Balanced Binocular Inputs Support Superior Stereopsis

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Purpose. Our visual system compares the inputs received from the two eyes to estimate the relative depths of features in the retinal image. We investigated how an imbalance in the strength of the input received from the two eyes affects stereopsis. We also explored the level of agreement between different measurements of sensory eye imbalance.

Methods. We measured the sensory eye imbalance and stereocuity of 30 normally sighted participants. We made our measurements using a modified amblyoscope. The sensory eye imbalance was assessed through three methods: the difference between monocular contrast thresholds, the difference in dichoptic masking weight, and the contribution of each eye to a fused binocular percept. We referred them as the “threshold imbalance,” “masking imbalance,” and “fusion imbalance,” respectively. The stereocuity threshold was measured by having subjects discriminate which of four circles were displaced in depth. All of our tests were performed using stimuli of the same spatial frequency (2.5 cycles/degree).

Results. We found a relationship between stereocuity and sensory eye imbalance. However, this was only the case for fusion imbalance measurement ($r = 0.52; P = 0.005$). Neither the threshold imbalance nor the masking imbalance was significantly correlated with stereocuity. We also found the threshold imbalance was correlated with both the fusion and masking imbalances ($r = 0.46$, $P = 0.011$ and $r = 0.49$, $P = 0.005$, respectively). However, a nonsignificant correlation was found between the fusion and masking imbalances.

Conclusions. Our findings suggest that there exist multiple types of sensory eye dominance that can be assessed by different tasks. We find only imbalances in dominance that result in biases to fused percepts are correlated with stereocuity.

Keywords: sensory eye imbalance, stereocuity, binocular function

In binocular vision, we integrate monocular visual information into a combined percept of the surrounding world. Along with the composite image of the two eye’s inputs, the visual system is also able to use the differences between the two eyes to calculate depth. This “stereopsis” makes use of the binocular disparity derived from the objects at different depths projecting to slightly different locations on the retinas in the two eyes. It is interesting that, even in subjects with healthy eyes, we find a wide variability in stereocuity in the population.1–14 In a recent study, we showed that stereocuity is broadly distributed. It extends over more than a hundred-fold range across the population. The distribution of stereocuity did not seem to be unimodal. Instead, our results suggested that the population of normally sighted individuals contains a large subgroup (approximately one-third) who have markedly poorer stereo than the remaining two-thirds.6

Stereopsis involves both fusion and suppression processes. The fusion process constructs a stereo percept by integrating the inputs from similar features in the images seen by the two eyes. At the same time, the dissimilar inputs from one eye are suppressed to promote a single binocular percept. The inputs from two eyes may not be balanced equally. One of the eyes may make a stronger contribution to the binocular percept.7 Both imbalanced temporal and spatial visual inputs could affect stereopsis. Previous studies have reported that interocular delay is associated with stereo perception, like the Pulfrich phenomenon.8–10 In addition, the extent of the ocular dominance imbalance from the spatial visual inputs of the two eyes varies in the population.11–14 This sensory eye imbalance may also affect stereopsis. In an extreme example, subjects with amblyopia have both a strong imbalance in their eye dominance and also typically exhibit poor (or no) stereopsis.15–17 However, whether the sensory eye imbalance limits stereocuity in subjects without amblyopia is controversial.

The relationship between sensory eye imbalance and stereopsis in the normally sighted population has been explored in recent studies. Xu et al.18 measured the sensory eye balance and stereocuity by using binocular rivalry stimuli and a random dot stereogram. They found observers with large sensory eye imbalance had poor stereocuity. Similar results were reported by Cooper and Mendola,19 who used both binocular rivalry and dichoptic masking to measure the
degree of imbalance, and by Han et al., who used binoc-
ular rivalry and binocular phase combination. These stud-
ies measured stereoaucity with spatially broadband random
dot stimuli, while using lower frequency gratings for their
measure of sensory eye balance. However, Wang et al. measured sensory eye balance and stereoaucity at the same
low spatial frequency using a binocular phase combination
task. They found that the two measurements were not corre-
lated significantly. Not only did these studies differ in the
relative spatial frequency used to assess sensory eye balance and stereoaucity, but also in the absolute spatial frequency. Wang et al. used a low-spatial frequency stimulus (0.3 c/deg) to assess stereoaucity, whereas Xu et al. and Cooper and Mendola used a moderate spatial frequency (ie, 2.5 c/deg).

