
ELSEVIER
VISION
RESEARCH
An International Journal for Functional Aspects of Vision
Biochemistry & Cell Biology • Molecular Biology & Genetics
Anatomy, Physiology, Pathology & Pharmacology • Optics, Accommodation & Refractive Error
Circuitry & Pathways • Psychophysics • Perception • Attention & Cognition
Computational Vision • Eye Movements & Visuomotor Control
ISSN 0042-6989 | Volume 49 | Number 15 | 22 July 2009

Vision Research 49 (2009) 1929–1938

Contents lists available at ScienceDirect

Vision Research

journal homepage: www.elsevier.com/locate/visres

The psychophysics of detecting binocular discrepancies of luminance

Monika A. Formankiewicz [a,b,*], J.D. Mollon [b]

[a] Anglia Vision Research, Department of Optometry and Ophthalmic Dispensing, Anglia Ruskin University, Cambridge CB11PT, United Kingdom
[b] Department of Experimental Psychology, University of Cambridge, Downing Street, Cambridge, United Kingdom

ARTICLE INFO

Article history:
Received 22 December 2008
Received in revised form 6 May 2009

Keywords:
Binocular luminance disparity
Binocular luster
Gloss
Color blindness
Weber's Law

ABSTRACT

In the natural world, a binocular discrepancy of luminance can signal a glossy surface. Using a spatial forced choice task, we have measured the ability of subjects to detect binocular luminance disparities. We show that the detection of binocular luminance disparity shares several basic psychophysical features with the detection of surface properties such as lightness and chromaticity: an approximation to Weber's Law, spatial summation, temporal summation, and a deterioration with increasing eccentricity. We also discuss whether color-deficient subjects could derive reliable information about chromaticity from the binocular disparities of luminance induced by a monocularly worn color filter.

1. Introduction

When the cyclopean visual system is presented with monocular stimuli of discrepant luminances, the two stimuli may be combined so that the fused percept has an intermediate brightness. The rules that govern this binocular summation of brightness have been investigated (e.g. Anstis & Ho, 1998; Curtis & Rule, 1978; Dawson, 1913; De Weert & Levelt, 1974; Engel, 1969; Levelt, 1965a; Sherrington, 1904; Teller & Galanter, 1967). However, the discrepant monocular images may also result in a number of other binocular percepts, such as binocular luster (e.g. Helmholtz, 1909; Pieper & Ludwig, 2002; Sheedy & Stocker, 1984; Yoonessi & Kingdom, 2009), binocular rivalry (Ludwig, Pieper, & Lachnit, 2007; Wolfe & Franzel, 1988), the sieve effect, the floating effect (Howard, 1995) or the Venetian blinds effect (Cibis & Harris, 1951). The exact nature of the percept is determined by the spatial and luminance profiles of the monocular images. Although these several effects have usually been studied by deliberately creating different dichopic images in a laboratory, it could be argued in each case that a particular three-dimensional arrangement in the real world would give rise to the corresponding percept.

1.1. Role of binocular luminance disparity in the perception of gloss

The reflectance properties of a surface can be represented as a sum of diffuse and specular reflections. Specular reflections are associated with glossy surfaces, and judgments of surface gloss are affected by the fraction of light that is reflected in the specular direction and by the spread of light to either side of the specular direction (Hunter, 1937; Hunter & Harold, 1987). The rating of the glossiness of a surface increases with an increase in the specular component (e.g. Wendt, Faul, & Mausfeld, 2008). The specular component is reflected at the same angle as the angle of incidence or is distributed around that angle. If the illuminant is directional, the intensity of the light reflected from glossy surfaces will therefore be different for different viewpoints, with the difference determined by the specular component (Bhat & Nayar, 1998). In other words, a given point on a glossy surface will usually present discrepant luminances to the two retinas: Since the surface reflects more light in one direction than another and since the two eyes are laterally separated, the light reaching one eye will be greater than that reaching the other (Ludwig et al., 2007; McCamy, 1998; Oppel, 1854). The visual system may therefore be exposed to discrepant levels of monocular luminances when viewing glossy surfaces. This discrepancy, which may subjectively be seen as luster, is potentially a cue to the smoothness or shininess of the surface (McCamy, 1998; Tyler, 1983, 2004). However, the percept of gloss has been shown to be multidimensional (e.g. Billmeyer & O'Donnell, 1987; Ferwerda, Pellacini, & Greenberg, 2001; Harrison & Poulter, 1951) and the binocular disparity of luminance would be only one of several cues that determine this complex percept.

Many of the classical studies of binocular luster studied monocular stimuli that are not just of different luminances but are of reversed contrast polarity. Dove (1851) viewed a stereoscopic pair of images, one of which had a white outline drawing of a geometrical figure on a black background and the other a black outline on a white background: When the images were fused, the solid appeared lustrous (see also Helmholtz (1909) and Whittle (1994)).

* Corresponding author. Address: Department of Optometry and Ophthalmic Dispensing, Anglia Ruskin University, Cambridge CB1 1PT.
E-mail address: monika.for@anglia.ac.uk (M.A. Formankiewicz).

0042-6989/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.visres.2009.05.001

Rated binocular luster peaks when the monocular spots have opposite contrast polarities in the two eyes (Anstis, 2000), but some level of luster may also be perceived when the contrast polarity of the dichoptic spots is the same (but their contrasts or luminances differ) (Anstis, 2000; Pieper & Ludwig, 2002; Sheedy & Stocker, 1984). In the natural world a local highlight visible to one eye will rarely be matched by an actual decrement in the other eye; and in the present paper we confine ourselves to the case where the dichoptic stimuli have the same contrast polarity. Without inquiring into the exact nature of the subjective percept that is being used, we measure the observer's ability to detect the binocular luminance disparity.

1.2. Binocular luminance disparity as a cue for the daltonian

Monocularly worn tinted filters have been proposed as a treatment for color deficiency (Cornsweet, 1970; Harris, 1998; Zeltzer, 1971). These could improve color discrimination by increasing the gamut of chromatic or luminance variation within a visual scene. However, monocular filters could also introduce a discrepancy in the intensity and chromaticity of light reaching the two eyes from a given surface. It has been suggested that the induced discrepancy of luminance, perceived subjectively as luster, could be used by color-deficient individuals to improve their color discrimination (Heath, 1974; Schmidt, 1976; Sheedy & Stocker, 1984). The amount of discrepancy between the monocular luminances produced by a given filter will depend on the spectral reflectance of the object, the spectral power distribution of the illuminant and the transmission spectrum of the monocular filter (see Fig. 1). The degree of this discrepancy will affect the probability of an object looking lustrous (Pieper & Ludwig, 2002), and so the probability of seeing luster will vary according to the spectral power distributions of different stimuli. The daltonian could learn to use this new sensory cue to discriminate colors that would normally be confused. The daltonian would be able to distinguish between true gloss and the luster produced by the colored lens, because there is usually a spatial binocular disparity of highlights in the former case but would not be in the second case. Whether the subjective percept was actually luster or rivalry (or indeed – after training – a chromatic one), the objective luminance discrepancy between the eyes could provide the daltonian with a cue to real-world spectral differences to which he was otherwise blind.

1.3. Aims of the present study

In the experiments below, we examine the rules that govern the detection of the binocular disparity in the intensity of light reaching the eyes from a given point in the scene. This cue potentially indicates the surface property of gloss in the real world and we ask whether the rules governing its detection are comparable to those that govern the detection of other surface properties such as lightness and chromaticity. We ask some of the basic questions that a psychophysicist might ask when first approaching lightness or chromaticity: Does the detection of binocular luminance disparity obey Weber's Law? Does it exhibit spatial summation comparable to that described by Riccó's Law? Does it exhibit temporal summation comparable to that described by Bloch's Law?

