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Centering biases in heterochromatic brightness matching

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Abstract

When the method of constant stimuli is used to measure heterochromatic brightness matches, the resulting matches can be strongly biased toward the center of the range of test luminances used [Teller, D. Y., Pereverzeva, M., & Civan, A. L. (2003). Adult brightness vs. luminance as models of infant photometry: variability, biasability, and spectral characteristics for two age groups favor the luminance model. *Journal of Vision*, 3, 333–346]. In the present paper, we investigate the source of this centering bias. The stimuli were 2° red squares presented in a gray surround. In the main experiments, two ranges of stimulus luminance were presented in separate physical locations on a video monitor, but with test trials interleaved in time. Subjects either fixated a fixation cross (fixation condition), creating different retinotopic locations for the two luminance ranges, or foveated each stimulus as it appeared (foveation condition), creating identical retinotopic locations for both ranges. In the fixation condition, the two different stimulus sets resulted in a simultaneous centering bias—two different brightness matches at two different retinotopic locations at the same time. This effect was essentially eliminated in the foveation condition. A dichoptic foveation condition also revealed no centering bias. The results suggest that under the conditions tested, the centering bias is caused by a process located at a post-retinal but still retinotopically organized level of the visual system, rather than by either a retinal process or a more central, spatiotopically organized one.

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1. Introduction

Psychophysical thresholds and points of subjective equality (PSE) can be influenced, or *biased*, by the choice of stimuli used to measure them. In particular, the PSE can be influenced by the range of stimuli, and a *centering bias* is said to occur when the PSE is shifted toward the center of the stimulus range (Poulton, 1979).

The concept of centering bias is illustrated in Fig. 1. In this graph, the centers of hypothetical stimulus ranges are plotted along the abscissa, and the PSEs obtained with the use of the different ranges are plotted along the ordinate. The identity line (solid line) represents an

example of *complete centering bias*. In this case, for any stimulus range, the PSE falls exactly in the center of the range. The dashed line (or any line parallel to the abscissa) represents an example of *no centering bias*. In this case, the PSE is completely independent of the stimulus range. The dotted line with an intermediate slope represents an example of an *imperfect* or *incomplete centering bias*. In this case, the PSEs are shifted towards the centers of the respective stimulus ranges.

Formal studies of centering biases are relatively rare. There are several studies describing centering biases in modalities other than vision: auditory (Marks, 1988; Schneider & Parker, 1990) and gustatory (Conner, Land, & Booth, 1987; Lawless, 1983; Stillman, 1993). But prior to our own work, we have found only one study describing centering bias in visual perception:

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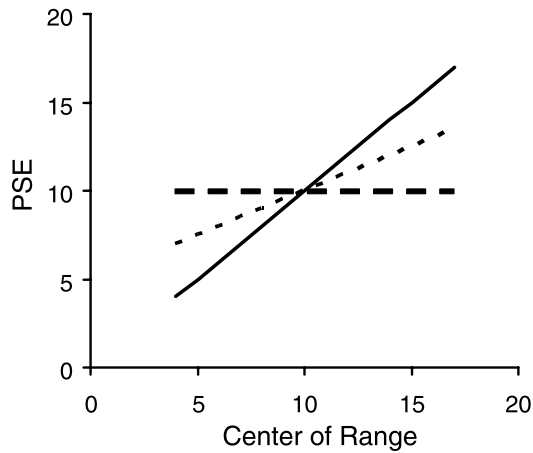


Fig. 1. Illustration of centering biases. The abscissa shows the centers of hypothetical stimulus ranges. The ordinate represents the PSEs obtained with the use of the different ranges (the units are given for comparison purposes only). The identity line (solid line) represents an example of a *complete centering bias*. The dashed line (or any other line parallel to the abscissa) represents an example of *no centering bias*. The dotted line with an intermediate slope represents an example of an *incomplete centering bias*.

Schneider, Parker, and Moraglia (1996) demonstrated a centering bias in perceived contrast judgments.