In this study, we are similarly interested in how sensory
eye imbalance affects stereoaucity in the population with
normal or corrected-to-normal visual acuity. We assessed the
sensory eye imbalance by measuring the difference between
monocular contrast thresholds, the difference in dichoptic
masking weight, and the contribution of each eye to fusion
binocular vision by using a binocular orientation combina-
tion task. All of these measurements were evaluated at
the same spatial frequency (2.5 c/deg). Because stereoaucity
could vary with spatial frequency of the testing stimuli, we measured stereoaucity at the same spatial frequency. We
set out to address two questions: (1) Does stereoaucity at a
moderate spatial frequency (2.5 c/deg) vary with the magni-
tude of sensory eye imbalance when both are measured at
that same spatial scale? That is to say, does a better balance
between the two eyes mean better stereo? (2) How are the
different measurements of sensory eye imbalance related
to each other when made at the same moderate spatial
frequency (2.5 c/deg)?

METHODS

Participants

Thirty adults (average age, 31 years old; range, 20–69 years
old) with normal or corrected-to-normal visual acuity partici-
pated in this study. All participants reported no history of
binocular dysfunction or ocular surgery. Subjects performed
the experiment with their best optical correction if needed.
This study followed the tenets of Declaration of Helsinki,
and was approved by Ethics Review Board of the McGill
University Health Center. Written informed consent was
obtained from all participants before data collection.

Equipment

Supplementary Figure S1 shows our experimental setup.
An Apple MacBook Pro running MATLAB (MathWorks,
Natick, MA) with Psychtoolbox 3.0.9 extension was used to
generate the stimuli. The stimuli were displayed on a pair
of gamma-corrected screens (refresh rate 75 Hz, resolution
800 × 600 pixels, mean luminance 87 cd/m²). We wrote a
customized bit-stealing algorithm (after Tyler) to simul-
taneously increase the bit depth, linearize the luminance
response of both screens, and make the two screens behave
equivalently to each other. The screens were installed in
a modified amblyoscope (Clement Clarke, Made in England),
also referred to as a synoptophore. A typical amblyoscope
uses an optical system to allow images to be aligned when
presented dichoptically to the two eyes of a patient. The
mechanism of the amblyoscope allows for 90° of move-
ment per eye. The images used for the alignment are
traditionally a pair of slides. Our modified amblyoscope
replaces the standard slide presentation with the two LCD
screens described elsewhere in this article. This setup
allows us to present computer-rendered stimuli dichopti-
cally with control over their alignment. The participants
viewed the stimuli presented separately to each eye through
the eyepieces of the modified amblyoscope. The effective
viewing distance was 17.5 cm. At this distance, there were
28 pixels on the screen for each degree of visual angle.

Stimuli and Procedure

General Procedure. Subjects completed a battery of
tasks using the modified amblyoscope. This process began
with an alignment of the images seen by the two eyes. The
standard alignment slides typically used in the amblyoscope
were reinserted for this step. Subjects only used a single
degree of freedom of the equipment for their alignment. The
equipment was adjusted to a large horizontal angle, and then
the subject decreased that angle until they comfortably saw
a fused image. These adjustments were repeated to ensure
they resulted in a stable value. The slides were removed, and
subjects then completed a series of psychophysical tasks.
Testing began with a modified version of the Worth 4 Dot
test. The right eye was presented with two red dots placed
vertically one above the other. The left eye was presented
with three green dots forming a V-shaped triangle with its
bottom point aligned with the lower red dot presented to
the other eye. The two other green dots flanked the center point
between the upper and lower red dot. In normal binocular
vision, this image is seen as a diamond array of four dots.
The upper dot is red, the left and right dots are green, and
the bottom dot is bistable and the percept alternates between
red and green. Other responses may indicate anomalies of
binocular vision. All the subjects exhibited normal fusion.