Our secondary purpose was to discover whether the rules that govern the detection of binocular luminance disparity would allow the luminance discrepancy induced by colored monocular filters to be used by daltonians to discriminate spectral power distributions that they were unable to discriminate under normal circumstances. If we know the typical human thresholds for detecting binocular luminance disparity, we can in principle estimate the number of detectable disparities that would be introduced into a natural scene by a monocular filter worn by a daltonian.

Our measurements were of psychophysical performance rather than phenomenological judgment. An analogy could be made here with another surface property, color: Some experiments on color vision are concerned with the observer's subjective judgment of hue whereas others strictly measure the ability to discriminate chromaticity. In studies of gloss and luster, the dependent measures have most often been phenomenological. Our limited aim in the present study is to apply performance psychophysics to the detection of binocular luminance disparity. Another example of the use of performance measures to establish dichoptic thresholds is seen in a recent study of natural images by Yoonessi and Kingdom (2009).

Operationally, we required our subjects to detect a target that had discrepant monocular luminances in a four-alternative spatial forced choice. It was therefore critical to ensure that only this cue could be used to solve the task. In the Methods we describe how the distractor stimuli were chosen to guarantee that the subject could not identify the target either by using monocular luminance or by using the binocular sum of the monocular luminances.

2. Experiment 1A: discrepant incremental contrasts

2.1. Method

2.1.1. Apparatus and stimuli

Stimuli were presented dichoptically on a Sony Trinitron monitor driven by a Visual Stimulus Generator (VSG 2/5; Cambridge Research Systems Ltd.), with a frame rate of 100 Hz and resolution 800×600 pixels. The monitor was calibrated using a CRS Ltd. ColorCal colorimeter. The stimuli were fused by means of a

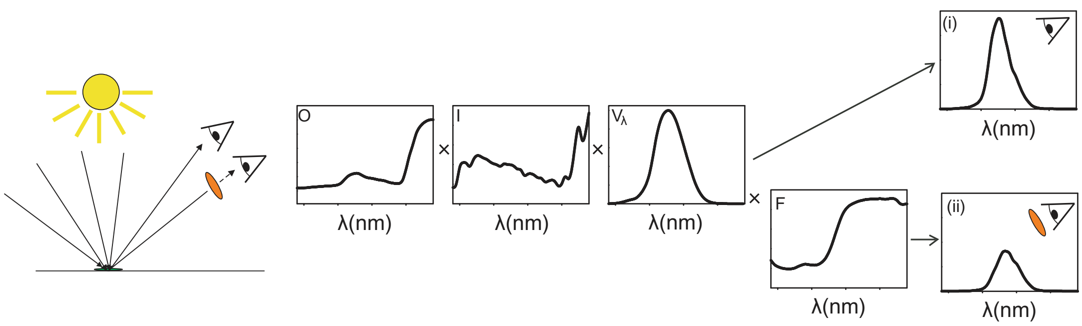

Fig. 1. Discrepant monocular luminances can be introduced by a monocularly worn filter. The luminance of the object seen by the eye without the filter is calculated by multiplying the spectral reflectance of the object (O) by the spectral radiance of the illuminant (I) and by the spectral luminosity function (V_λ). To calculate the luminance seen by the eye wearing the filter, this product is also multiplied by the transmission spectrum of filter (F). Each result ((i) and (ii)) is then integrated across wavelength to obtain the luminance as seen by each eye.

four-mirror haploscope. Each pixel subtended an angle of 0.032 deg at the effective viewing distance of 760 mm. Care was taken to match the planes of accommodation and convergence.

Geometrically the arrays presented to the two eyes were identical and consisted of an array of 16 disks each subtending 1.4 deg of visual angle. The array was divided into 4 subsets of 4 disks by means of vertical and horizontal black lines (Fig. 2). The minimum horizontal and vertical separation between disks was 0.31 deg and the maximum was 1.28 deg. One of the 16 disks, chosen at random, was of different luminance for the two eyes and constituted the target. The remaining disks served as distractors. The target, distractors and background were gray with a MacLeod–Boynton chromaticity of $r = 0.650$ and $b = 0.0199$ (MacLeod & Boynton, 1979). The subject's task was to press one of four buttons to identify the quadrant in which the target fell on a given trial.

The lower monocular luminance of the target was fixed in each run and the higher one was changed according to a staircase procedure to obtain the threshold (see below). The eye that received the lower target luminance was chosen at random in each presentation. We define the monocular contrast of the target by the Weber fraction:

$$C = \frac{L_o - L_b}{L_b}, \tag{1}$$

where L_b is the luminance of background and L_o is the luminance of the disk.

In different experimental sessions we used backgrounds of three different luminances: 4.45, 8.9, and 17.8 cd·m^{-2}. In each experimental session, 10 fixed monocular contrasts were used, from 0.1 to 1.875 in equal logarithmic steps. The range of luminances used was therefore different on each background.

Since the measurements were performance ones, we were concerned to ensure that the only cue that was consistent across trials was the presence of a discrepancy in monocular luminances. In particular, we wished to ensure that the subject could not use either monocular luminance or the binocular sum of luminance. To this end, 15 (rather than just 3) distractors were used.

Distractors were chosen from three different groups. Group 1 spanned the lower monocular target contrast (taking at random a value in the range ±10% of the target value), Group 2 similarly spanned the higher monocular target contrast, and Group 3 spanned the mean of the monocular target contrasts. The first two types of distractor ensured that the target was not distinguishable monocularly from the distractors. The third type of distractor ensured that the target was not distinguishable by binocular summation of luminance.

Additional precautions were introduced to ensure that the subject could not solve the task by considering the distributions of contrasts in different quadrants. In the quadrant containing the target, one distractor was initially chosen from each of the three groups described above. However, one of the three distractors, chosen at random, was then replaced as follows: a Group 1 distractor by a Group 2 distractor, or a Group 2 distractor by a Group 1 distractor, or a Group 3 distractor by a distractor from one of the other two groups. In non-target quadrants, one distractor was initially drawn from each of the three Groups, and the fourth could be chosen from any of the three groups. Then, at random, one or two distractors from Group 1 were replaced by Group 2 or one or two distractors from Group 2 were replaced by Group 1. A maximum of one quadrant was allowed to have three distractors from the same group.

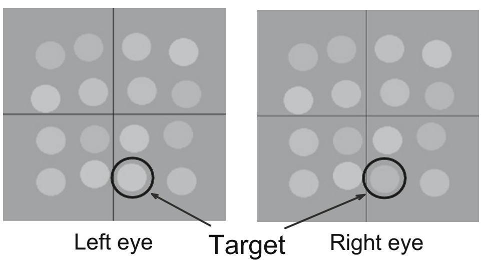

Fig. 2. Example of a stimulus used in the experiments.

2.1.2. Procedure

On each trial, the stimulus array was presented for a maximum of 7 s. The subject was permitted to respond during or after the stimulus presentation. His or her response initiated the next trial. A blank screen of the background luminance was displayed for at least 1 s before the next stimulus array was presented.

Thresholds for detection of the binocular percept were obtained by a 1-up/3-down staircase method, which converges to the 70.71% point on the psychometric function (Levitt, 1970). According to the subject's responses, the difference between the monocular target contrasts was increased or decreased by a factor, which was 1.12 until 2 reversals had been completed and 1.06 thereafter. The first 2 reversals were ignored and the next 8 were used to estimate the threshold.

All experimental sessions were repeated three times.

