Visual Adaptation to Interocular Brightness Differences Induced by Neutral-Density Filters

Ewen S. MacMillan, Lyle S. Gray, and Gordon Heron

PURPOSE. Interocular brightness differences such as those caused by asymmetrical cataract have been found to have a minimal effect on interocular brightness matches. In the present study, the measured binocular visual response to interocular differences in retinal illuminance was measured over time.

METHODS. Interocular differences in retinal illuminance of magnitudes 0.3, 0.6, and 0.9 log units were induced using neutral density (ND) filters under two conditions: (1) naturally mobile pupils and (2) with fixed artificial pupils (3 mm). Interocular brightness differences were quantified by measuring interocular brightness matches using the simultaneous interocular brightness sense test every 15 minutes over a 2-hour period in eight visually normal subjects.

RESULTS. Initial interocular brightness matches were as predicted by the induced interocular differences in retinal illuminance ($P > 0.05$). A significant reduction in the interocular difference in brightness was observed over time ($P < 0.01$). These reductions in the interocular difference in brightness over time followed a logarithmic progression reaching asymptotic values equal to the reciprocal of the square root of the interocular retinal illuminance ratio. This value is equal to the midpoint of the induced interocular difference in retinal illuminance at time 0 and that found without the introduction of the ND filters. Binocular visual adaptation to interocular brightness differences occurred with both mobile and fixed pupils.

CONCLUSIONS. Visual adaptation occurs in response to interocular brightness differences induced by asymmetrical ND filters. The level of visual adaptation can be predicted by Fechner’s Paradox and is independent of interocular differences in pupil diameter. (Invest Ophthalmol Vis Sci. 2007;48:935–942) DOI: 10.1167/iovs.06-0958

A symmetrical cataract, in which cataract formation in one eye differs significantly from that of the fellow eye, can produce considerable interocular differences in retinal brightness. Despite this finding, asymmetrical cataracts do not cause significant interocular differences in perceived luminance. This implies that the binocular visual system can compensate for these interocular differences in retinal illuminance.

Interocular differences in retinal illuminance can have disturbing effects on visual function, such as illusory depth. Visual adaptation to interocular differences in retinal illuminance would allow the visual system to reduce the potentially disturbing effects caused by interocular brightness differences. Significant asymmetrical cataract is a common clinical finding, yet symptoms of reduced visual function caused by anomalous binocular processing of interocular brightness differences are rarely reported. This anecdotal evidence supports the notion of binocular visual adaptation to interocular differences in retinal illuminance.

Visual adaptation to ambient illumination is a well-known feature of the visual system. The visual system is able to shift its optimum operating level depending on retinal illuminance, and as a result, it is able to function over a wide range of luminances, spanning at least 10 log units, which allows the visual system to maintain stable visual sensitivity.

The physiological processes underlying this visual adaptation are found in the neural elements of the retina. Cones are able to encode light intensities over a range of only 3 log units; however, the retina overcomes the limitations of the anatomic elements through automatic gain control. Once there is sufficient light impinging on the retina, the overall gain of the photosensitive elements of the retina is reduced so that the neural response does not become saturated. This process is mediated by the bipolar, horizontal, and amacrine cells in the retina, which alter both the output gain and receptive field properties of the retinal ganglion cells. This system allows constancy in the retinal response to visual stimuli across the physiological range of retinal illuminance. If the retina did not change luminance gain, sensitivity to changes in luminance would drop significantly at high levels of illuminance, and reflective objects would not be seen because of a light-saturated retina. Fortunately, luminance sensitivity and contrast gain increase as retinal illuminance increases and then level off to asymptotic values in very bright light. When retinal illuminance is dimmed, luminance adaptation occurs in a similar manner but in this instance the gain is increased.

Retinal illuminance is usually equal in both eyes, and luminance adaptation normally occurs in both eyes at the same time. Only a minor role in luminance adaptation is attributable to the accompanying changes in pupil size (~1 log unit). However, the pupil response may be important initially when there is a large change in illumination for the visual system to deal with.

The Naka-Rushton equation, a variant of the Michaelis-Menten equation, approximately describes the light intensity-response function of retinal neurons, which respond to light impinging on the retina. The equation describes a system in which the response increases with increasing light intensity but eventually reaches a point at which it can make no further response and becomes saturated.