After presenting the dot stimuli to the patient, we asked
whether the bottom dot was seen as a single dot or whether
two dots were visible. All subjects saw a single bottom dot
without further adjusting the amblyoscope. This indicated
that the initial alignment was successful.

Monocular Contrast Detection Threshold.
Contrast detection thresholds were measured in each
eye. The stimuli to be detected were sinusoidal gratings
(Fig. 1A). They had a spatial frequency of 2.5 c/deg. The
method was a two-alternative forced-choice (2AFC) task
where subjects were asked to identify the orientation of
the presented grating. The gratings could be presented
with the bars sloping at either −45° or +45° (left or right
oblique). The spatial extent of the grating was limited by a
rounded raised-cosine envelope with the plateau of 3° of
visual angle and cosine half-period of 0.2°. The temporal
properties of the presentation were also controlled by a
raised cosine function. The contrast first increased from
zero to the nominal contrast according to the shape of a
half-period of a cosine function over 240 ms. There was
then a 240 ms plateau where the stimulus remained at its
nominal contrast. Then, the contrast decreased from the
nominal contrast to zero, mirroring the initial increasing
ramp (again over 240 ms). Therefore, the duration for which
the stimulus was presented at more than half of its nominal
contrast (full width at half magnitude) was 480 ms.

Grating contrast was calculated as root mean square
certainty before applying the spatial envelope. This is simply
the standard deviation of the pixel values when the mean of
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The stimulus is zero and +1 and −1 are the maximum and minimum presentable luminances. For any stimulus there is a 1:1 linear relationship between the root mean square contrast and the Michelson contrast. We present stimulus contrast in decibel logarithmic units, calculated as

\[ c_{\text{dB}} = 20 \times \log_{10} (c_{\text{RMS}}) \].

We used a 2AFC method to obtain thresholds for detecting a grating presented to one eye. Throughout the experiment, a binocular frame was presented around the stimuli to help the participants maintain their convergence. The eye being tested was randomly selected on each trial. The target grating was presented only to the tested eye. Subjects then pressed one of two buttons to indicate the orientation of the target grating (−45° or +45°). They were given an audio feedback based on whether they were correct. Target grating contrast was controlled by a pair of staircases (one for each eye). Each of them had a three-down–one-up rule and a 3-dB step size (therefore converging the staircase sampling at the 79% correct point). The initial grating contrast was −12 dB. The 2 staircases were randomly interleaved and terminated after 9 reversals or 120 trials for each (whichever was reached first). Subjects completed two repetitions of this test. Data from the two repetitions were combined. Psychometric functions were fit to the combined data for each eye to obtain the monocular thresholds (see the Data Analysis section).

**Dichoptic Masking Thresholds.** After measuring contrast detection thresholds, we next measured the strength of dichoptic masking. On each trial, the tested eye was presented with a sinusoidal grating similar to that used in the previous test. The other eye was presented with a patch of contrast-modulated noise (Fig. 1B). The noise was generated by filtering white noise with an isotropic log-Gabor filter. The peak spatial frequency of the noise was the same as for the grating (2.5 c/deg). The spatial frequency bandwidth of the noise was 1.4 octaves. The spatial extent of the noise masks was controlled by a circular raised-cosine envelope. The width of the plateau was 6° and cosine half-period was 0.2°. We used the same temporal envelope as used for the gratings to control the presentation duration of the noise.

We used a 2AFC method in combination with an adaptive staircase procedure to measure dichoptic masking. However, in this test we fixed the contrast of the grating stimuli. In each eye, they were presented at a fixed level above that eye’s contrast detection threshold. This was the monocular contrast detection threshold plus 9 dB. We then controlled the contrast of the noise presented to the other eye using our staircases (one staircase for each eye). The staircases used a three-down–one-up rule with a 3-dB step size. The direction of travel was reversed compared to the staircase in the

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**FIGURE 1.** Sample stimuli of the four tasks in this study. (A) Monocular contrast detection threshold test. (B) Dichoptic masking test. (C) Stereo threshold test. The arrows indicate the direction of horizontal offset in each eye (blue arrows for inward or pink arrows for outward). (D) Binocular orientation combination test.
previous test (as increasing the noise contrast makes the task harder). The initial noise contrast was set at −56 dB. After each trial, subjects were asked to indicate the orientation of the grating. They were given an audio feedback based on whether they were correct. Subjects completed two repetitions of the test. Data were combined across the repetitions and the psychometric functions were fit to find threshold levels of the dichoptic mask required to have a criterion effect on detection performance for suprathreshold targets.