2.1.3. Subjects

Four subjects completed Experiment 1A with luminance increments and two completed Experiment 1B with luminance decrements. Subjects PT, MT, and MP were naïve to the purpose and design of the experiment. The fourth subject (MF) was one of the authors. All subjects had normal stereopsis and corrected-to-normal vision.

2.2. Results

We raised above the question of whether Weber's Law holds for the detection of binocular luminance disparity, but the question arises: In terms of which quantity should the Weber fraction be expressed: the absolute luminances of the monocular stimuli or the contrasts of the monocular stimuli?

In Fig. 3 we plot for each of the four subjects the logarithm of the difference in monocular luminances (ΔL) against the logarithm of the fixed, lower, luminance (L). The data are well-ordered and approximately linear, and they are very similar for the four subjects. However, the slopes of the functions are much greater than unity, showing that Weber's Law does not hold when the data are expressed in this way. Nor do the datasets for different backgrounds form a single continuum.

An alternative is to express thresholds in terms of the monocular contrasts of the target, where contrast is defined as in Eq. (1). We can then ask whether a second-order Weber's Law holds for the threshold difference in contrast between the two monocular contrasts. Whittle (1986) has shown that a second-order Weber's Law of this kind describes threshold when the observer is asked to discriminate two spatially separated pedestals set on a background. The present case is formally equivalent to that of Whittle except that here the two pedestals are coincident but detected by independent monocular pathways. Although Whittle defined contrast as $\frac{L_{max} - L_{min}}{L_{min}}$, this is equivalent to Weber's contrast for luminance increments, where $L_{max} = L_o$, and $L_{min} = L_b$.

In Fig. 4 we show for each of the four subjects the relationship between the log of the fixed monocular contrast (C) and the log change in contrast (ΔC) required for the target to be detected. When the data thus are expressed in terms of monocular contrasts, the functions are very similar for the different backgrounds and the

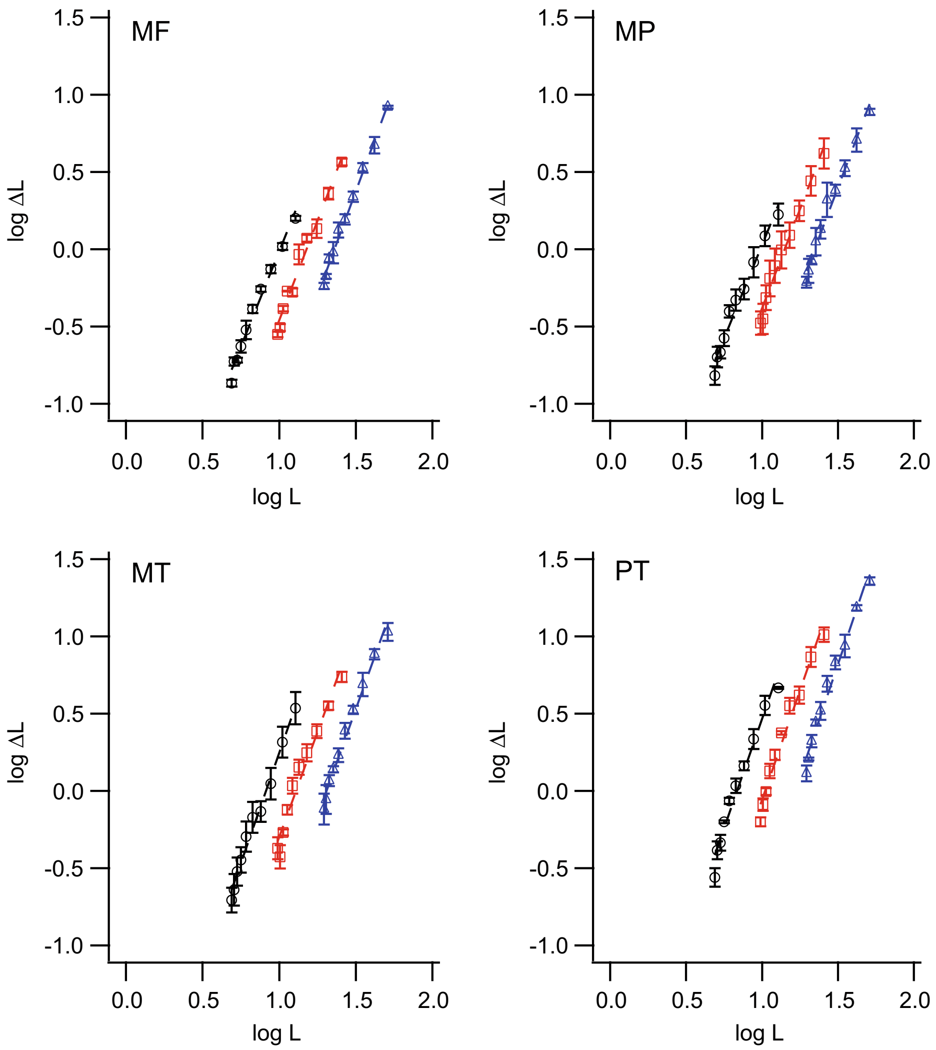

Fig. 3. Results of Experiment 1A expressed as a logarithm of the difference in monocular luminances at threshold ($\triangle L$) against the logarithm of the fixed luminance (L) on backgrounds of 4.45 (○), 8.9 (□), and 17.8 (△) cd·m^{-2}. Error bars represent ±1 SEM.

slopes are close to unity, indicating that Weber's Law holds approximately. In the subsequent Fig. 5 we show the actual Weber fraction (W) for contrast (C), averaged across subjects: $W = \frac{\Delta C}{C_{\text{fixed}}}$, where C_{fixed} is the contrast of the fixed component and ΔC is the increment in contrast.

A similar pattern is seen for all backgrounds: The Weber fraction first shows a small decline as the contrast of the fixed stimulus increases; there is then a plateau; and then there is a small increase at high fixed contrasts.

3. Experiment 1B: discrepant decremental contrasts

In a second experiment, we investigated the rules that govern the detection of binocular luminance disparity when both the monocular targets are decrements from the luminance of the background. Would the results for decrements be analogous to those found for increments in Experiment 1A?

3.1. Methods

Eight fixed values were used for the lower monocular target contrast: from −0.100 to −0.425, in logarithmic steps. Three backgrounds were again used, but now they were: 8.9, 13.35, and 17.8 cd·m^{-2}. Backgrounds and contrasts were chosen so that there would be some overlap between the target luminances on the different backgrounds. All other details of the method were the same as those described for Experiment 1. Two subjects participated in the experiment: MF and PT.

3.2. Results

We again plot the results as the logarithm of the difference in monocular luminances against the logarithm of the fixed luminance (Fig. 6a). The data show a linear relationship, but do not form a continuum.

To express the data in terms of monocular contrasts on a logarithmic scale we redefined contrast as

$$C = \frac{L_{\max} - L_{\min}}{L_{\min}} \tag{2}$$

This expression converts the negative contrasts to positive ones and allows the results obtained with luminance decrements to be compared to those obtained with luminance increments (Whittle, 1986). Only the contrasts of the decrements change with the new definition.

