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# Two eyes: $\sqrt{2}$ better than one?

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ABSTRACT

Classical data on the detection of simple patterns show that two eyes are more sensitive than one eye. The degree of binocular summation is important for inferences about the underlying combination mechanism. In a signal detection theory framework, sensitivity is limited by internal noise. If noise is added centrally after binocular combination, binocular sensitivity is expected to be twice as good as monocular. If the noise is added peripherally at each eye prior to combination, binocular sensitivity will be $\sqrt{2}$ higher than monocular. In a large sample of observers (51), we measured contrast sensitivity for detection of gratings at several spatial frequencies using left, right, or both eyes. Estimates of binocular summation using both binocular summation ratios and Minkowski coefficients show a summation ratio with means in the range of 1.5–1.6. The 95% confidence interval overlaps with the value of $\sqrt{2}$ predicted by the peripheral noise model and does not overlap with the value of 2 predicted by the central noise model.


## 1. Introduction

Having two eyes confers many advantages. Binocular stereopsis is the most obvious benefit of having two eyes. But another benefit is that having two eyes allows the viewer to detect faint patterns better. Exactly how such binocular summation in the detection of luminance patterns is performed in the brain is unknown. In an effort to find the mechanism, many studies have been done.

Detection of a faint pattern is a problem of detecting a signal in noise (Green & Swets, 1988). Besides noise contained in the stimulus delivered to the observer (either deliberately generated or due to imperfect electronics, for example), there is also noise inside the observer's visual system (Burgess, Wagner, Jennings, & Barlow, 1981; Legge, Kersten, & Burgess, 1987; Pelli, 1990; Pelli & Farrell, 1999; Simpson, Falkenberg, & Manahilov, 2003). In the case of binocular detection of signals, there are two possible ways in which noise might be introduced in the visual system. In the central noise model, the outputs of left and right eyes are combined at some central site (binocular simple cells in V1 for example), and noise is introduced at that stage (Blake, Sloane, & Fox, 1981, p. 274). In the peripheral noise model, noise is introduced peripherally at each eye prior to binocular combination. These models make different predictions about binocular summation. The models predict the performance of an ideal observer who knows the signal exactly, including such things as its spatial frequency, phase, and whether it is binocularly or monocularly presented to the left or right eye.

First let us consider monocular detection, and then we can compare binocular detection to monocular. A stimulus composed of a contrast signal $c(x,y,t)$ embedded in Gaussian noise with variance $\sigma^2$ is delivered to the observer. The ideal observer cross-correlates the noisy stimulus with a stored representation of the signal. Cross-correlation means that the observer multiplies the stimulus point-by-point with the signal and sums. Because of the cross-correlation operation, the observer's performance depends on the signal energy; if the stimulus matches the signal, the product at each point amounts to squaring, and the sum gives the energy. The energy $E$ is proportional to $\int\int\int c^2(x,y,t)dxdydt$. The detectability $d'$ of a signal having energy $E$ and having added noise with variance $\sigma^2$ is

$$d' = \sqrt{\frac{E}{\sigma^2}}$$

(Whalen, 1971, pp. 159–163). In many experiments there is little or no added noise in the stimulus. Therefore, the assumption is made that the noise is added internally. At threshold $d' = 1$. By squaring both sides and solving for the threshold energy, the result is $\sigma^2$. Energy is proportional to the sum of contrast squared, so the monocular contrast threshold is $\sigma$.

Now suppose that two eyes view the same stimulus, and that the decision is based on the central combination of the outputs of the two eyes. Then the contrast signal is $2c(x,y,t)$ and so the energy is $4\int\int\int c^2(x,y,t)dxdydt$, four times the monocular signal

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energy. Let us now assume that the noise discussed earlier is added peripherally, at each eye, before binocular combination (peripheral noise model). Since variances are additive, we have

$$d' = \sqrt{\frac{4E}{2\sigma^2}}.$$

The binocular energy threshold is $\frac{\sigma^2}{2}$; the contrast threshold is $\frac{\sigma}{\sqrt{2}}$. In the experiments reported here, we will be measuring contrast sensitivity for detecting sine-wave gratings. Since contrast sensitivity is the reciprocal of contrast threshold, the peripheral noise model predicts binocular sensitivity to be $\sqrt{2}$ better than monocular sensitivity.

Another possibility is that the noise is added centrally, after binocular combination of the signals coming from the two eyes. As before, in the binocular case the contrast signal is $2c(x,y,t)$ and so the energy is $4\int\int\int c^2(x,y,t)dxdydt$, four times the monocular signal energy. This time, though, there is one source of noise with variance $\sigma^2$. Thus

$$d' = \sqrt{\frac{4E}{\sigma^2}}.$$

For central noise, the threshold energy is $\frac{\sigma^2}{4}$ for binocular viewing. In terms of contrast, the monocular threshold is $\sigma$ and the binocular threshold is $\frac{\sigma}{2}$. Since contrast sensitivity is the reciprocal of contrast, the binocular contrast sensitivity is twice as big as monocular.