When retinal illuminance is equal, binocular visual sensitivity to luminance stimuli is greater than the individual sensitivity of either eye alone. The situation where the response of the two eyes are combined to give better vision is termed binocular summation. Luminance detection is improved by a factor of $\sqrt{2}$ when both eyes are used for detection. Campbell and Green proposed that each monocular channel contains some internal noise that increases the threshold for stimulus detection by $\sqrt{n}$, and since we have two eyes ($n = 2$) binocular sensitivity thereby increases by $\sqrt{2}$. This power function can also be written as $n^{0.5}$.

From the Department of Vision Sciences, Glasgow Caledonian University, Glasgow, Scotland, United Kingdom. Submitted for publication August 11, 2006; revised October 17, 2006; accepted December 18, 2006.

Disclosure: E.S. MacMillan, None; L.S. Gray, None; G. Heron, None

The publication costs of this article were defrayed in part by page charge payment. This article must therefore be marked ‘advertisement’ in accordance with 18 U.S.C. §1734 solely to indicate this fact.

Corresponding author: Lyle S. Gray, Senior Lecturer, Department of Vision Sciences, Glasgow Caledonian University, Cowcaddens Road, Glasgow, G4 0BA, Scotland, UK; lgray@gcal.ac.uk.


Copyright © Association for Research in Vision and Ophthalmology
Binocular summation has been demonstrated objectively through comparison of the binocular and monocular amplitude of the visually evoked response. More recently, it has been measured subjectively by studies measuring Snellen acuity, absolute luminance thresholds, critical flicker frequency, and performance tasks. The quadratic equation below predicts binocular summation for luminance (B) and holds true when right (R) and left (L) eyes are equally stimulated.

\[ B^2 = R^2 + L^2 \]

The equation does not hold if each eye is stimulated differently. For instance, if a neutral-density (ND) filter is placed before one eye during binocular viewing, and the binocular impression of brightness is compared with that obtained by the unfiltered eye alone, the visual scene appears brighter when viewed monocularly. In this situation the binocular brightness is less than the brightness of the two unequal monocular brightnesses. This finding is known as Fechner’s paradox, because binocular brightness does not follow the summation equation, which predicts that the binocular brightness will be greater than the monocular brightnesses. If the binocular brightness is less than the larger monocular brightnesses, then some form of averaging process must have taken place.

The quadratic summation model just outlined cannot account for inhibitory phenomena such as Fechner’s paradox. Other models have addressed binocular inhibition by treating the binocular response as a vector summation, which is a generalization of the quadratic summation model, or as a weighted summation. Both allow adjustment of the binocular response to take account of monocular stimulus differences and/or ocular dominance and are thus more complete descriptions of binocular luminance interaction.

Fechner’s paradox suggests the presence of an interocular inhibitory mechanism. The existence of inhibitory interactions in binocular rivalry is well known. The origin of these binocular interaction mechanisms may be in the visual cortex.

The purpose of these experiments was to investigate the binocular visual adaptation that occurs when interocular differences in retinal illumination are introduced to the visual system by using ND filters.

**METHODS**

**The Simultaneous Interocular Brightness Sense Test**

The simultaneous interocular brightness sense test (SIBST) quantifies interocular brightness differences. It is a valid and repeatable measure of interocular brightness differences in visually normal subjects that was first reported by Sadun and Lessell in 1985. The barely noticeable difference in interocular brightness that can be reliably detected is ~3% with the SIBST.

The apparatus of the SIBST consists of a bipartite polarized lightbox that subjects view through a visor. The two oculars of the visor consist of pairs of crossed polarizers. The polarization of each side of the lightbox and posterior polarizer of the corresponding ocular of the visor were set in the same direction. This arrangement enables the subject’s right eye to see the luminance (luminance of 600 cd m⁻²) of the right side of the lightbox but not that of the left side of the lightbox. Conversely, the left eye sees the luminance (luminance of 600 cd m⁻²) from the left side of the lightbox but not that of the right side. A septum, adjustable for interpupillary distance, also ensures haploscopic presentation.

