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Contrast and lustre: A model that accounts for eleven different forms of contrast discrimination in binocular vision

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ABSTRACT

Our goal here is a more complete understanding of how information about luminance contrast is encoded and used by the binocular visual system. In two-interval forced-choice experiments we assessed observers' ability to discriminate changes in contrast that could be an increase or decrease of contrast in one or both eyes, or an increase in one eye coupled with a decrease in the other (termed *IncDec*). The base or pedestal contrasts were either in-phase or out-of-phase in the two eyes. The opposed changes in the *IncDec* condition did not cancel each other out, implying that along with binocular summation, information is also available from mechanisms that do *not* sum the two eyes' inputs. These might be monocular mechanisms. With a *binocular* pedestal, monocular increments of contrast were much easier to see than monocular decrements. These findings suggest that there are separate binocular (*B*) and monocular (*L*,*R*) channels, but only the largest of the three responses, *max*(*L*,*B*,*R*), is available to perception and decision. Results from contrast discrimination and contrast matching tasks were described very accurately by this model. Stimuli, data, and model responses can all be visualized in a common *binocular contrast space*, allowing a more direct comparison between models and data. Some results with out-of-phase pedestals were *not* accounted for by the *max* model of contrast coding, but were well explained by an extended model in which gratings of opposite polarity create the sensation of *lustre*. Observers can discriminate changes in lustre alongside changes in contrast.

1. Introduction

1.1. Functional architecture of binocular vision from psychophysics

Two eyes are better than one, but not always. Observers with normal binocular vision typically show faster reaction times, better spatial acuity and higher contrast sensitivity using two eyes rather than one (for reviews see Blake & Fox, 1973; Blake, Sloane, & Fox, 1981). When measured with forced-choice techniques, contrast thresholds with one eye are on average 1.6–1.7 times higher than with two eyes (Meese, Georgeson, & Baker, 2006; Simmons, 2005; Simmons & Kingdom, 1998) – consistently higher than the classical figure of $\sqrt{2}$ (1.41) (Campbell & Green, 1965). It seems clear that this *binocular advantage* in visual performance arises from *binocular summation* of signals from each eye (Fig. 1a), carried out by binocular cells in the primary visual cortex (Anzai, Bearse, Freeman, & Cai, 1995; Hubel & Wiesel, 1962).

Surprisingly however, the binocular advantage in a variety of spatial tasks (Landolt C acuity, letter recognition, orientation discrimination) tends to evaporate at higher contrasts (Bearse & Freeman, 1994; Home, 1978). We focus here on another simple visual task – *contrast discrimination* – which also appears to show no binocular advantage. The task is to decide which of two otherwise-identical sinewave gratings has the higher contrast. When the base or *pedestal* contrast (C) is above threshold, then the contrast difference ΔC required to distinguish the two contrasts, C and C + ΔC, is the same whether the test gratings are shown to one eye or to both eyes (Legge, 1984; Maehara & Goryo, 2005; Meese et al., 2006). This may seem paradoxical, but it does *not* imply that binocular summation is absent above threshold. Rather, this and related results reveal that the process of binocular summation is accompanied by a process of *interocular suppression* that operates in addition to the *self-suppression* that is common in contrast gain control models of contrast discrimination (e.g. Legge & Foley, 1980). When the same image is in both eyes, the benefit of binocular summation is almost exactly offset by the doubling of suppression, leaving signal:noise ratio and visual performance unchanged (Meese et al., 2006). Interestingly

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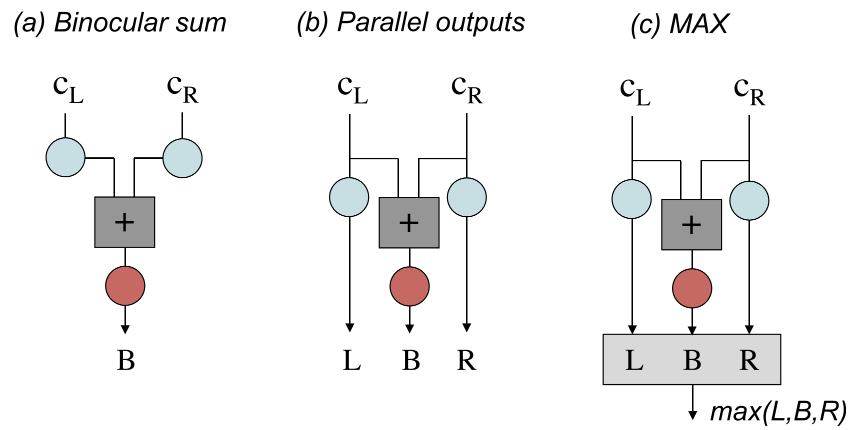

Fig. 1. Some basic ideas about binocular combination. (a) Binocular summation: a single binocular output channel (B, red) combines monocular responses to contrasts (c_L, c_R) in the left and right eyes. Blue disks are monocular units. (b) Monocular outputs (L,R) in parallel with the binocular one. (c) In this paper we explore the idea that parallel outputs are available initially, but only the largest of them, *max(L,B,R)*, is selected for further processing. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

then, binocular summation does not always lead to binocular advantage.