When the data are expressed in terms of monocular contrasts, as a log of the fixed monocular contrast against log change in contrast, the three datasets obtained on the different backgrounds are

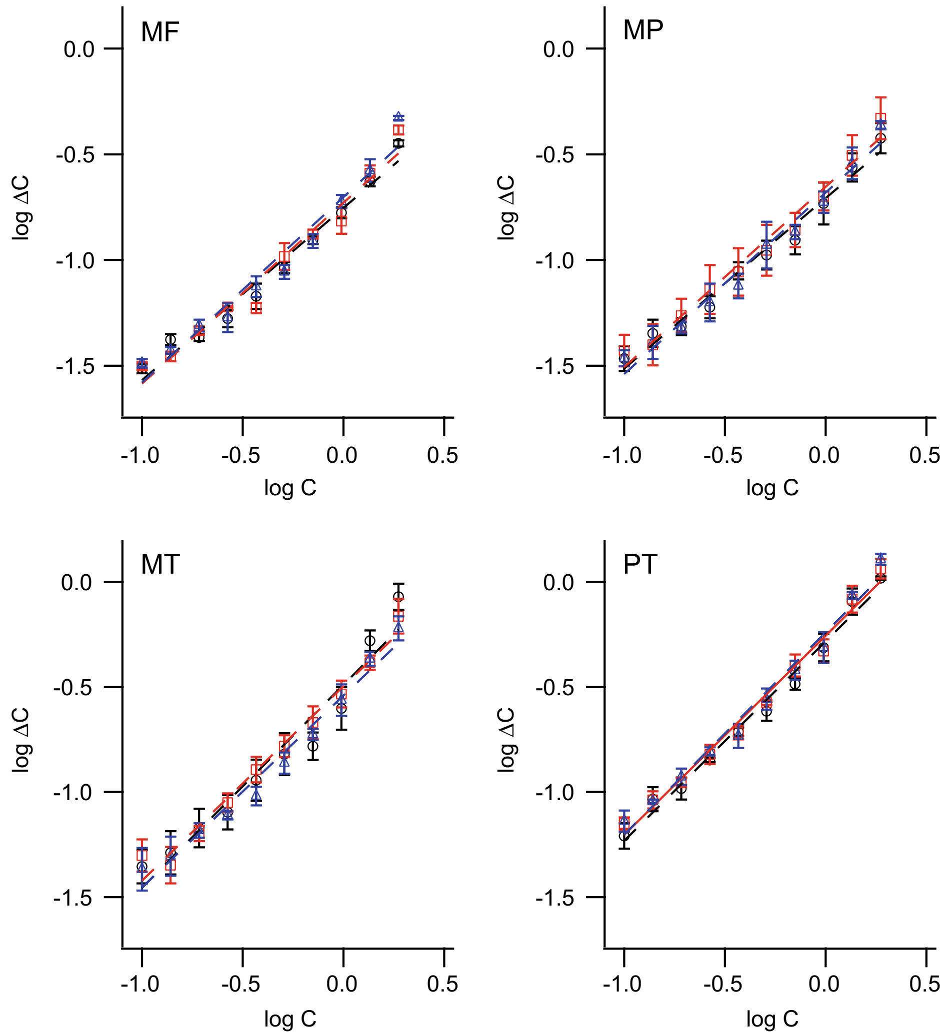

Fig. 4. Results of Experiment 1A expressed as a logarithm of the difference in monocular contrasts at threshold ($\triangle C$) against the logarithm of the fixed contrast (C) on backgrounds of 4.45 (○), 8.9 (□), and 17.8 (△) cd·m^{-2}. Error bars represent ±1 SEM.

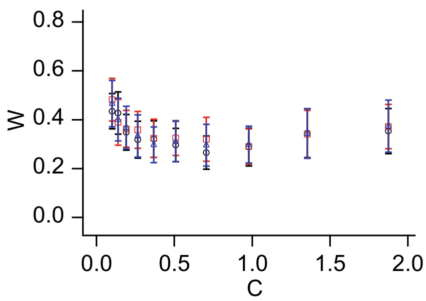

Fig. 5. Weber fraction (W) for the detection of binocular luminance disparity as a function of fixed contrast (C) averaged on backgrounds of 4.45 (○), 8.9 (□), and 17.8 (△) cd·m^{-2}. Error bars represent ±1 SEM.

very similar and the slopes of the functions approach unity (Fig. 6b). In Fig. 7 we plot the Weber fractions for decrements together with those for increments, averaged for the two subjects who participated in both experiments. Across most of the range there is a great deal of overlap between the results obtained using positive and negative contrasts.

In sum, the pattern of results found for decrements is extremely similar to that found for increments in Experiment 1A.

3.3. Discussion

We argued in the Introduction that in natural environments a binocular disparity of luminance could indicate the gloss of a surface and that this cue could be considered as analogous to those for other surface properties such as lightness and chromaticity. Our results are consistent with this view of binocular luminance disparity, in that thresholds for detecting this cue can be measured psychophysically with lawful and reliable results (Figs. 3–7). When thresholds are expressed in terms of the monocular contrasts, the function that describes detection approximates to Weber's Law and is similar to those for detection of other sensory attributes (e.g. Laming, 1986; Sharpe, Fach, Nordby, & Stockman, 1989; Whittle, 1986).

Our Weber fractions for detecting binocular luminance disparity are lower than those that have been obtained when the stimulus conditions were similar but the subject was asked to make a phenomenological judgment of luster. When contrasts of opposite polarity are used, only a very small discrepancy is required to give a phenomenological appearance of luster (Anstis, 2000; Paille, Monot, Dumont-Becle, & Kemeny, 2001), but much larger disparities are required when the contrasts are of the same polarity. In the studies of Sheedy and Stocker (1984) and Pieper and Ludwig (2002), subjects were asked to indicate whether a spot that had disparate monocular luminances appeared lustrous. Sheedy and

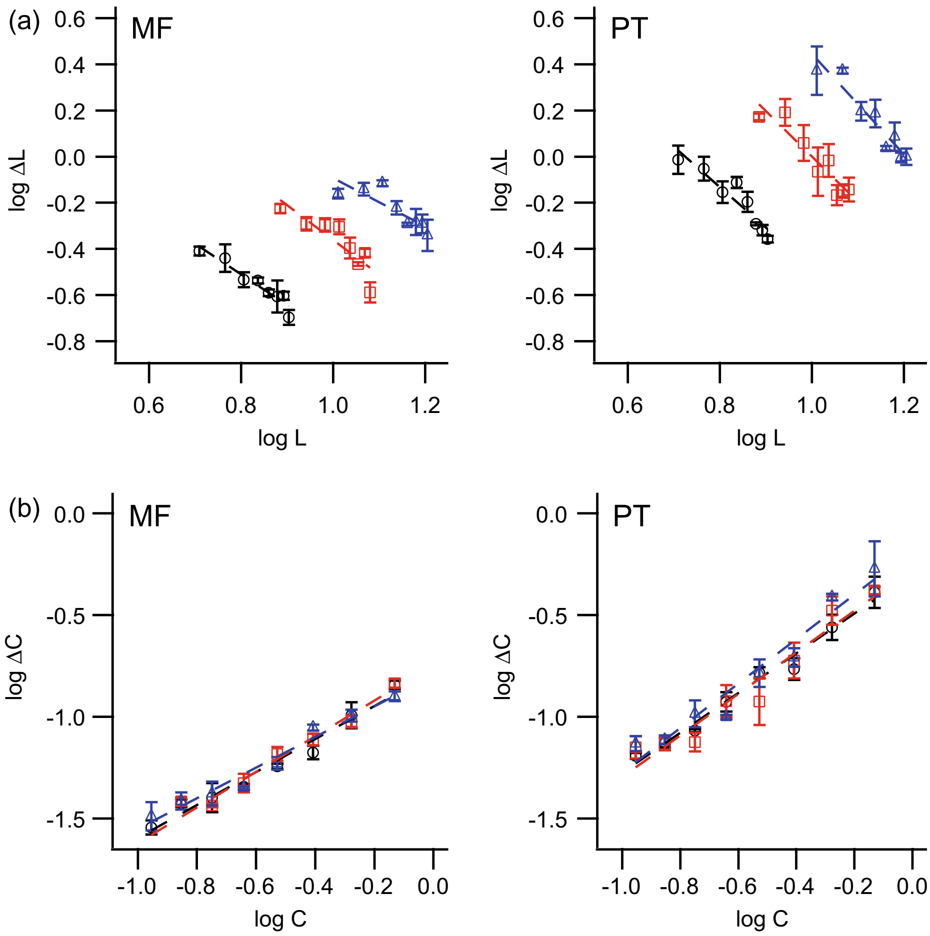

Fig. 6. Results of Experiment 1B expressed as (a) a logarithm of the difference in monocular luminances at threshold ($\triangle L$) against the logarithm of the fixed luminance (L) and (b) a logarithm of the difference in monocular contrasts at threshold ($\triangle C$) against the logarithm of the fixed contrast (C) on backgrounds of 8.9 (○), 13.35 (□), and 17.8 (△) cd·m^{-2}. Error bars represent ±1 SEM.