**Brightness Matching**

For the measurement of all brightness matches, the anterior polarizing filter of the right ocular was fixed at 45° and provided the comparison field (luminance 150 cd m⁻²) which was matched by the left eye. Adjustments were made to the orientation of the anterior polarizer of the left ocular (thereby altering the apparent brightness of the light patch seen by the left eye) while the observer looked at the screen through the visor, attending only to the brightness of the light patches seen by each eye. The test was performed under standard room illumination at 0.4 m, and spectacle correction was worn if appropriate. An ascending and descending method of limits was used. Initially, the anterior polarizer of the left ocular was set for maximum transmission. This filter was then rotated until the subject perceived the two light patches as equiluminant (thus establishing the descending limit threshold). The polarizer angle setting of the match was then recorded. This procedure was repeated, with the left ocular set initially for minimum transmission, and again the match was obtained (thereby establishing the ascending limit threshold). Hence ascending and descending limits were determined in alternation. Ten values were obtained for each subject—five ascending measures alternating with five descending measures.

**Figure 1.** The Naka-Rushton relationship. This is a plot of \( R/R_{\max} = L/(L_0 + L) \) on linear-linear coordinates, to illustrate the response compression. The semisaturation constant \( L_0 \) was chosen to be 100 in arbitrary units. \( R \) is the response of the neuron measured as the change in membrane potential from its totally dark-adapted level, \( L \) is the luminance of the stimulus, \( L_0 \) is the semisaturation constant also equal to the luminance at which \( R \) reaches its half-maximum value. The equation describes a system that saturates (after Shapley, 1991).
descending measures—and the mean value was determined. The time
taken to perform the test was 2 to 3 minutes.

The Brightness Sense Ratio

The comparison of right and left eye brightness perceptions was quantified by the determination of the brightness sense ratio (BSR).

The BSR can be calculated in two ways:

1. If the ratio of luminances is calculated by always taking the luminance in the left eye and dividing by the value from the right eye, then the value of the BSR is dependent on how each eye perceives the brightness of the screen. Any value greater than 1.00 is obtained when the left eye needs more light to make a brightness match; similarly, any value <1.00 means that the right eye may be defective and requires more luminance to make a brightness match. We call this the polarized BSR.

2. If the BSR is calculated more simply as the ratio of the lower luminance value corresponding to the eye covered by the denser ND filter divided by the higher luminance of the eye covered by the less dense ND filter then which eye sees the higher or lower luminance is no longer important. All values are <1.00, irrespective of which eye requires more light at the brightness match point. We call this the depolarized BSR.

Subjects

Eight young (age range, 23–32 years), visually normal subjects participated in the experiments. All subjects gave informed consent to participate in this study in accordance with the Declaration of Helsinki. All had VA of 6/6 or better in each eye and normal binocular function as assessed by standard clinical tests. Subjects wore their full refractive corrections during all the trials.
Table 1. The Interocular Difference in Effective Retinal Illuminance and the Expected BSR, Based on Retinal Illuminance, for Each Pair of ND Filters

<table>
<thead>
<tr>
<th>ND Filters (Log Units)</th>
<th>Interocular Difference in Effective Retinal Illumination (Log Units)</th>
<th>Expected BSR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right</td>
<td>Left</td>
<td>Δ</td>
</tr>
<tr>
<td>0.4</td>
<td>0.1</td>
<td>0.3</td>
</tr>
<tr>
<td>0.7</td>
<td>0.1</td>
<td>0.6</td>
</tr>
<tr>
<td>1.0</td>
<td>0.1</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Experiment 1: The BSR over Time

In this experiment, subjects had a brightness match measured every 15 minutes over a period of 2 hours.

Experiment 2: The Effect of Asymmetrical ND filters on the BSR over Time

In this experiment, interocular brightness differences were induced by goggle-mounted ND filters (Wratten gelatin: No. 96; Eastman Kodak, Rochester, NY) which is analogous to light reduction in asymmetrical cataract. Three ND filter pairs were used to reduce retinal illuminance as follows: 0.4 and 0.1 log unit, 0.7 and 0.1 log unit, and 1.0 and 0.1 log unit. The filter pairs produced an interocular difference in retinal illuminance of 0.3, 0.6, and 0.9 log unit, respectively. The denser ND filter was mounted in the right ocular of the goggles. Interocular brightness matches were recorded with naturally mobile pupils and fixed artificial pupils (clear pupil, occlusive iris; 58% Filcon 4a material, Igel International, Ltd., Leighton Buzzard, UK) were used to create fixed 3-mm pupils. Brightness sense measures were recorded every 15 minutes over 2 hours, and the measurement cycle commenced immediately after the ND goggles were placed over the subject's eyes.

