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

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\textbf{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, noise is introduced 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.

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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.

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 $\int \int c^2(x,y,t) dxdydt$. 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 $4\int \int c^2(x,y,t) dxdydt$, four times the monocular signal...
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 \( \frac{E}{\sigma^2} \); the contrast threshold is \( \frac{E}{\sigma^2} \). 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 \( 4 \int \int c^2(x,y,t) \, dx \, dy \, dt \), 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 \( \frac{E}{\sigma^2} \) for binocular viewing. In terms of contrast, the monocular threshold is \( \sigma \) and the binocular threshold is \( \frac{E}{\sigma^2} \). 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 gratings 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 number of such experiments, 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 number of observers 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 × 3.6 deg at the viewing distance of 265 cm and had an average luminance of 72 cd/m².

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 with 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.
2.2.2. Apparatus and stimuli

The stimuli were presented as stereopairs presented on a computer monitor and viewed via a haploscope. The haploscope was an arrangement of four front-silvered mirrors that permitted the stereoscopic viewing of a pair of images drawn side-by-side on the monitor. A black divider between the fields extended from the monitor to the observer.

The display was presented on an iyama Vision Master Pro 454 monitor with short-persistence phosphor and was refreshed at 100 Hz. The RGB outputs were combined electronically (Pelli & Zhang, 1991) and an optimum linearized palette of 256 luminances (out of 4096) was used. The mean luminance was 50 cd/m². The stimuli were Gaussian-windowed sine-wave gratings having spatial frequencies of 1.5, 3, 6, 12, and 18 c/deg. The display was viewed from a chinrest at a distance of 162 cm. Each field subtended 6° square in total, with a central Gabor patch whose subtense for three standard deviations was 3.6°. A black fixation cross whose arms were 0.7 min in thickness and 28 min long with a fixation point 4 min square was centred on each field. Vertical and horizontal Nonius lines flanked the fixation mark. A black square 0.7 min in thickness surrounded the stimulus just inside the outer boundary. The stimulus was presented as a trapezoidal pulse whose ramp was 60 ms followed by 200 ms at full contrast and then a down ramp of 60 ms, giving a total duration of 320 ms.

2.2.3. Procedure

The five spatial frequencies were viewed in random order within each block. The blocks were for order of viewing with left, right, or both (i.e. LRB, BLR, or RBL). These blocks were counterbalanced. Each run consisted of 60 trials. A run was a combination of spatial frequency, ocularity, and order of viewing. Thus each threshold was based on 180 trials.

The task was to say which of two intervals contained a grating. The two intervals were separated by 200 ms. The grating contrast was varied according to a +++- staircase converging on 79% correct. After each run, the data were saved to disk. Thresholds were computed from the binary data (correct/incorrect) through maximum likelihood fitting of a 2AFC cumulative Gaussian.

3. Results and discussion

The complete set of contrast sensitivities for left, right and both eyes for the 51 observers is presented as a scatterplot matrix in Fig. 1. Each row of the figure shows the sensitivities for one spatial frequency. The left column shows the contrast sensitivity for the right eye as a function of that of the left eye. In the middle column, the sensitivity for both eyes is plotted as a function of that of the left eye. The data are actually (L,R,8) triplets, and the scatterplots represent slices through the 3D data cloud. This cloud is cigar shaped, as can be seen from the 3D spinning scatterplot of the 3 c/deg data. Each scatterplot has a somewhat linear pattern showing positive correlation with a fair amount of spread between observers.

The data shown in Fig. 1 are presented in summary form in Fig. 2. The top panel shows the binocular summation ratios as a function of spatial frequency. The summation ratios were calculated individually for each observer as the binocular contrast sensitivity divided by the average of left and right eye sensitivities. As can be seen in the figure, the ratio increases with spatial frequency from a value near 1.2 to an asymptotic value near 1.6. This is unlike the pattern measured by Campbell and Green (1965), who found a summation ratio of \( \sqrt{2} \) at all frequencies. It is not clear why we observed this variation in summation ratio with spatial frequency.

Finding different summation ratios at different spatial frequencies is not unprecedented (Baker et al., 2007).