More recently, in the course of a study of visual development, we (Teller, Pereverzeva, & Civan, 2003) came upon a centering bias in heterochromatic brightness matching in adult subjects. Using the method of constant stimuli and stimulus sets with different mean luminance levels in sequential blocks of trials, we found that a change of mean luminance of 0.6 log units (lu) yielded a shift of the brightness match of 0.37 lu—a very substantial *sequential* centering bias. As shown in the present study, when the two different ranges of stimuli are presented in different retinal locations, and fixation is controlled, a *simultaneous* centering bias can also be seen.

In classical signal detection theory (Green & Swets, 1966; Macmillan & Creelman, 2004), a centering bias could be caused by either one of two mechanisms. One possibility is that it is caused by an early sensory process, such as retinal light/dark adaptation. When sets of test stimuli with different mean luminance values are used, the retinal adaptation state will vary with the mean luminance of the test stimuli, and so will the magnitude of the sensory signal arising from each test stimulus. In consequence, the subject's brightness judgments should vary with the mean luminance of the stimulus set, in the appropriate direction to produce a centering bias. Alternatively, the centering bias could be attributed to a high-level cognitive decision process. To take the simplest example, within each stimulus set, the subject could decide to use each of the two response alternatives—"brighter" vs. "darker"—on equal numbers of trials. The PSE would then track the mean luminance of the stimulus set, and a centering bias would occur.

In more consistently physiological terms, a centering bias could have at least three potential, serially distinct sources within the visual system. For brevity, these three sources of bias will be called the *retinal* or *retinal-retinotopic process*, the *cortical* or *cortical-retinotopic process*, and the *spatiotopic* or *physical-location-specific process*, respectively.

The first potential source is a *retinal-retinotopic process* such as classical light/dark adaptation (Hahn & Geisler, 1995; Walraven, Enroth-Cugell, Hood, MacLeod, & Schnapf, 1990; Wolfson & Graham, 2001). Under conditions of steady fixation, the two different stimulus ranges should create different levels of retinal adaptation at the two different retinal locations. If the level of retinal adaptation influences perceived brightness, then retinal adaptation processes could create a centering bias. In this case, the two different PSEs would be attached to the retinal locations of the two stimulus sets, and not to their physical locations on the video monitor. The term *retinal* is used for brevity and is somewhat misleading, since any site at which inputs from the two eyes remain segregated could have similar properties.

The second potential source would be a *cortical-retinotopic process*—a cortical, binocular, but still retinotopically organized process. Candidate anatomical sites would include all visual cortical areas that are retinotopically organized (cf. Wade, Brewer, Rieger, & Wandell, 2002). As was the case with the retinal-retinotopic process, a bias process located at a cortical-retinotopic site could also produce two different PSEs simultaneously, with the two PSEs attached to the two different retinotopic locations rather than to the physical locations of the stimuli.

The third potential source would be a *spatiotopic process*. In ordinary perception, stationary objects occupy fixed physical locations, even across variations in eye position and eye movements. One therefore expects to find a high-level representation of the visual world, within which an object at a specific physical location gives rise to a physical-location-labeled representation that is robust across variations of eye position. Like the two retinotopic bias processes (retinal and cortical), a spatiotopic bias process could also yield a centering bias. But unlike the two retinotopic processes, a spatiotopic bias would be attached to the physical locations rather than the retinal locations of the two different stimulus ranges (Irwin, 1996; Melcher & Morrone, 2003). Since left and right stimuli are seen perceptually as occupying different spatiotopic positions, it seems likely that any cognitive biases (Green & Swets, 1966) would be applied at the spatiotopic level.

Now, assuming that a simultaneous centering bias can be established, the next question is, is the bias process retinotopic, that is, tied to the retinal locations of the test stimuli? Or is it spatiotopic, that is, tied to the perceived physical locations of the test stimuli in space?

This question can be addressed by varying the fixation/foveation pattern the subject uses in viewing the stimuli. If the subject *fixates* a fixation mark throughout the test sequence, and the centering bias occurs, the causes of the centering bias are not addressed. But if the subject *foveates* each stimulus as it occurs, then signals from both sets of test stimuli must traverse a common neural path, starting at the two foveas and continuing through all levels of the visual system that are retinotopically organized. We assume that this neural path cannot maintain two separate brightness matching functions simultaneously, so foveation should eliminate a centering bias if it is retinotopically based. On the other hand, perceptually, even under foveation conditions, the two stimulus sets clearly maintain their separate physical locations, and it seems likely that a different bias could be applied to each location. Thus, if a simultaneous centering bias continues to occur under foveation conditions, the bias process probably occurs within a high level, spatiotopic representation.