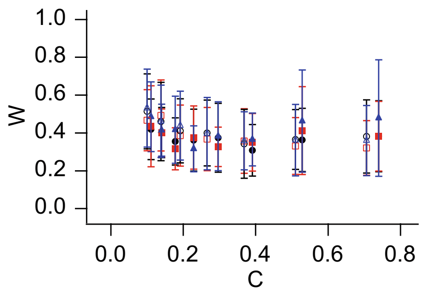

Fig. 7. Weber fraction (W) for the detection of binocular luminance disparity as a function of fixed contrast (C) obtained using increments on backgrounds of 4.45 (□), 8.9 (○), 17.8 (△) cd·m^{-2}, and decrements on backgrounds of 8.9 (●), 13.35 (■), and 17.8 (▲). Error bars represent ±1 SEM.

Stocker (1984) report their data in terms of luminance ratios, while Pieper and Ludwig (2002) give theirs in terms of Michelson-Contrast. In Table 1 we have converted the thresholds obtained in the two studies to contrasts (C) and Weber fractions for contrast (W). In all cases, the second-order Weber fractions for phenomenological judgments of luster were higher than our own performance measures.

In one important respect, Sheedy's and Stocker's results resemble our own: For two of their subjects, the thresholds expressed as second-order Weber fractions were similar across the range of contrasts used, and for the third subject (MT) the thresholds were similar across most contrasts.

Table 1
Lower monocular contrast (C) and Weber fraction (W) calculated from the results of Sheedy and Stocker (1984) for their three subjects: GC, ES, and MT using discrepant luminance increments. The lowermost values are from Pieper and Ludwig (2002) who used decrements.

	C	W
Increment – GC	6.12	4.70
	3.02	4.37
	1.31	4.51
	0.60	3.68
Increment – ES	12.74	1.22
	6.02	1.19
	2.73	1.13
	0.98	1.46
Increment – MT	7.23	3.66
	3.17	4.05
	1.51	3.68
	0.32	8.71
Decrement	11.5	12.34

Although they are smaller than thresholds for phenomenological luster, the absolute values of our Weber fractions for binocular luminance disparity are much higher than the values obtained for increment thresholds on adapting fields of increasing luminance, where the Weber fraction may be 1% or less (Wyszecki & Stiles, 1967). However, it is more appropriate to compare the present values with those obtained by Whittle (1986) for the photopic discrimination of separated patches of varying luminance presented on a steady adapting fields. Expressed as second-order Weber fractions (i.e. Weber fractions for contrast) Whittle's thresholds for targets of 0.93 deg width were 12% for two subjects. Our own values for the dichoptic case were higher, but not of a different order of magnitude: around 20% for subjects MF and MP, 30%, for subject MT and 55% for subject PT. It is possible that the monocular contrasts are extracted before binocular combination and that it is these contrast signals that are binocularly compared rather than luminance signals. Electrophysiological recordings suggest that most visual channels encode contrast rather than luminance (Kaplan, Shapley, & Purpura, 1988), with the one exception of the pathway originating in the giant monostratified, melanopsin-containing ganglion cells (Dacey et al., 2005).

4. Experiment 2: size

The detection of simple increments of luminance obeys Riccó's Law of total spatial summation for stimulus sizes less than a critical size and exhibits partial summation at larger sizes (Barlow, 1958). In Experiment 2, we ask whether analogous behavior is seen for the detection of the target that has discrepant monocular luminances.

4.1. Methods

To assess the effect of target size on the detection of binocular contrast disparities we used disks of six diameters: 0.0648, 0.130, 0.227, 0.454, 0.843, and 1.62 deg. For the smallest targets the pixelation of the image distorts the form of the disk and therefore we estimated areas from the number of pixels that were actually used to draw the disk on the display. The same range of separations between the disks (min. of 0.13 and max. of 0.648 deg of visual angle) was used for all disk sizes, resulting in an increase of the display area with an increase of disk size. All items in a display were of the same size and trials were blocked so that the staircase for one size finished before the next one began. Two fixed monocular contrasts of 0.3 and 0.95, and a background of 8.9 cd·m^{-2} were used. Three subjects took part in the experiment: MF, MP, and PT. All other experimental details were as for Experiment 1.

4.2. Results

Thresholds improved with increasing target size up to a certain area, beyond which thresholds stabilized. Two straight lines (Fig. 8) were fitted to the data expressed on a logarithmic scale to estimate the stimulus area at which summation ceased. The first line defined by: $y = a(x - x0) + b$ describes the data up to the limit of spatial summation ($x0$), and the absolute value of the slope of the line (a) indicates the level of summation that takes place. The second line $y = b$ represents the stable threshold, which shows no further improvement with increasing area.

For all subjects and for both contrasts, the level of summation was incomplete, as indicated by slopes of less than 1, although the slopes were significantly different from 0 ($p = 0.010$ and $p = 0.008$ for the lower and higher contrasts, respectively). The average slope was greater when the fixed contrast was 0.3 (Mean slope = −0.307, SD = 0.0534) than when the fixed contrast was 0.95 (Mean slope = −0.172, SD = 0.0269) and this difference was statistically significant ($t(2) = 4.936$, $p = 0.039$). For all three subjects, the total extent of summation was greater when the fixed contrast was 0.95 (Mean = 0.241 square deg, SD = 0.275) than when it was 0.3 (Mean = 0.122 square deg, SD = 0.140).

In the present experiment, the spacing of the disks was the same for all disk sizes, so the smaller disks were separated by relatively greater distances than were the larger disks. The results of a control experiment in which spacing was proportional to the size of the disks were not significantly different from those obtained with the configuration described above (Formankiewicz, 2005).