A similar relationship was seen in fMRI responses to grating contrast. At 2% contrast, BOLD responses to binocular input were notably larger than to monocular input, but at 10% contrast there was no difference in response, and this lack of additivity was attributed to interocular suppression or binocular contrast normalization (Moradi & Heeger, 2009).

A functionally important consequence of this balance between binocular summation and interocular suppression is *ocularity invariance*. Despite the marked difference in contrast thresholds, the perceived contrast of supra-threshold gratings is almost the same for one eye and for two eyes (Baker, Meese, & Georgeson, 2007; Ding, Klein, & Levi, 2013; Legge & Rubin, 1981). This form of perceptual constancy is likely to be important where the view of an object is partly obscured by a nearer one, such that part of the object's surface is seen by both eyes while the occluded part is seen by one eye (a 'half-occlusion'). Without ocularity invariance this switch in viewing conditions across the surface could be falsely taken as a change in contrast – a texture boundary – on the object itself.

Despite ocularity invariance, and the associated lack of binocular advantage in contrast discrimination, we found direct evidence that binocular summation occurs at all levels of contrast. The novel tactic here was to keep suppression almost constant by using a *binocular* pedestal grating of contrast C, and then to compare the detectability of monocular *versus* binocular contrast increments ΔC. A binocular advantage was revealed at all contrast levels C, because it was not offset by a corresponding increase in suppression (Meese et al., 2006).

Beginning with the pioneering work of Legge (1984), studies of this kind have aimed to make systematic and fairly precise measurements of contrast-difference thresholds over a wide range of binocular conditions, and from these increasingly rich datasets to construct and evaluate models for the functional architecture of signal-processing in binocular vision (Baker, Meese, & Hess, 2008; Baker, Meese, & Summers, 2007; Ding & Levi, 2016; Ding & Sperling, 2006; Hou, Huang, Liang, Zhou, & Lu, 2013; Huang, Zhou, Zhou, & Lu, 2010; Maehara & Goryo, 2005; Meese et al., 2006). Such models must specify the nature of the pathways from each eye, what the relevant signals are and how they interact, how the signals are combined, what and where the nonlinearities are, where the performance-limiting noise occurs, and how trial-by-trial perceptual decisions are made on the basis of one or more available outputs. Successful models for these contrast discriminations are likely to offer further insight into other binocular processes, such as binocular fusion, rivalry and stereoscopic vision.

In the present paper we extend the discrimination experiments of Meese et al. (2006) with a set of critical new conditions that enable us to refine and expand our account of the functional architecture of human binocular contrast coding. The new experiments include conditions where (i) the target is a decrement of contrast rather than an increment, (ii) the target is an increment in one eye but a decrement in the other eye, and (iii) for each type of target, the pedestal gratings are out-of-phase ('antiphase') in the two eyes, rather than in-phase. Combining 6 new and 7 previous datasets gives us a total of 13 different discrimination functions (also known as *TvC* [threshold *versus* contrast] functions, or 'dipper functions') that need to be accounted for. The 13 functions comprise 11 distinct tasks, plus two replicates. This great variety of related discrimination tasks puts strong constraints on possible models of binocular signal processing. Put simply, we found that many models can fit data from some or even most of the eleven tasks; we found only one that accurately accounted for all eleven tasks at all contrast levels.

1.2. The discrimination tasks

The 11 tasks are defined schematically in Fig. 2A. Grey bars represent the pedestal contrasts presented to one or both eyes; increments of contrast magnitude are shown in red, decrements of contrast magnitude in blue. Giving a short, unambiguous name to each task is not easy, but we have attempted to do so (see panel headings in Fig. 2A). The names can be cumbersome, so we rely a good deal on the numbering of tasks 1–11 throughout the paper, and invite the reader to decode the numbers via Fig. 2A.

It is also not easy to see much order or structure in the 11 conditions of Fig. 2A. The structure emerges clearly, however, when we consider the experiment in a two-dimensional *binocular contrast space*, whose axes are (c_L,c_R) – the contrasts shown to the left and right eyes (Fig. 2B). Monocular pedestals lie on the cardinal axes, binocular in-phase pedestals lie on the positive diagonal, and binocular antiphase pedestals lie on the negative diagonal (red symbols in Fig. 2B). Any change in (c_L,c_R) can be seen as a displacement from the pedestal point in some direction through this space. Red lines in Fig. 2B are *test vectors*, defining the direction of binocular contrast change for a given condition (1–11). For example, condition 2 (*BinInc*) has a binocular in-phase pedestal (top right in Fig. 2B), and a binocular contrast increment that is an oblique displacement up and to the right. Condition 9 (*IncDec*)