**Stereo Thresholds.** We measured stereo thresholds using a digital stereo task. The stimuli were four identical spatially bandpass circles (spatial frequency 2.5 c/deg, circle diameters 1°). These were generated with a cross-section based on the fourth-order derivative of the Gaussian function. This method is similar to that used to generate radial frequency patterns. The four circles were arranged into a diamond shape (four locations: top, bottom, left, and right). Each circle was placed at an eccentricity of roughly 2° from the center of the display. Each circle was presented binocularly; however, one of the four was presented with a horizontal disparity. This disparity was achieved by adding equal and opposite horizontal offsets to the positions of a particular circle shown to each eye. The direction of horizontal offset in each eye (inward or outward) determined whether the binocular perception of the circle would have a crossed or uncrossed disparity (Fig. 1C). These offsets will break-up the diamond shape formed by the four circles. To prevent this being used as a cue, all of the horizontal and vertical positions of the circles were slightly randomized (with the same random offsets being used in the two eyes). The amount of this randomization was equal to the one-half of the disparity shift in each trial.

We conducted a psychophysical test using a four-alternative-force choice to obtain the stereo thresholds. Subjects indicated which circle had depth by pressing one of the four keys. They were given an audio feedback based on their performance. The direction of the target disparity (crossed or uncrossed) and the location of the target circle were randomly selected on each trial. Two staircases were used to control the disparity. Each of them had a two-down-one-up rule with the step size set to a ratio of \(\sqrt{2}\). The initial disparity was 512 arc sec. The two staircases were randomly interleaved and terminated after 9 reversals or 30 trials for each (whichever was reached first). Subjects completed two repetitions of the measurement. Data were combined across the repetitions and the psychometric functions were fit to the combined data to find stereo thresholds.

**Binocular Eye Balance.** Finally, we measured the contribution of each eye to fused binocular vision. We used a binocular orientation combination task as described by Wang et al. We illustrated in Figure 1D, the stimuli were a pair of dichoptically presented tilted gratings (2.5 c/deg). The two gratings had an equal and opposite tilt of 4°. The gratings had a spatial envelope with a plateau of 1.4° and a cosine half-period of 0.2°, and the same temporal envelope as described elsewhere in this article. They were accompanied by two black reference horizontal lines and surrounded by the circular frame. The base contrast of the gratings was 45%. We measured the binocular orientation combination at seven interocular contrast ratios (1/4, 1/2, 1/√2, 1, √2/1, 2, and 4). For each of these ratios, the contrast in one eye was increased and the contrast in the other eye was decreased to achieve that specific ratio. There were 20 repetitions for each ratio. In each trial, the interocular ratio was chosen randomly. Binocular presentation of these two gratings produced one fused grating percept. The relative strength of the stimulus seen by each eye determined the weight of its contribution to the binocular percept. Subjects then were asked to answer which side of this grating (left or right) was tilted up by pressing one of the two buttons. After data collection, psychometric functions were fit to find the balance point of the two eyes.

**Data Analysis**

We obtained the monocular contrast detection thresholds, dichoptic masking thresholds, and stereo thresholds by fitting logistic psychometric functions using Palamedes. In all cases, the lapse rate was fixed at 1% for fitting. The thresholds for the 2AFC and four-alternative-force choice data were calculated at a proportion correct of 75.0% and 62.5%, respectively. We used parametric bootstrapping routines to obtain bootstrapped estimates of standard error and 95% confidence intervals (1000 samples).