If foveation experiments show that the bias process is retinotopic, its source can be further broken down by using foveation in conjunction with a *dichoptic transfer paradigm* (Bedford & Reinke, 1993; Meese & Georgeson, 1996). That is, the subject can view the lefthand stimulus set with the left eye, and the righthand stimulus set with the right eye, but foveate the stimulus on each trial. In this case, signals generated by the two sets of stimuli pass through separate retinas, but are superimposed in early cortical processing. If the centering bias occurs under dichoptic foveation conditions, it can be attributed to a retinal-retinotopic bias process rather than a cortical-retinotopic bias process. Alternatively, if the centering bias is eliminated under dichoptic foveation conditions, its occurrence under other conditions can be attributed to a cortical-retinotopic bias process.

In the present study, we undertake three experiments. In Experiment 1, we replicate the basic successive centering bias reported by Teller et al. (2003) using steady fixation rather than foveation (see Section 2). In Experiment 2, we show that a simultaneous centering bias occurs under fixation conditions, and that it is essentially eliminated under foveation conditions. And in Experiment 3, we show that the simultaneous centering bias is also essentially eliminated with dichoptic foveation.

2. General methods

2.1. Subjects

The subjects were laboratory personnel or graduate students at the University of Washington. Five subjects aged 29–37 participated in the experiments. The subjects had no known history of color deficiencies, and were

color normal according to Ishihara Color Plates, FM 100 Farnsworth–Munsell Color Test, and a modified Nagel anomaloscope. Five subjects participated in Experiment 1, Experiment 3, and the Fixation condition of Experiment 2; three of these subjects also participated in the Foveation condition of Experiment 2.

2.2. Apparatus and stimuli

The apparatus consisted of a Sony GDM-FW900 color graphics display monitor controlled by a Macintosh Power PC 7500, and calibrated with a PR 650 spectroradiometer. The monitor had a peak luminance of 63 cd/m² and a black level of 0.1 cd/m². The CIE 1931 *x,y* chromaticity coordinates of the red, green and blue video phosphors were (.62, .35), (.29, .61), and (.15, .06), respectively. The color name *red* will be used to describe test stimuli composed of the isolated red phosphor, and the color name *gray* will be used to describe the surround, with *x,y* chromaticity of (.34, .34).

A 1° × 1° fixation cross was present at the center of the screen at all times during the experiment. The test stimuli were 2° red squares located 7° either to the left or to the right of the fixation cross. A 10 cd/m² gray surround filled the rest of the screen, which subtended 68 × 42°. Between trials, the grey field filled the entire screen. The viewing distance was 38 cm. In the dichoptic condition of Experiment 3, a baffle was placed between the subject's nose and the monitor, allowing the left test stimulus to be viewed with the left eye, the right test stimulus with the right eye, and the fixation cross with both eyes.

The luminances of the test stimuli are specified in log relative units, relative to the surround luminance of 10 cd/m², which is set to zero on the abscissae of Figs. 2–4. In each experiment, the luminances of the red test squares varied from trial to trial. Test stimuli were selected from two different luminance ranges, low (Lo) and high (Hi). Each range spanned 0.5 log units (lu) in eleven 0.05 lu steps. In Experiments 1 and 2, the Lo luminance range had a mean of −0.6 lu, with test stimuli spanning the range from −0.85 to −0.35 lu (1.4–4.5 cd/m²). The Hi luminance range had a mean of 0.0 lu, with test stimuli spanning the range from −0.25 to 0.25 lu (5.6–17.8 cd/m²). The difference between the mean luminance values was 0.6 lu. In Experiment 3, the Lo luminance range had a mean of −0.45 lu, spanning the range from −0.7 to −0.2 lu (2.0–6.3 cd/m²). The Hi luminance range had a mean of −0.2 lu, spanning the range from −0.45 to 0.05 lu (3.5–11.2 cd/m²). The difference between the mean luminance values was 0.25 lu.