4.3. Discussion

In exhibiting slopes much less than unity, the present results do not differ from what would be expected for the case of simple detection of luminance increments. Riccó's Law holds most exactly

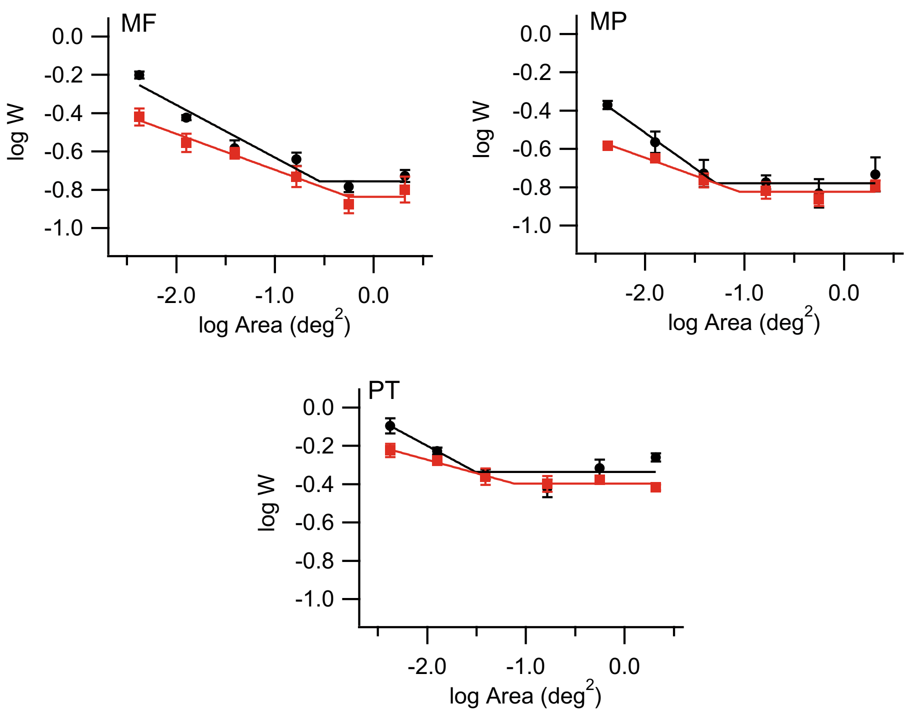

Fig. 8. Weber fraction for the detection of binocular luminance disparity as a function of area plotted on a logarithmic scale for a fixed contrast of 0.3 (●) and 0.95 (■). Straight lines were fitted to the data to estimate the extent and degree of summation (see text for more details). Error bars represent ±1 SEM.

for low background intensities and for short durations. For higher background levels and for long durations, as used here, only partial summation is observed for all but the very smallest stimuli (Barlow, 1958).

The results show that the threshold for the detection of binocular luminance disparity is affected by the size of the item, up to a certain limiting area. Pieper and Ludwig (2002) found no dependence of threshold for luster detection on size for spots that subtended visual angles in the range of 0.5–3 deg. Our results are consistent with their findings, in that detection thresholds vary little beyond 0.5 deg.

Our subjects could detect binocular luminance disparities when the diameter of the disks was 0.06 deg – a value much smaller than the 1 deg given by Howard (1995) as the size at which luster becomes evident. According to Howard (1995) and Paille et al. (2001), it is the sieve effect that should have been perceived with the smaller disk sizes. However, only one item in our displays had a luminance discrepancy whereas in the displays used by Howard (1995) and Paille et al. (2001), all items had different monocular luminances and opposite contrast polarities. Furthermore, the present measurements are performance ones: we did not formally inquire about our subjects' sensations but instead measured their ability to detect binocular disparities of luminance.

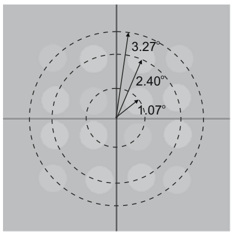

Fig. 9. Diagram showing the arrangement of the disks on an imaginary annulus used in Experiment 3.

5. Experiment 3: duration and eccentricity

In Experiment 3, we varied the viewing times to ascertain whether the detection of binocular luminance disparity shows temporal summation similar to that described by Bloch's Law. A second variable in this experiment was the eccentricity of disks.

5.1. Methods

We used stimulus durations from 10 to 2560 ms. Subjects were instructed to fixate on the intersection of the black lines that marked the center of the screen and the eccentricity at which the disks were presented was controlled. The spatial arrangement of the array resembled that seen in the previous experiments but the disks were placed on an imaginary annulus whose radius equaled the eccentricity: 1.07, 2.40 or 3.27 deg of visual angle (Fig. 9). Two fixed monocular contrasts of 0.3 and 0.95 on a background of 8.9 cd·m^{-2} were used. Two subjects completed the experiment: MF and MT. All other details were as in Experiment 1.

5.2. Results

Subjects were unable to reliably detect the target at the two shortest durations of 10 and 20 ms: at these short durations, a threshold was not set in at least one of the three repetitions of a given experimental condition. The minimum duration at which the target was detected was shorter at an eccentricity of 1.0 deg (80 ms for MT and 40 ms for MF) than at eccentricities of 2.40 and 3.27 deg (160 ms for MT and 80 ms for MF at eccentricities 2 and 3). There was then a gradual improvement of the thresholds with increasing durations up to a certain limiting duration, beyond which a plateau was reached (Fig. 10).

As in the case of Experiment 2, two straight lines were fitted to the complete sets of data, one line of variable slope to estimate the

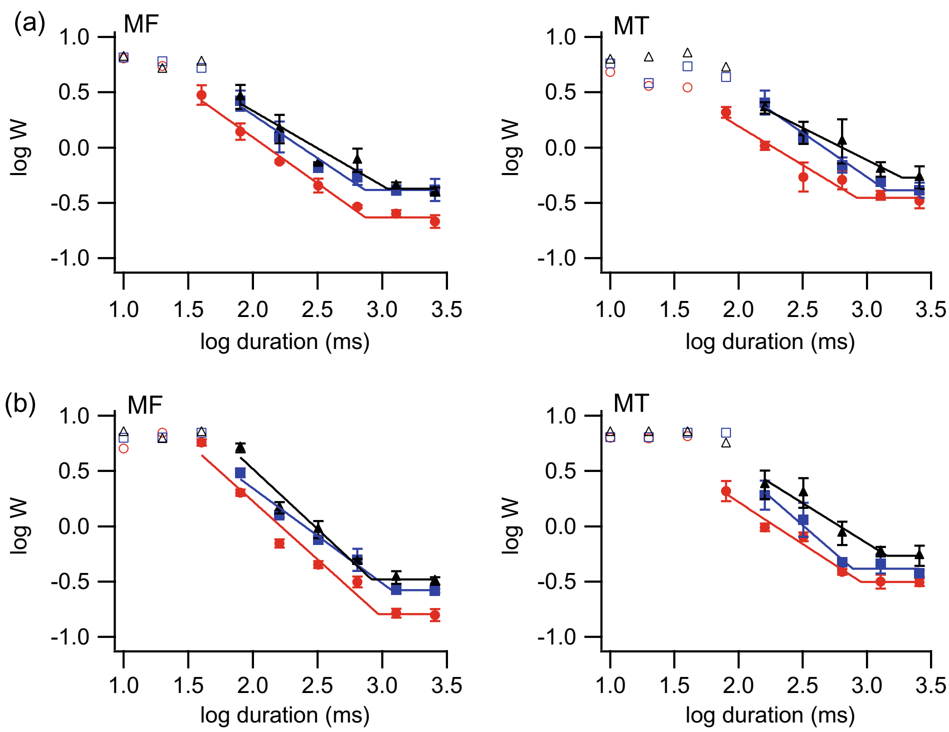

Fig. 10. Weber fraction for the detection of binocular luminance disparity as a function of duration plotted on a logarithmic scale at eccentricities of 1.07 (●), 2.40 (■), and 3.27 (▲) deg and for a fixed contrast of 0.3 (a) and 0.95 (b). Straight lines were fitted to the data to estimate the extent and degree of temporal summation (see text for more details). Unfilled symbols (○, □, and △) indicate that the point was derived from an incomplete set of data. Error bars represent ±1 SEM.

degree of the summation at short durations and a second, horizontal, line to estimate the limiting duration beyond which temporal summation was not evident. The slopes ranged from -0.60 to -1.09 (Mean = -0.80). Summation continued up to durations of the order of 1 s.