The bottom panel of Fig. 2 shows the Minkowski coefficients at all spatial frequencies. A Minkowski coefficient is the parameter \( p \) in the equation

\[
S_B = (S_L^p + S_R^p)^{1/p},
\]

where \( S_L, S_R, \) and \( S_B \) are the contrast sensitivities for both, left, and right eyes, respectively. If \( p \) equals 2, then the equation is the one given by Legge’s (1984b) quadratic summation model. When \( p \) equals 2, the data are consistent with the peripheral noise model and binocular sensitivity is superior by a factor of \( \sqrt{2} \). The Minkowski coefficients were determined by using a nonlinear regression routine on the data set at each spatial frequency. It was not possible to fit the coefficients separately for each observer because in some cases the binocular sensitivity was lower than that for either the left or the right eye, and in such a situation the coefficient is undefined. The standard errors for the coefficient estimates were obtained by jackknife. The obtained Minkowski coefficients decline from a value near 6 at the lowest spatial frequency to a value near 1.8 for higher frequencies.

The general pattern presented by both summation ratios and Minkowski coefficients is that binocular summation is poor at
low spatial frequencies and improves as spatial frequency increases. For the purposes of distinguishing between central and peripheral noise models, the most important thing is the maximum summation ratio: if summation is significantly greater than $\sqrt{2}$, the mechanism cannot be based on peripheral noise. At the highest levels of binocular advantage, both summation ratios and Minkowski coefficients show a degree of binocular summation that is greater than that expected from the peripheral noise model (a factor of $\sqrt{2}$) and less than that expected from the central noise model (a factor of 2). For summation ratios, the asymptotic value at a spatial frequency of 18 c/deg is 1.63; the 95% confidence interval is 1.40–1.86. The 95% confidence interval overlaps marginally with the peripheral noise model prediction of $\sqrt{2}$. For Minkowski coefficients, the asymptotic value is 1.72 with a standard error of 0.0071. The 95% confidence interval for the Minkowski coefficient, 1.71–1.74, is 1.49–1.50 when expressed as a summation ratio. This is slightly higher than predicted from the peripheral noise model.

Fig. 3 shows the relation between the obtained binocular contrast sensitivities and those predicted by the central and peripheral noise models (we thank an anonymous reviewer for suggesting this analysis). Before continuing, we will derive the predictions in the two cases.

First consider the case of central noise. A grating of contrast $C$ is presented to the observer. At the left eye, the stimulus is multiplied by a gain $k_L$, giving a signal of $k_LC$, and Gaussian noise with standard deviation $\sigma$ is added at the point of binocular combination. At threshold, $d' = 1$, and so signal equals noise: $k_LC = \sigma$. Similarly, for the right eye, we have $k_RC = \sigma$. Thus, after binocular combination we have $(k_L + k_R)C$ and noise with standard deviation $\sigma$. If we call the binocular contrast threshold $C_B$, then $(k_L + k_R)C_B = \sigma$, giving

$$C_B = \frac{\sigma}{k_L + k_R}.$$  

Now let us convert from contrast to contrast sensitivity, which is the reciprocal of contrast. For the left eye we have $\frac{k_L}{\sigma} = \sigma$ or $k_L = S_L\sigma$. For the right eye we have $\frac{k_R}{\sigma} = \sigma$ or $k_R = S_R\sigma$. The sensitivity for both eyes is

$$S_B = \frac{k_L + k_R}{\sigma}.$$  

Substituting for $k_L$ and $k_R$ we have

$$S_B = \frac{S_L\sigma + S_R\sigma}{\sigma} = S_L + S_R.$$  

In the left column of Fig. 3 the predicted value of binocular contrast sensitivity, $S_B$, is plotted against the obtained binocular sensitivity for each observer. We have derived the predicted contrast sensitivity in the case of central noise. Now we do the same for peripheral noise. A grating of contrast $C$ is delivered to the left eye. The output is $kC$ with standard deviation $\sigma$. Similarly, for the right eye we have $kC$ with standard deviation $\sigma$, giving $\frac{kC}{\sigma} = \sigma$. If we call the binocular contrast threshold $C_B$, then $(k + k)C_B = \sigma$, giving

