in a contrast-weighted sum, but also remain separately available to perception via a *max* operator. Vision selects the largest of the three responses. With in-phase gratings the binocular channel dominates, but antiphase gratings cancel in the binocular channel and the monocular channels mediate detection. The small antiphase disadvantage might be explained by a subtle influence of background responses on binocular and monocular detection.

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1. Introduction

The analysis of spatial information in vision unfolds over successive stages of the retino-cortical pathways, and involves combination of signals from the two eyes. A good deal is known from both psychophysics and neurophysiology about the spatial analysis and binocular combination of signals derived from spatial variations of luminance in the retinal image – often called *first-order* information – but rather less is known about mechanisms supporting the representation of *second-order* information, arising from spatial variation in higher-order image properties such as local contrast, local orientation or texture density (Cavanagh & Mather, 1989; Chubb & Sperling, 1989; Landy & Bergen, 1991). Over an ensemble of natural images, spatial variations in local luminance and local contrast amplitude (first- and second-order structure) were found to be uncorrelated (Schofield, 2000), while in the laboratory the two kinds of structure can be usefully isolated in computer-generated synthetic images (Fig. 1). This experimental approach has yielded much evidence for the idea of separate pathways encoding first- and second-order motion (see literature summary in Table 1 of Clifford & Vaina, 1999), with these paths perhaps converging to produce an integrated perception (e.g. Lu & Sperling, 1995; Scott-Samuel & Georgeson, 1999; Wilson, Ferrera, & Yo, 1992). Our studies of first- and second-order grating detection, and perceptual aftereffects, revealed a similar picture of separate encoding pathways responding to the spatial structure of luminance modulation (LM) and contrast modulation (CM) (Georgeson & Schofield, 2002; Schofield & Georgeson, 1999). In this paper we focus specifically on contrast modulation (CM) as a second-order property (see Fig. 1, bottom row), and we ask some basic questions about the binocular processing of CM signals.

In first-order vision, stereo disparity is encoded by populations of binocular neurons that combine input from monocular receptive fields that have similar size and position, and similar selectivity for orientation and direction, but are driven separately by the left and right eyes (e.g. Hubel & Wiesel, 1968; Ohzawa, DeAngelis, & Freeman, 1996). This neural binocular summation leads to a

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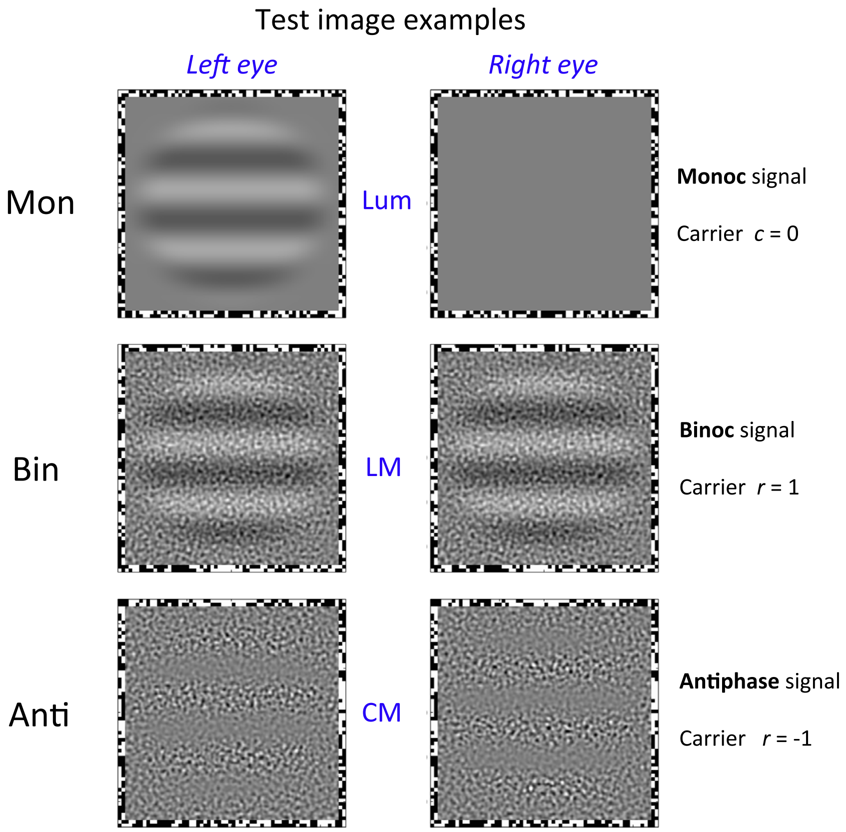