There was no consistent effect of the fixed contrast on the limiting durations or slopes, but the limiting durations increased with increasing eccentricities, particularly between 1.0 and 2.4 deg. In addition, the absolute value of Weber fraction at long durations increased with increasing eccentricity. Thus eccentricity also plays a role in determining the thresholds for the discrepant monocular luminances.

5.3. Discussion

All visual processes exhibit integration over time (e.g. Barlow, 1958; Krauskopf & Mollon, 1971) but the extent of temporal summation has been found to be different for different tasks. Thus Kahneman (1964) found that critical durations for brightness judgments seldom exceeded 100 ms whereas, under the same conditions, critical durations for resolution of a Landolt C might extend to 1 s. The present experiments show that the detection of binocular luminance disparity resembles other visual attributes in exhibiting temporal summation; and the absolute extent of summation resembles that for acuity tasks.

Our experiments were limited by the available contrast. In other studies that investigated the detection of binocular luster and reported viewing times (Paille et al., 2001; Sheedy & Stocker, 1984), the viewing times were longer than the shortest durations at which we were able to set thresholds. Therefore we cannot conclude what the minimum time for the detection of binocular luminance disparity is.

Any experiment in which time is a variable invites an analysis in terms of the magnocellular and parvocellular systems of the visual pathway. The two systems differ in their temporal characteristics, the parvocellular system having a poorer temporal resolution and longer latency than the magnocellular, and these differences have been exploited to assign visual functions to the two systems. Smithson and Mollon (2001) proposed that the lightness signal, representing a property of surfaces in the natural world, is carried not by the magnocellular systems – as sometimes supposed – but by the parvocellular system. If binocular luminance disparity is regarded as the property of surfaces that arises from a discrepancy of lightness signals, it is reasonable to assign it to the parvocellular system. This is consistent with the extended temporal summation seen for the detection of binocular luminance disparity in the present experiment.

6. Conclusions

In natural scenes, a binocular disparity of luminance is a potential cue to the smoothness of a surface. The rules that govern its detection are similar to those for the detection of cues for other surface properties such as lightness and chromaticity. We have shown that the detection of binocular luminance disparity obeys Weber's Law over a substantial range and that the second-order Weber fractions are not greatly dissimilar from those measured monocularly for discrimination of spatially separated pedestals on a steady field. The thresholds exhibit spatial and temporal summation and a deterioration with increasing eccentricity. From studies of visual search, Wolfe and Franzel (1988) have similarly argued that binocular luster is a basic surface feature recognized by the visual system – although they found a parallel search only for the case where the monocular contrasts were of opposite sign.

It is has sometimes been suggested that binocular luster is secondary to a process of binocular rivalry occurring at a micro level (Levelt, 1965b). Our own experiments do not bear directly on this issue, since our measurements are performance ones. However, if there is a systematic mapping between a property of real-world surfaces and the perception of luster, then there seems no need to invoke a hidden intermediate process of local rivalry: The visual scene has a particular physical property and we experience the corresponding percept. The neural mechanism that extracted the physical property would be a binocular differencing channel, not unlike the binocular differencing channels postulated to account for other aspects of binocular vision (Anstis, 1970; Cohn & Lasley, 1976) but differencing contrast rather than luminance.

7. A cue for the daltonian?

In principle, binocular luminance disparity induced by a colored monocular filter could be used by the daltonian to identify colors if he could reliably judge the ratio of the two monocular luminances, one as seen through the filter, the other without. This ratio is fixed for a given filter and spectral power distribution (determined by the illuminant and the spectral reflectance of the object). Could a daltonian, by wearing the same monocular filter at all times, learn to associate a particular level of binocular luminance discrepancy with a particular spectral power distribution?

Our results suggest that two cautions are appropriate here. Firstly, the Weber fractions for detecting binocular contrast disparity are larger than those for normal color discrimination on a red–green axis (Chaparro, Stromeyer, Huang, Kronauer, & Eskew, 1993; Danilova & Mollon, 2006) and so the daltonian would still have poorer color discrimination than the normals.

Secondly, our evidence suggests that what the visual system detects is not the disparity of monocular luminances but the disparity of monocular contrasts. So the computation that faces the daltonian visual system is not simple. For a given filter and an object with a given spectral reflectance characteristics, there will not be a fixed ratio between the monocular contrast with the filter and the contrast without one. Under a given illuminant, the ratio will depend not only on the initial luminances of the object and the background, and but also on the spectral reflectances of both the object *and* the background, which will be independently modified by the filter.

Nevertheless, our results allow us to make empirically testable predictions as to when and when not a dichromat will be able to discriminate a pair of colored targets on a specified background. As an illustration, we have modeled the ability of a deuteranope to discriminate the chips of the 'Minimalist' color test (Mollon, Astell, & Reffin, 1991) when presented on a neutral background. Using spectral reflectance curves for the Munsell papers used in the test (obtained from Spectral Database http://spectral.joensuu.fi/), and assuming that the illuminant had the spectral power distribution of CIE Illuminant *C* (Wyszecki & Stiles, 1967) and that the deuteranope wore a monocular red filter of cut-on wavelength 570 nm, we calculated the binocular discrepancies of contrast for each stimulus and asked whether the second-order contrast $(\frac{\Delta C}{C_{\text{lower}}})$ was above threshold. On a neutral background of lightness 0.1, the deuteranope should not be able to discriminate between a gray chip and the two least saturated chips on the deutan confusion line, which have Munsell chromas of 1 and 2, respectively. These chips are readily discriminated by the normal observer. However, our calculation suggests that the deuteranope, wearing the red filter, would be able to discriminate between a gray chip and a chip on the deutan line that had a chroma of 4. Similar testable predictions could be made for any targets, backgrounds, and illuminants.

Acknowledgment

This research was supported by the Cambridge Commonwealth Trust Packer Scholarship (MF).

References

Anstis, S. M. (1970). Phi movement as a subtraction process. *Vision Research, 10*(12), 1411–1430.

Anstis, S. M. (2000). Monocular lustre from flicker. *Vision Research, 40*, 2551–2556.

Anstis, S. M., & Ho, A. (1998). Nonlinear combination of luminance excursions during flicker, simultaneous contrast, afterimages and binocular fusion. *Vision Research, 38*(4), 523–539.

Barlow, H. B. (1958). Temporal and spatial summation in human vision at different background intensities. *Journal of Physiology, 141*, 337–350.

Bhat, D. N., & Nayar, S. K. (1998). Stereo and specular reflection. *International Journal of Computer Vision, 26*(2), 91–106.

Billmeyer, F. W., & O'Donnell, F. X. D. (1987). Visual gloss scaling and multidimensional scaling analysis of painted specimens. *COLOR Research and Application, 12*(6), 315–326.

Chaparro, A., Stromeyer, C. F., 3rd, Huang, E. P., Kronauer, R. E., & Eskew, R. T. Jr., (1993). Colour is what the eye sees best. *Nature, 361*(6410), 348–350.

Cibis, P. A., & Harris, H. (1951). Anisopia and perception of space. *Journal of the Optical Society of America, 41*, 676–683.

Cohn, T. E., & Lasley, D. J. (1976). Binocular vision: Two possible central interactions between signals from two eyes. *Science, 192*(4239), 561–563.

Cornsweet, T. N. (1970). *Visual perception*. New York: Academic (pp. 194–198).

Curtis, D. W., & Rule, S. J. (1978). Binocular processing of brightness information: A vector-sum model. *Journal of Experimental Psychology: Human Perception and Performance, 4*, 132–143.