Naka-Rushton Equation

The Naka-Rushton equation was used to describe the relationship between the BSR and time. The data collected from each subject for each condition was plotted on linear–linear coordinates and a Naka-Rushton relation was fitted to describe the visual response to interocular brightness differences over time. The Naka-Rushton equation is given in Figure 1 and the Naka-Rushton relationship is illustrated in Figure 2.

RESULTS

Experiment 1: The BSR over Time

BSRs were recorded from eight normal observers over 2 hours. Figure 3 shows the mean BSR ± SD of the eight observers at each time interval.

Repeated-measures analysis of variance shows that there was no systematic change in the BSR for all subjects tested (F_{8,72} = 1.72; P = 0.1).

The mean BSR and SD for the group (n = 8) is 1.03 ± 0.14. This is representative of the normal sample and a one group Student's t-test shows that the mean BSR is as expected on the basis of retinal illuminance and is not significantly different from the expected BSR of 1.00: t_{1,7} = 0.57; P = 0.58.

Experiment 2: The Effect of Asymmetrical ND Filters on the BSR over Time

BSRs were recorded over 2 hours from eight visually normal observers, during which time various pairs of ND filters were introduced to the observer that created three distinct magnitudes of interocular differences in retinal Illuminance. The goggle mounted ND filters were used to simulate the light transmission of asymmetrical cataracts although they do not mimic the lens inhomogeneities or light scatter associated with cataract.
Table 1 shows the perceived interocular difference, termed the effective retinal illuminance ratio and the BSR expected for each pair of ND filters on the basis that the BSR equals 1.00 in a normal subject under normal no-filter conditions. Figures 4, 5, and 6 are for one subject and are representative of the change in the BSR as a function of time when interocular differences in retinal illuminance are created by goggles-mounted ND filters. BSRs recorded when there is natural pupillary activity behind the goggles were labeled Mobile Pupils. BSRs recorded when pupil size is fixed, by 3-mm pupil prosthetic soft contact lenses were labeled Fixed Pupils. The normal BSR for this subject was 0.99. The results shown in Table 2 indicate that the BSR at time 0 was comparable to that predicted on the basis of the inter.

Repeated-measures analysis of variance indicates that there was systematic variation in the BSR up to time 30 minutes and time 75 minutes for fixed and mobile pupil conditions, respectively. A paired t-test shows that there is no significant change in the BSR between time 30 minutes and time 120 minutes for the fixed pupil condition ($t_{1,9} = 0.19; P = 0.85$) and no significant change in the BSR between time 75 minutes and time 120 minutes for the mobile pupil condition ($t_{1,9} = 0.24; P = 0.98$).
ocular difference in retinal illuminance for the Δ0.3 and the Δ0.6 condition for both mobile and fixed pupils. For the Δ0.9 condition, the BSR was lower than expected for both mobile and fixed pupils at time 0. At time 120, the BSR was significantly greater than the expected BSR, based on the interocular difference in retinal illuminance, for all conditions.

Table 3 shows the results of the paired t-tests that indicate the mobile and fixed pupils had equivalent BSRs at time 0 but the mobile pupil BSR is significantly greater than the fixed value in all three conditions at time 120.

Table 4 shows that the expected BSR based on binocular inhibition (Fechner’s Paradox) predicts the level to which the curve saturates for all fixed pupil conditions but not for the Δ0.3 mobile pupil condition and the Δ0.9 mobile pupil condition where the measured BSR is significantly greater than the expected BSR.

Figure 7 shows the relationship between the BSR after visual adaptation and the ratio of the effective retinal illuminance. Asymmetrical ND filters reduced the BSR significantly with the BSR predicted by the equation displayed in Figure 7. The equation describing the data in Figure 7 suggests that binocular inhibition after 2 hours of filter wear is equal to the inverse square root of the effective retinal illuminance ratio (ERIR)^-0.5, where ERIR is the ratio of retinal illuminances (≥1.0), as calculated from the ND filter values.