In Experiment 1, the two luminance ranges were presented in separate blocks of trials. In Experiments 2 and 3, the two luminance ranges were presented at two separate locations, 7° to the left or right of the fixation cross, in randomly interleaved trials. Within each luminance

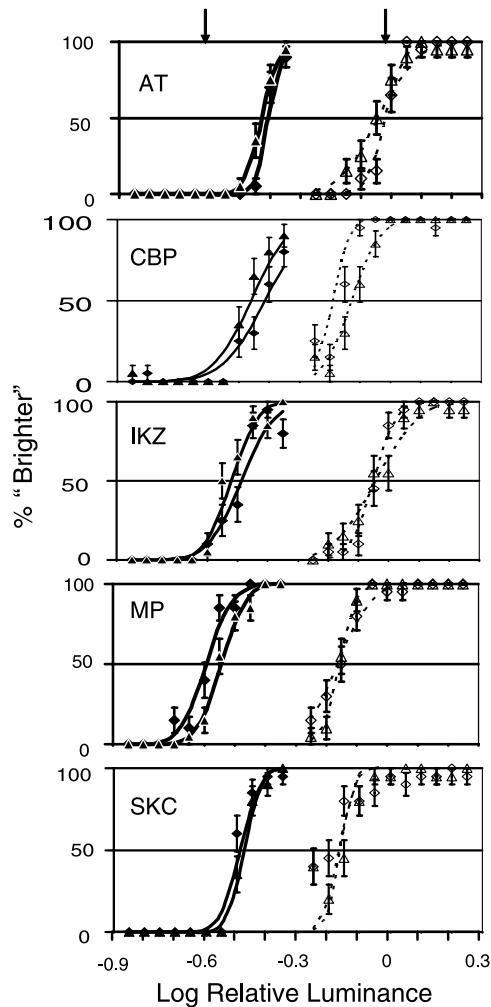


Fig. 2. Experiment 1: The Successive/Fixation condition. The abscissa shows the log relative luminances of the test stimuli, with the luminance of the 1 log cd/m² surround represented at zero. The centers of the ranges are shown by vertical arrows above the upper abscissa. The means of the Lo and Hi luminance ranges differed by 0.6 lu. The ordinate represents the proportion of trials on which the subject reported that the red test field appeared brighter than the surround. The dashed and solid lines show probit fits to the data. The error bars represent the binomial errors of proportions. Diamonds: stimuli presented in the left location on the screen; triangles: stimuli presented in the right location. Closed symbols/solid lines: Lo luminance range; open symbols/dashed lines: Hi luminance range.

range/location, the order of test stimuli was randomized over trials. The locations of the two stimulus ranges were counterbalanced across sessions and subjects.

2.3. Procedure

The method of constant stimuli was used for data collection. The subject initiated each trial by pressing a start key. A red test square then appeared randomly in one of the two stimulus locations on the monitor. The subject was instructed to press the right key on the keypad if the red test square appeared brighter than the