Let us summarise the two model predictions. If the noise is peripheral and added at each eye prior to binocular combination, we predict that binocular contrast sensitivity will be twice as big as monocular sensitivity. If the noise is central and added at the point of binocular combination, the binocular contrast sensitivity will be $\sqrt{2}$ better than monocular sensitivity.

Many previous studies have supported the peripheral noise model. In a classic paper, Campbell and Green (1965) derived the peripheral noise model and found that binocular contrast sensitivity functions were superior to monocular by the predicted factor of $\sqrt{2}$. Subsequent studies on binocular summation in grating detection have supported the peripheral noise model (Anderson & Movshon, 1989; Arditi, Anderson, & Movshon, 1981; Blake & Cormack, 1979; Blake & Levinson, 1977; Blake & Rush, 1980; Blakemore & Hague, 1972; Legge, 1984a; Meese, Georgeson, & Baker, 2006; Pardhan & Rose, 1999; Rose, 1978; Simmons & Kingdom, 1998). Legge (1984b) found $\sqrt{2}$ summation in grating contrast discrimination.

Some results have been in line with the central noise model. Simmons (2005), Simmons and Kingdom (1998) found binocular performance better by a factor of 2 for detection of chromatic horizontal gratings. For detection of motion rather than detection of pattern, Rose (1978) found a binocular to monocular summation ratio of 1.9. For ordinary detection of stationary patterns he found a summation ratio of $\sqrt{2}$. Medina and Mullen (2007) studied detection of flickering gratings and found a range of summation ratios that varied according to the temporal frequency. For 16 Hz flicker the summation ratio was on the order of 2. Meese et al. (2006) found a summation ratio of about 1.7, which is larger than the $\sqrt{2}$ summation expected from the peripheral noise model but less than the ratio of 2 expected from the central noise model. Other studies from the same group found summation ratios of 1.7 (Baker, Meese, & Summers, 2007) and 1.62 (Meese, Challinor, & Summers, 2008). Baker, Meese, Mansouri, and Hess (2007) found a summation ratio near 1.7 (i.e. greater than $\sqrt{2}$) for a 3 c/deg grating, and near 1.3 (i.e. less than $\sqrt{2}$) for a 9 c/deg grating.

From our review of previous work, it is obvious that binocular summation in detection of gratings has already received plenty of attention. Our contribution in this paper will be to provide results from a study involving a large number of observers. Previous studies of the advantage of binocular viewing have used a traditional psychophysical design with small numbers of observers. We will measure detection thresholds at several spatial frequencies, monocularly and binocularly, in 51 observers. In a large *n* design such as ours, we can get an idea of the population binocular summation ratio and use that ratio to make inferences about the advantage of binocular viewing and the underlying mechanism.

## 2. Methods

In the main experiment, binocular summation in viewing sine-wave gratings was measured in the course of aircrew screening for 51 Canadian Armed Forces pilots. In this large *n* survey no measure of within-observer contrast threshold variability was obtained; the between-observer variability of binocular summation ratios was used instead. In order to assess whether the between- and within-observer summation ratio variability was comparable, we ran a second experiment with nine observers where within-subject threshold variability was measured.

### *2.1. Main experiment*

#### *2.1.1. Participants*

The participants were 51 pilots from the Canadian Armed Forces. Their ages ranged from 16 to 26 years, with a mean of 20.04 and a standard deviation of 2.72. All observers had normal binocular vision and normal acuity in both eyes.

#### *2.1.2. Apparatus and stimuli*

The basic task facing the participant was to detect a vertical sine-wave grating. The spatial frequency was varied, and the threshold contrast at each spatial frequency was measured. The spatial frequencies tested were: 1.5, 3, 6, 12, and 18 c/deg. The contrast threshold functions were measured using a Nicolet CS-2000 system. The cathode ray tube was calibrated daily. The display subtended $3 \times 3.6$ deg at the viewing distance of 265 cm and had an average luminance of 72 cd/m$^2$.

#### *2.1.3. Procedure*

The data were obtained by the Central Medical Board in the course of screening aircrew candidates in the Canadian Forces (McFadden, 1994). Contrast thresholds were measured using an adaptive staircase procedure (Levitt, 1971) and two-interval forced choice. Initially, the grating had enough contrast to be clearly visible. Thereafter, contrast was lowered 2 dB after three correct responses and raised by 2 dB after one error (this staircase rule converges on 79% correct). The run ended after six reversals. The threshold log contrast was computed as the average of the log contrast at the last five reversal points.

On each trial, a vertical grating was presented in one of two successive intervals. The duration of each interval was 534 ms, composed of a 17 ms rise time, a 500 ms stimulus (either blank or grating) presentation, and a 17 ms decay period. Observers indicated which interval contained the grating by pressing one of two buttons. The next trial started 200 ms after the response.

Each observer was tested in blocks of trials for left, right, or both eyes in random order. The monocular data were obtained by use of a white paddle occluder. Within each block, the order of testing spatial frequencies was random.

### *2.2. Control experiment*

#### *2.2.1. Participants*

There were nine observers with normal or corrected-to-normal vision.