**DISCUSSION**

These results demonstrate that the perceived binocular brightness level after visual adaptation to asymmetrical retinal illuminance can be predicted by an arithmetic model of binocular inhibition (Fechner’s paradox).27,28

Other findings of the study were as follows: Visually normal subjects were able to make reliable brightness matches with no systematic change in the BSR when measured over 2 hours. Asymmetrical ND filters caused an initial interocular brightness perception difference that was predicted by the interocular difference in retinal illuminance.

The interocular brightness difference created by ND filters decreased with time to a level predicted by Fechner’s paradox.

The adaptation to interocular brightness differences identified in this study was found with both fixed and mobile pupils.

It was important to assess the variability of the BSR over time, to determine whether the SIBST would be suitable for investigating binocular visual adaptation to induced interocular differences. If the BSR was found to vary excessively or shift systematically, then it may not have been possible to monitor visual adaptation using this method of quantifying interocular brightness differences. The results for interocular brightness matches measured over time in normal subjects show that the BSR did not vary systematically when measured every 15 minutes over a 2-hour period. The magnitude of the variation in the BSR over this time was found to be very small (<0.1) in all observers, indicating that the measure is sensitive enough for the purposes of the present study. Two hours was chosen as a time period for investigation after previous workers found no variation in brightness matches after 90 minutes.29 These results suggest that the SIBST is useful in detecting systematic changes of interocular retinal sensitivity that may occur when interocular differences are artificially induced or in disease.

The results for interocular brightness matches measured over time in normal subjects wearing asymmetrical ND filters show that the initial BSR was predictable on the basis of interocular differences in retinal illuminance caused by the ND filters (Table 2).

Visual adaptation to the presence of an interocular brightness difference occurred whether the pupils were mobile or fixed. It was important to investigate both mobile and fixed pupils because a relative afferent pupillary defect (RAPD) was induced by the interocular difference in retinal illuminance caused by the ND filters, with the pupil behind the denser ND filter dilating relative to the other. This may have influenced the measured BSR, because the increase in pupil size under the denser ND filter increased retinal illuminance in that eye and thereby lessened the magnitude of the interocular difference in retinal illuminance created by the ND filters. The initial BSR obtained with asymmetrical ND filters for both mobile and fixed pupils was equivalent to that predicted on the basis of the interocular difference in retinal illuminance, and visual adaptation was found to be independent of pupil mobility. This result is consistent with the hypothesis that for visual adaptation, only a minor role is attributable to the accompanying changes in pupil size.6,7

The BSR increased as a function of time to a level close to that predicted by Fechner’s paradox in both the mobile and fixed pupil conditions. It should be noted that in the mobile pupil condition, the BSR level beyond which no further change in the BSR occurs was significantly greater than that of the fixed pupil condition. This indicates that the RAPD induced by the asymmetrical ND filters reduces the effect of the ND filter used. This amelioration of the asymmetrical brightness is not witnessed initially but occurs later as visual adaptation reaches cessation.

**TABLE 3.** Paired t-Tests Comparing Mean BSRs for Fixed and Mobile Pupils at Time 0 and Time 120

<table>
<thead>
<tr>
<th>Time 0</th>
<th>Time 120</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t_{1.9} = 1.12 )</td>
<td>( t_{1.9} = 3.38 )</td>
</tr>
<tr>
<td>( t_{1.9} = 0.12 )</td>
<td>( t_{1.9} = 9.20 )</td>
</tr>
<tr>
<td>( t_{1.9} = 2.12 )</td>
<td>( t_{1.9} = 4.68 )</td>
</tr>
</tbody>
</table>

\( P = 0.29 \) \( P = 0.01 \)

\( P = 0.06 \) \( P = 0.01 \)

The BSR data are the mean ± SD.