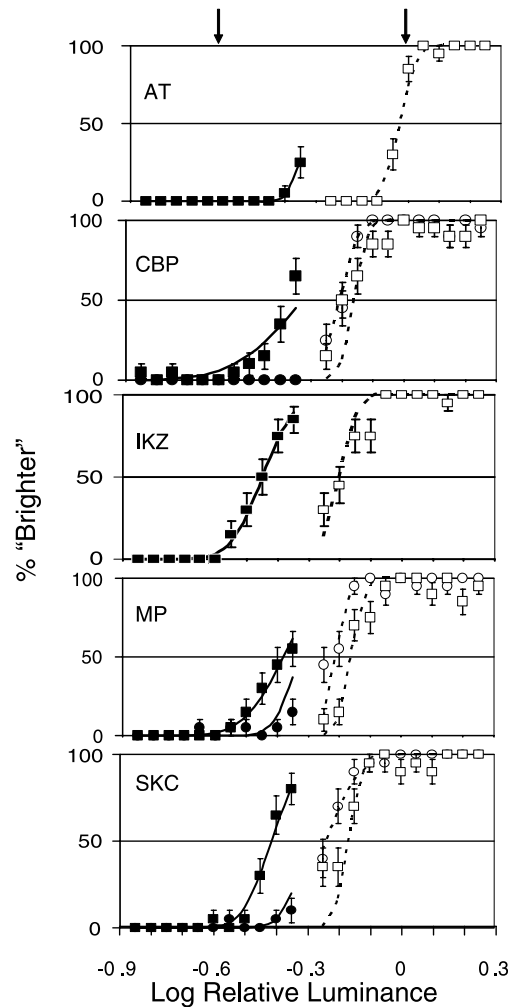


Fig. 3. Experiment 2: The Simultaneous/Fixation and Simultaneous/Foveation conditions. Conventions are as in Fig. 2. Squares: Simultaneous/Fixation condition; circles: Simultaneous/Foveation condition. For the Lo range in the Simultaneous/Foveation condition, most or all test stimuli were judged to appear darker than their surround. See text for details of the procedure used to score these data.

gray surround, and the left key if the square appeared dimmer than the surround. The trial was terminated by the observer's judgment. There was no time limit for making a judgment, but on average the test squares were present for about 600 ms. The inter-trial interval was about 500 ms. Each psychometric function is based on 220 trials (20 trials per stimulus luminance).

The fixation instructions were different in different experiments and conditions, as described below.

2.4. Data analysis

Data sets were analyzed separately by luminance range. Curves were fit to each data set by probit analysis (Finney, 1971). With an exception of two data sets in the second experiment for which the slope parameters were fixed (for details see Experiment 2), all the data sets were fit with cumulative normal curves with variable slope.