We obtained interocular suppression weights by fitting our data with the two-stage model of contrast gain control based on that described by Meese et al. For the case where targets are presented to the left eye, the response at the first stage is given by:

\[
\text{resp}_L = \frac{(g_L \times C_L)^m}{1 + g_L \times C_L + w_R \times g_R \times C_R},
\]

where \(C_L\) and \(C_R\) are the contrasts of the target in the left eye and the mask in the right eye, respectively. The three fitted parameters are the gain in the left and right eyes (\(g_L\) and \(g_R\)) and the interocular masking weight from the right eye \(w_R\). The exponent \(m\) is set at 1.3 based on previous results. The target is only presented to one eye at a time, so for targets presented in the left eye the second stage is given by

\[
\text{resp} = \frac{\text{resp}_L^p}{1 + \text{resp}_L^q},
\]

where \(p\) and \(q\) are fixed at \(p = 8\), and \(q = 6.6\) based on previous results. Therefore, accounting for left and right eye target conditions requires four fitted model parameters: \(g_L, g_R, w_L,\) and \(w_R\). It is worth noting that the construction of Equation 1 means that the masking weight parameters for each eye have an effect that is separate from the input gain parameters. Any imbalances found in masking weight are additional to the effects of any imbalances in input gain. Assuming a constant internal noise variance, predicting thresholds requires simply solving for some criterion value of \(\text{resp}\) (we chose to solve for a value of \(\text{resp} = 1\)). We fit this model in MATLAB using the fminsearch function to minimize the root mean square error between the thresholds predicted by the model and the empirical data.

To obtain the balance point of each subject, we fitted the proportion of trials in which they reported that the left side of the grating tilted up by using a logistic function. The estimated midpoint of the logistic function defines the point of subjective equality, which indicates the balance point where the two eyes were balanced in binocular combination. For this analysis, the lapse rate of 1% affected both the upper and lower asymptotes (gamma and lambda parameters) of the psychometric function. The estimated points of subjective equality were derived from 1000 parametric bootstrapped samples.
RESULTS

Stereoacuity, monocular contrast thresholds, and monocular dichoptic masking thresholds are respectively presented in Figures 2A, C, E. Interocular differences in contrast threshold and interocular differences in masking weight were obtained by the monocular contrast thresholds and monocular dichoptic masking thresholds.

The mean absolute interocular difference in contrast thresholds was $2.9 \pm 0.5$ dB (mean ± standard error; 95% confidence interval [CI], 2.0–3.9). The mean absolute interocular difference in masking weight was $9.5 \pm 1.1$ dB (95% CI, 7.2–11.8). The mean stereoacuity was $6.1 \pm 0.2 \log_2$ (arc sec) (95% CI, 5.7–6.4). Inverting the log-transformation gives an average threshold of 69 arc sec. The mean absolute

![Graphs showing distributions of stereoacuity, monocular contrast thresholds, and monocular dichoptic masking thresholds.](image-url)
balance point was 2.2 ± 0.4 dB (95% CI, 1.4–2.9). We also display the distributions of the measures of binocular function with signed value in all subjects.

For each of those measures, we refer to them as a type of sensory eye imbalance. For the binocular fusion task with the oriented gratings, the value of the balance point for when the two eyes contribute equally to the percept is termed the “fusion imbalance.” In the threshold task, the difference in threshold between the two eyes is termed the “threshold imbalance.” With the dichoptic mask, the difference in masking weight between the two eyes is termed the “masking imbalance.” The results of those sensory eye imbalance are presented in Figures 2B, D, F. Negative value along the x-axis of each graph represent the amount of right eye sensory eye dominance.

Figures 3A, B, C each plot the subject’s stereoacuity as a function of sensory eye imbalance. We performed a Shapiro–Wilk test on the normality of the data distribution. The absolute fusion imbalance and absolute threshold imbalance were not normally distributed (P = 0.002 and P = 0.004, respectively). The Spearman’s ρ correlation test and Pearson’s r correlation test were used to analyze as appropriate. We found a significant correlation between stereovisual acuity and the absolute fusion imbalance (Fig. 3A; ρ = 0.52; 95% CI, 0.17–0.76; P = 0.003), suggesting that the subjects with well-balanced contributions to binocular vision from the two eyes have better stereoacuity. However, we found no significant correlation between stereoacuity and the absolute threshold or masking imbalances (Fig. 3B; ρ = 0.01; 95% CI, −0.39 to 0.38; P = 0.961; Fig. 3C, r = −0.01; 95% CI, −0.38 to 0.48; P = 0.950). This finding suggests that imbalances in performance at threshold or the effectiveness of dichoptic masking do not predict stereoacuity.