$$C_B = \frac{\sigma}{kL + kR}.$$  

Now let us convert from contrast to contrast sensitivity, which is the reciprocal of contrast. For the left eye we have $\frac{kL}{\sigma} = \sigma$ or $k_L = S_L\sigma$. For the right eye we have $\frac{kR}{\sigma} = \sigma$ or $k_R = S_R\sigma$. The sensitivity for both eyes is

$$S_B = \frac{k_L + k_R}{\sigma}.$$  

Substituting for $k_L$ and $k_R$ we have

$$S_B = \frac{S_L\sigma + S_R\sigma}{\sigma} = S_L + S_R.$$  

In the left column of Fig. 3 the predicted value of binocular contrast sensitivity, $S_B$, is plotted against the obtained binocular sensitivity for each observer. We have derived the predicted contrast sensitivity in the case of peripheral noise.
both eyes). Since $d' = 1$ at threshold, both $\sigma_l$ and $\sigma_R$ are equal to $kC$. It will be useful to define the left and right eye sensitivities as $S_l = \frac{1}{kC}$ and $S_R = \frac{1}{kC}$. Next, consider what happens when the left and right eye outputs are combined. The mean output will be the sum $2kC$. The standard deviation is $\sqrt{(\sigma_l^2 + \sigma_R^2)}$. Since $d'$ is the ratio of the mean to the standard deviation, we have

$$\frac{2kC}{\sqrt{(\sigma_l^2 + \sigma_R^2)}}$$

In terms of contrast sensitivity we have

$$\frac{2k}{\sqrt{(\sigma_l^2 + \sigma_R^2)}}$$

giving

$$S_B = \frac{2k}{\sqrt{(\sigma_l^2 + \sigma_R^2)}} = \frac{2S_lS_R}{\sqrt{S_l^2 + S_R^2}}$$

Substituting for $\sigma_l$ and $\sigma_R$,

$$S_B = \frac{2k}{\sqrt{(\frac{1}{kC})^2 + (\frac{1}{kC})^2}} = \frac{2S_lS_R}{\sqrt{S_l^2 + S_R^2}}$$

In the right column of Fig. 3 the predicted value of binocular contrast sensitivity is plotted against the obtained binocular sensitivity for each observer.

Having derived the predicted binocular sensitivity for both the central and the peripheral noise models, let us now examine Fig. 3 where we plot obtained against predicted binocular contrast sensitivities. If a model describes the data well, the points will fall along the predicted = obtained diagonal. It is clear that the peripheral noise model provides a much better description of the data. Whereas the points fall more-or-less symmetrically about the diagonal for the peripheral noise model, they tend to fall below the diagonal for the central noise model. In other words, the actual binocular contrast sensitivities are lower than those predicted by the central noise model. If we look closely at the column in the figure giving the peripheral noise model predictions, the clouds of points are not distributed perfectly symmetrically about the diagonal. At the lowest spatial frequencies many points fall below the diagonal (indicating less than $\sqrt{2}$ summation) and at the highest spatial frequencies many points fall above it (indicating more than $\sqrt{2}$ summation).

As mentioned in the Introduction, most studies of binocular summation have used a psychophysical approach where data from individual observers are analysed and presented separately. Here we have been presenting the results from a large survey of binocular summation, which is a very different approach. The reader may be wondering how appropriate it is to base inferences on the mechanism of binocular summation based on averages across observers rather than averages within observers. The first point to make is that if binocular summation is described by a particular relation, for example if it is limited by peripheral or central noise, then this pattern will be shown both within observers and across them. If we test a number of subjects, each score is a sample from a population having some mean and standard deviation. The mean of the sample is an unbiased estimate of the mean of the population. The second point concerns the variability of the estimates. Is the variability of binocular summation ratios measured within observers comparable to that measured across observers? In the large n survey only the threshold and not its variability for each observer was recorded. Thus, it was not possible to assess the variability of the summation ratios within observers. The standard deviations of the summation ratios, measured across observers, were 0.26, 0.31, 0.39, 0.61, and 0.83 for spatial frequencies of 1.5, 3, 6, 12, and 18 c/deg, respectively.