Dacey, D. M., Liao, H. W., Peterson, B. B., Robinson, F. R., Smith, V. C., Pokorny, J., et al. (2005). Melanopsin-expressing ganglion cells in primate retina signal colour and irradiance and project to the LGN. *Nature, 433*(7027), 749–754.

Danilova, M. V., & Mollon, J. D. (2006). The comparison of spatially separated colours. *Vision Research, 46*(6–7), 823–836.

Dawson, S. (1913). Binocular and uniocular discrimination of brightness. *British Journal of Psychology, 6*, 78–108.

De Weert, C. M., & Levelt, W. J. (1974). Binocular brightness combinations: Additive and nonadditive aspects. *Perception and Psychophysics, 15*(3), 551–562.

Dove, H. W. (1851). Ueber die Ursachen des Glanzes und der Irradiation, abgeleitet aus chromatischen Versuchen mit dem Stereoskop. *Poggendorffs Annalen, 83*, 169–183.

Engel, G. R. (1969). The autocorrelation function and binocular brightness mixing. *Vision Research, 9*, 1111–1130.

Ferwerda, J. A., Pellacini, F., & Greenberg, D. P. (2001). A psychophysically-based model of surface gloss perception. *Proceedings of SPIE, 4299*, 291–301.

Formankiewicz, M. A. (2005). The psychophysics of lustre and the use of monocular filters to treat colour deficiencies. (PhD dissertation). University of Cambridge, Cambridge.

Harris, D. (1998). *ChromaGen Clinical Procedures*. Northants: Cantor & Silver Ltd.

Harrison, V. G. W., & Poulter, S. R. C. (1951). Gloss measurement of papers – The effect of luminance factor. *British Journal of Applied Physics, 2*, 92–97.

Heath, G. G. (1974). The handicap of color blindness. *Journal of the American Optometric Association, 45*(1), 62–69.

Helmholtz, H. L. F. (1909). Handbuch der Physiologischen Optik (Hamburg Voss, 1909). In J.P.C. Southall (Ed.), *Optical Society of America, 1924–25 (translated as Helmholtz's treatise on physiological optics)*.

Howard, I. P. (1995). Depth from binocular rivalry without spatial disparity. *Perception, 24*, 67–74.

Hunter, R. S. (1937). Methods of determining gloss. *Journal of Research, NBS, 17*(77), 281.

Hunter, R. S., & Harold, R. W. (1987). *The measurement of appearance*. New York: John Wiley & Sons, Inc.

Kahneman, D. (1964). Temporal summation in an acuity task at different energy levels. A study of the determinants of summation. *Vision Research, 4*(11), 557–566.

Kaplan, E., Shapley, R. M., & Purpura, K. (1988). Color and luminance contrast as tools for probing the primate retina. *Neuroscience Research Supplement, 8*, S151–165.

Krauskopf, J., & Mollon, J. D. (1971). The independence of the temporal integration properties of individual chromatic mechanisms in the human eye. *Journal of Physiology, 291*, 611–623.

Laming, D. R. J. (1986). *Sensory analysis*. London, Orlando: Academic Press.

Levelt, W. J. M. (1965a). Binocular brightness averaging and contour information. *British Journal of Psychology, 56*, 1–13.

Levelt, W.J.M. (1965b). *On binocular rivalry*. Soesteberg – The Netherlands: Institute for Perception RVO-TNO.

Levitt, H. (1970). Transformed up–down methods in psychoacoutics. *The Journal of the Acoustical Society of America, 49*(2), 467–477.

Ludwig, I., Pieper, W., & Lachnit, H. (2007). Temporal integration of monocular images separated in time: Stereopsis, stereoacuity, and binocular luster. *Perception and Psychophysics, 69*(1), 92–102.

MacLeod, D. I. A., & Boynton, R. M. (1979). Chromaticity diagram showing cone excitation by stimuli of equal luminance. *Journal of the Optical Society of America, 69*, 1183–1186.

McCamy, C. S. (1998). Observation and measurement of the appearance of metallic materials. Part II. Micro appearance. *COLOR Research and Application, 23*(6), 362–373.

Mollon, J. D., Astell, S., & Reffin, J. P. (1991). A minimalist test of colour vision. In B. Drum, J. D. Moreland, & A. Serra (Eds.). *Colour vision deficiencies* (Vol. 10, pp. 59–67). Dordrecht: Kluwer Academic Publishers.

Oppel, J. J. (1854). Ueber die Entstehung des Glanzes bei zweifarbigen, insbesondere bei schwarzen und weissen stereoskopischen Bildern. *Jahresbericht des Physikalischen Vereins zu Frankfurt am Main, 1854–1855*, 52–55.

Paille, D., Monot, A., Dumont-Becle, P., & Kemeny, A. (2001). Luminance binocular disparity for 3D simulation. *Proceedings of SPIE, 4299*, 622–633.

Pieper, W., & Ludwig, I. (2002). The minimum luminance-contrast requirements for stereoscopic lustre. *Perception, 31*(Suppl.), 185.

Schmidt, I. (1976). Visual aids for correction of red–green colour deficiencies. *Canadian Journal of Optometry, 38*, 38–47.

Sharpe, L. T., Fach, C., Nordby, K., & Stockman, A. (1989). The incremental threshold of the rod visual system and Weber's law. *Science, 244*, 354–356.

Sheedy, J. E., & Stocker, E. G. (1984). Surrogate color vision by luster discrimination. *American Journal of Optometry and Physiological Optics, 61*(8), 499–505.

Sherrington, C. S. (1904). On binocular flicker and the correlation of activity of corresponding retinal points. *British Journal of Psychology, 1*, 26–60.

Smithson, H. E., & Mollon, J. D. (2001). Forward and backward masking with brief chromatic stimuli. *COLOR Research and Application, 26*(Suppl.), S165–S169.

Spectral Database, University of Joensuu Color Group. <http://spectral.joensuu.fi/>. (accessed 27.04.09).

Teller, D. Y., & Galanter, E. (1967). Brightnesses, luminance and Fechner's paradox. *Perception and Psychophysics, 2*(7), 297–300.

Tyler, C. W. (1983). Sensory processing of binocular disparity. In C. Schor & K. Ciuffreda (Eds.), *Vergence eye movements: Basic and clinical aspects* (pp. 199–295). Boston: Butterworth.

Tyler, C. W. (2004). Binocular vision. In W. Tasman & E. A. Jaeger (Eds.). *Duane's foundations of clinical ophthalmology* (Vol. 2). Philadelphia: J.P. Lippincott Co.

Wendt, G., Faul, F., & Mausfeld, R. (2008). Highlight disparity contributes to the authenticity and strength of perceived glossiness. *Journal of Vision, 8*(1): 14, 1–10.

Whittle, P. (1986). Increments and decrements: Luminance discrimination. *Vision Research, 26*, 1677–1691.

Whittle, P. (1994). The psychophysics of contrast brightness. In A. L. Gilchrist (Ed.), *Lightness, brightness and transparency* (pp. 35–110). Hillsdale, New Jersey: Lawrence Erlbaum Associates, Inc.

Wolfe, J. M., & Franzel, S. L. (1988). Binocularity and visual search. *Perception and psychophysics, 44*(1), 81–93.

Wyszecki, G., & Stiles, W. S. (1967). *Color science: Concepts and methods, quantitative data and formulae*. New York: John Wiley & Sons, Inc.

Yoonessi, A., & Kingdom, F. A. A. (2009). Dichoptic difference thresholds for uniform colour changes applied to natural scenes. *Journal of Vision, 9*(2), 1–12.

Zeltzer, H. (1971). The X-chrom lens. *Journal of the American Optometric Association, 42*(9), 933–939.