**TABLE 2.** Comparison of the Mean BSR at Time 0 and Time 120 for All ND Filter Conditions with both Fixed and Mobile Pupils

<table>
<thead>
<tr>
<th>ND Filter (Log Unit)</th>
<th>Pupil Status</th>
<th>BSR (Time 0)</th>
<th>BSR (Time 120)</th>
<th>Expected BSR (time:0)</th>
<th>Measured BSR (time:120)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Δ0.3</td>
<td>Fixed</td>
<td>0.47 ± 0.13</td>
<td>0.64 ± 0.10</td>
<td>( t_{1.9} = 0.64 )</td>
<td>( t_{1.9} = 4.51 )</td>
</tr>
<tr>
<td>Δ0.3</td>
<td>Mobile</td>
<td>0.43 ± 0.14</td>
<td>0.81 ± 0.08</td>
<td>( t_{1.9} = 1.24 )</td>
<td>( t_{1.9} = 11.58 )</td>
</tr>
<tr>
<td>Δ0.6</td>
<td>Fixed</td>
<td>0.27 ± 0.05</td>
<td>0.48 ± 0.06</td>
<td>( t_{1.9} = 1.14 )</td>
<td>( t_{1.9} = 9.82 )</td>
</tr>
<tr>
<td>Δ0.6</td>
<td>Mobile</td>
<td>0.26 ± 0.04</td>
<td>0.53 ± 0.08</td>
<td>( t_{1.9} = 0.04 )</td>
<td>( t_{1.9} = 8.54 )</td>
</tr>
<tr>
<td>Δ0.9</td>
<td>Fixed</td>
<td>0.08 ± 0.03</td>
<td>0.34 ± 0.08</td>
<td>( t_{1.9} = -4.47 )</td>
<td>( t_{1.9} = 29.36 )</td>
</tr>
<tr>
<td>Δ0.9</td>
<td>Mobile</td>
<td>0.06 ± 0.02</td>
<td>0.50 ± 0.04</td>
<td>( t_{1.9} = -9.73 )</td>
<td>( t_{1.9} = 0.54 )</td>
</tr>
</tbody>
</table>

1.14 \( P = 0.001 \)

8.54 \( P < 0.001 \)
The level of binocular visual adaptation for the ND filters for both fixed and mobile pupils was found to be the mean of the difference in effective retinal illuminance. The binocular visual adaptation level approximates to the square root of the reciprocal of the effective retinal illuminance ratio (greatest retinal illuminance to lesser retinal illuminance). The level of interocular brightness difference is described by the following formula:

$$1/\sqrt{E/E'}$$

where E is the effective retinal illuminance in one eye, E’ is the effective retinal illuminance of the other eye, and (E/E’) ≥ 1.

Interocular differences in retinal illuminance arise clinically in ocular conditions such as anisocoria and asymmetrical cataract, and as a result the binocular percept may be worse than that of the better eye because of binocular inhibition.30,40 As stated previously, this is rarely reported in a clinical setting, suggesting that some form of binocular visual adaptation may account for the lack of visual symptoms. Preliminary studies show that patients with anisocoria or asymmetrical cataract prove normal when tests for illusory depth (the Pulfrich stereo phenomenon) and afferent defects (SIBST and swinging flashlight test) are performed, although differences in retinal illuminance must occur (Weir C et al. IOVS 1997;38:ARVO Abstract 335). These findings suggest that a binocular visual adaptation mechanism is present. The magnitude of visual adaptation that occurs when interocular differences in retinal illuminance are introduced to the visual system has not been quantified previously.

Our study suggests that binocular visual adaptation is the reason that some subjects with asymmetrical cataract do not demonstrate symptoms that would be expected in cases of substantial interocular brightness differences. Those patients with symptoms of interocular brightness differences41 have an interocular brightness difference that is too great to be overcome by binocular visual adaptation (i.e., the visual system cannot adapt to a level at which visual symptoms are absent). Alternatively, it may be that the visual system cannot adapt because the neural basis of the brightness difference is beyond the anatomic reach of the gain control system. The interocular brightness difference in these patients can be overcome by the use of a tinted lens placed over the better eye, thereby alleviating symptoms of illusionary depth.3

![Figure 7](image_url)

**Figure 7.** The relationship between the visual adaptation level calculated from Naka-Rushton equations and the ratio of retinal illuminance induced by ND filters (mobile pupils). The visual adaptation level is approximately the reciprocal of the square root of the interocular retinal illuminance ratio.
References