In order to measure within-subject summation ratio variability, we ran the binocular summation experiment in a second study and recorded the responses trial-by-trial for each of nine subjects. Then each contrast threshold was derived through fitting a psychometric function to the binary responses by maximum likelihood. This gave us the threshold and a measure of its standard deviation for each spatial frequency, eye (left, right, or both) and observer. From these contrast thresholds, the binocular summation ratios were computed. The variability of these summation ratios was not straightforward to derive. If each threshold is normally distributed, in the binocular summation ratio we have a ratio of two normal variables (the binocular threshold and the average of the monocular thresholds). Unfortunately, this ratio has a Cauchy distribution. The Cauchy is a pathological distribution with no mean, variance, or any higher moment. Thus, we cannot derive the variance of the summation ratio analytically from the variances of the left, right, and binocular thresholds. Instead, we used the following procedure. For each observer and each spatial frequency, we calculated the threshold and its standard deviation. Each time, we computed the binocular summation ratio for 10,000 simulation trials, drawing random normal values for each of the left, right, and binocular thresholds. The values in the simulation were each drawn from a normal distribution having a mean equal to the observed threshold, and a standard deviation equal to that measured. The resulting standard deviations for the different observers and spatial frequencies had a median value of 0.42. No systematic pattern was shown for the spatial frequency either within or between observers. This within-observer standard deviation for the summation ratio is very comparable to the between-observer standard deviations found in the large n survey (0.26–0.83). Given this comparability of within- and between-observer variability, it seems reasonable to use averages across observers in making inferences about the binocular summation mechanism.

To summarise, we find that the binocular summation ratio for higher spatial frequencies has a value near 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. The plot of obtained vs predicted binocular contrast sensitivity shows that the peripheral noise model gives a good description of the data. One unexpected aspect of our data is that the degree of binocular summation increases with increasing spatial frequency.

Although our results conform to the peripheral noise prediction, some previous studies have found binocular summation ratios higher than $\sqrt{2}$. How can this be explained? For the findings with chromatic gratings (Simmons, 2005; Simmons & Kingdom, 1998), it is possible that the detection of chromatic patterns is different from that of achromatic patterns, and thus a different mechanism (central noise model) underlies chromatic binocular summation. It is known that there are two cone opponent channels (red–green and blue–yellow) and a luminance channel (red + green), and that these channels have separable responses at threshold (Mullen & Sankeralli, 1999). Thus it is not unlikely that the channels have different mechanisms of binocular combination. The Simmons data are consistent with the central noise model. Turning now to achromatic flickering gratings, Medina and Mullen (2007) find mean binocular summation ratios as high as 2.24 with a confidence interval well above $\sqrt{2}$. However, this figure of 2.24 is for observer JM at a temporal frequency of 16 Hz (and no added noise). For KTM the figure is 1.18 and for LA it is 1.98. If we average the ratios we get a 95% confidence interval of 1.16–2.44. It is hard to make solid conclusions from such a wide interval. If the observer is the appropriate level of analysis, then either markedly different mechanisms operate in different conditions.
observers, or the experimental error is underestimated. To consider a final example, Meese et al. (2006) found a binocular summation ratio near 1.70 in a study of achromatic static grating detection (much like our own). These authors consider versions of the central and peripheral noise models with power nonlinearities, and show that binocular summation results such as theirs can be fit assuming nonlinear transduction and central noise.

4. Conclusions

From an examination of binocular summation for sine-wave gratings in a large sample of observers, we find the following:

- Scatterplots of contrast sensitivity of left vs right, left vs both, and right vs both eyes show a linear cigar-shaped relationship.
- Estimates of binocular summation using both binocular summation ratios and Minkowski coefficients show a summation ratio 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.
- Both the summation ratio and Minkowski coefficients vary systematically with spatial frequency, showing increased summation as spatial frequency increases.
- A plot of observed vs predicted binocular contrast sensitivity shows that observations consistently fall below the values predicted by the central noise model, and are well described by the peripheral noise model.

We conclude, from our large sample of observers, that detection of spatial patterns is primarily limited by noise introduced peripherally at each eye prior to binocular combination. Our results do not perfectly conform to the peripheral noise predictions: we found summation ratios to vary across spatial frequencies, and they were sometimes above and sometimes below \( \sqrt{2} \). Other interpretations of the data are possible if one assumes the presence of transduction nonlinearities.

Acknowledgements

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.actpsy.2009.03.006.

References