Fig. 1. Experiment 1. Examples of left/right image pairs used in the various experimental conditions. Top row: luminance gratings (Lum), monocular signal (Mon), no noise carrier (contrast, $c = 0$). Middle row: luminance modulation (LM) of a noise carrier, binocular in-phase signal (Bin), with correlated noise in the two eyes (correlation, $r = 1$). Bottom row: contrast modulation (CM) of a noise carrier, binocular anti-phase signal (Anti), with anti-correlated noise in the two eyes ($r = -1$).

behavioural *binocular advantage*: contrast detection thresholds for luminance gratings of the same orientation, SF and spatial phase shown to both eyes are markedly better than for gratings shown to one eye (Anzai, Bearse, Freeman, & Cai, 1995; Campbell & Green, 1965; Meese, Georgeson, & Baker, 2006; Simmons & Kingdom, 1998).

Since stereo depth discrimination is possible on the basis of CM disparity alone (Edwards, Pope, & Schor, 2000; Hess & Wilcox, 2008; Langley, Fleet, & Hibbard, 1999; Wilcox & Hess, 1996), it is natural to ask whether there is a corresponding binocular advantage for detection of CM. We test this by measuring detection thresholds for CM gratings presented to one eye or to both eyes, when the carrier pattern (dynamic noise texture, Fig. 1) is shown to both eyes. If a clear binocular advantage is found for CM, then we can ask whether it arises from binocular summation of second-order contrast envelope (CM) signals, or whether it might be inherited from summation of the first-order carrier signals. We did this in three experiments by assessing the binocular advantage for CM with pairs of noise carriers that were the same (perfectly correlated) in the two eyes, and comparing it with conditions where the carriers were (1) uncorrelated or anti-correlated, (2) uncorrelated but with the same or orthogonal orientations, and (3) uncorrelated but with the same or opposite contrast polarity in the two eyes. If matching carrier signals are important for summation then binocular CM performance should be better when the carriers are the same or similar than when they are very dissimilar in spatial correlation, orientation or polarity. The use of oriented carriers (Experiment 2) and arrays of light vs. dark blobs (Experiment 3) might also be informative in light of the suggestion that second-order channels specific to carrier orientation, and channels specific to light/dark polarity, both contribute to CM detection (Motoyoshi & Kingdom, 2007). In a fourth experiment we examined the nature of the combination process for CM: whether it might be better described as a simple linear sum of each eye's modulation, or as a contrast-weighted sum in which the contribution made by each eye is driven by the carrier contrast visible to that eye (Zhou, Georgeson, & Hess, 2014).

We might also learn a good deal about the combination process by comparing detection of in-phase and out-of-phase ('antiphase') binocular inputs. For example, if binocular summation were strictly linear, then antiphase inputs should cancel each other, and be undetectable. In this way, and guided by computational modelling, we aim to build a picture of the functional architecture for binocular CM processing.

2. Methods

In all experiments a two-alternative forced-choice (2AFC) staircase method was used to estimate thresholds for detection of contrast-modulated (CM) gratings, and in experiment 1 for luminance gratings (Lum) and luminance-modulated noise (LM) gratings as well. Details of image generation, display and procedure are given here for Experiment 1. Changes in conditions and procedure for Experiments 2–4 will be noted in the Results.

2.1. Experiment 1

2.1.1. Image display

Image arrays were generated in *Matlab* on a Macintosh G4 computer and displayed using *PsychToolbox* software (Brainard, 1997) on a Clinton Monoray CRT monitor with a fast-decay

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