In addition, we examined the correlation between the different measures of sensory eye imbalance. We found significant (but moderate) correlations between fusion imbalance and threshold imbalance (Fig. 3D; r = 0.46; 95% CI, 0.05 to 0.7; P = 0.011), and between threshold imbalance and masking imbalance (Fig. 3F; r = 0.49; 95% CI, 0.12 to 0.79; P = 0.005). These accounted for 21% and 24% of the variance, respectively. We found no significant correlation between fusion imbalance and masking imbalance (Fig. 3E; r = −0.20; 95% CI, −0.5 to 0.17; P = 0.298).

**DISCUSSION**

In this study, we assessed stereoacuity and sensory eye imbalance in subjects with normal healthy vision, and examined the relationships between these measures. The average stereoacuity was 69 arc sec. Stereoacuity was distributed over a broad range (Fig. 2A, Fig. 3A), which is similar to previous studies.\(^1\)\(^3\)\(^6\) We also showed that the inputs from the two eyes are not perfect balanced in subjects with
otherwise normal vision. The extent of the imbalance also varied over a significant range (Fig. 2, Fig. 3). Our results showed that stereoeacuity significantly correlated with fusion imbalance, but not with absolute contrast threshold or contrast masking imbalance. In addition, we found some correlations between these three measures of sensory eye imbalance. There was a moderate correlation between the fusion and threshold imbalances; however, we did not find a correlation between fusion and masking imbalances. The construction of Equation 1 gives us a measure of masking imbalance that factors out the effects of any imbalances in input sensitivity to the two eyes. Even with these effects factored out, however, we found a moderate correlation between threshold and masking imbalances. Because the threshold imbalance was correlated with both the fusion and masking imbalances, it is perhaps a little surprising that the fusion and masking imbalances were not significantly correlated with each other. This finding can be explained by the significant correlations we found not being very strong. It is possible that the subset of data points driving the correlation between fusion and threshold imbalances are not the same as the subset of data points driving the correlation between threshold and masking imbalances.

Our results show a relationship between stereoeacuity and sensory eye balance, but only when balance is assessed with a task that measures fusion for suprathreshold stimulation. We do not find a relationship between stereoeacuity and measures of eye balance at threshold. This finding is in agreement with previous studies that found stereoeacuity was significantly correlated with sensory eye balance. However, our study has the advantage of measuring eye balance and stereoeacuity using stimuli of the same spatial frequency. Both stereoeacuity and sensory eye balance are known to depend on stimulus spatial frequency and so it is essential to use targets of the same spatial frequency for their comparison. However, our results are in disagreement with a previous study that used the same spatial frequency to make these two measurements. Wang et al. assessed sensory eye balance and stereoeacuity in a relatively large sample (142 adults) by using a binocular phase combination task. They found that stereoeacuity was not correlated significantly with sensory eye balance. However, a possible explanation was that their spatial frequency was relatively low (0.3 c/deg). Our results suggest that their conclusions do not apply to higher spatial frequencies.

The spatial frequency used in our study was comparable with that used in previous studies that did find a relationship between sensory eye balance and stereoeacuity. Although the relatively moderate sample size of our study may decrease the statistical power, we still found a strong correlation between stereoeacuity and the sensory eye balance (Fig. 3A), suggesting that the subjects with well-balanced contributions to binocular vision from the two eyes have better stereoeacuity (at least when assessed by a task that measures the contribution from the two eyes to suprathreshold perception). We hypothesize that this relationship may be dependent on spatial frequency.

The subjects in this study ranged in age from 20 to 69 years old; however, we had not set out to study any effects of age and so did not analyze this aspect of our data (because we would have lacked statistical power). It would be useful in subsequent studies to set out with a view to performing a specific analysis on this dimension of interest, by recruiting a larger number of subjects across a range of ages. This would allow for a further evaluation of the relationship between stereoeacuity and the sensory eye balance across the lifespan.

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