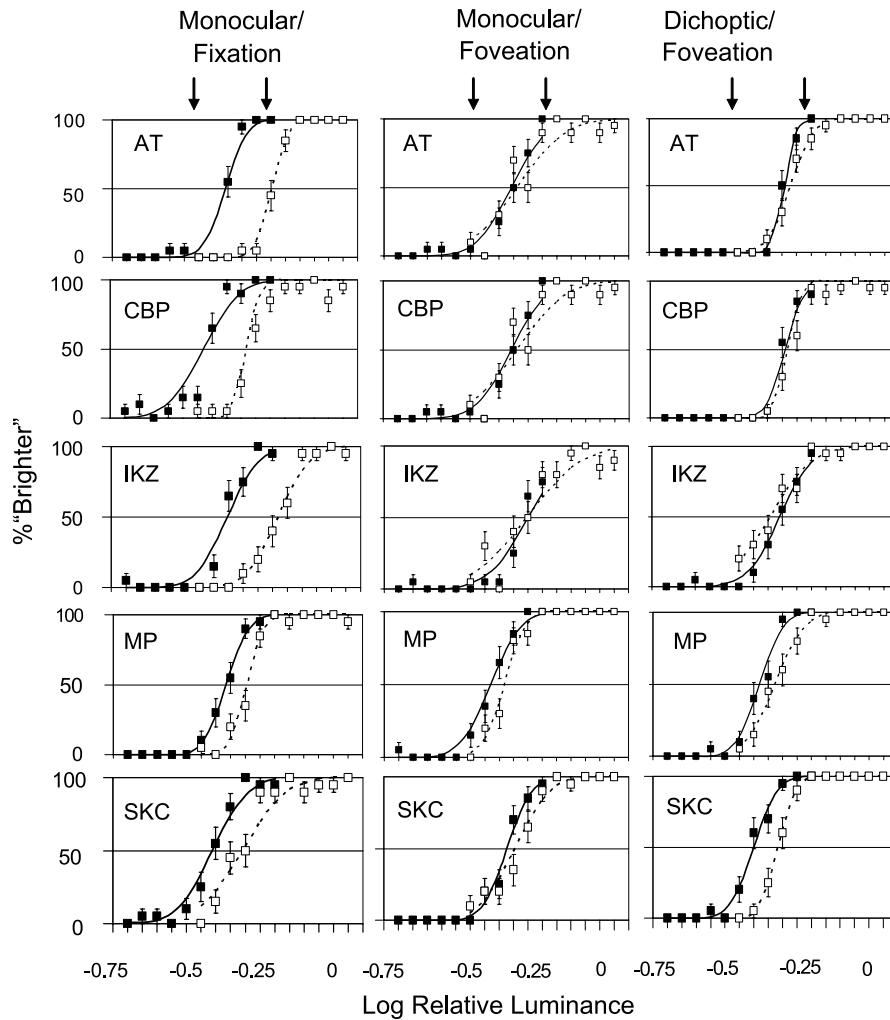


Fig. 4. Experiment 3: The Monocular/Fixation, Monocular/Foveation, and Dichoptic/Foveation conditions. Conventions are as in Fig. 3, except that the abscissa has been expanded. Left column of panels: The Monocular/Fixation condition; center column: The Monocular/Foveation condition; right column: the Dichoptic/Foveation condition. Closed squares/solid lines: Lo range; open squares/dashed lines: Hi range. The means of the Hi and Lo stimulus ranges differed by 0.25 lu.

The point of subjective equality (PSE) was defined as the luminance level at which the stimulus was reported as brighter than the surround on 50% of the trials.

In order to estimate the significance of differences between PSEs in Hi and Lo ranges for individual subjects in Experiments 2 and 3 individual data sets were broken in half and PSEs were estimated for these subsets by probit analysis. Student's *t*-tests were then performed to compare the PSEs across Hi and Lo range subsets.

3. Experiments and results

3.1. Experiment 1

3.1.1. The Successive/Fixation condition

The Teller et al. (2003) study was undertaken as part of a study of infant photometry. In that study, test stimuli selected from different luminance ranges were pre-

sented to adult subjects in successive blocks of trials. In order to mimic the looking patterns used by infants, adult subjects were instructed to foveate the stimulus on each trial. We refer to this experiment as the *Successive/Foveation* condition.

The goal of Experiment 1 was to replicate the basic centering bias described by Teller et al., but under conditions of steady fixation. To that end, test stimuli were again selected from different luminance ranges in successive blocks of trials, but subjects were instructed to fixate the central fixation cross throughout the experiment. We refer to this experiment as the *Successive/Fixation* condition.

Subjects fixated the fixation cross at the center of the monitor. The stimuli from one luminance range (e.g., the Lo range) were presented in random alternation between the two monitor locations in a single block of 440 trials (220 trials at each location). The stimuli from the other luminance range (e.g., the Hi range) were then

presented in random alternation between the two locations in a second block of 440 trials, which followed the first after about a minute. The order of presentation of the two test ranges was randomized across subjects and across sessions.

The results of Experiment 1 are shown in Fig. 2. Panels show psychometric functions for five subjects: AT, CBP, IKZ, MP (the first author), and SKC. The data are presented for two monitor locations, left (diamonds) and right (triangles) for two ranges: Lo (closed symbols, solid lines) and Hi (open symbols, dashed lines). As expected, the psychometric functions in the two locations are similar, and this variable will be suppressed in reports of later experiments.

The major finding from Experiment 1 is that the PSEs clearly differ for the two stimulus ranges. The respective means of the PSEs for the Lo and Hi stimulus ranges, for five subjects together with the respective differences between Hi and Lo range PSEs are shown in Appendix Table 2. All the differences were statistically reliable.

The group average data for all five subjects show a similar result. The mean PSEs for the Lo and Hi ranges were -0.49 ± 0.03 lu and -0.11 ± 0.03 lu, respectively, for a mean difference in PSEs of 0.38 ± 0.03 lu. This difference was statistically reliable.

Under Successive/Foveation conditions, with a difference in mean luminance of 0.6 lu, Teller et al. (2003) found a mean centering bias of 0.37 lu. In the present experiment, under Successive/Fixation conditions, we find an equal centering bias of 0.38 lu. Thus, Experiment 1 shows that the centering bias is not idiosyncratic to the Successive/Foveation condition used by Teller et al. (2003), but is robust across variations of fixation patterns. In addition, the same magnitudes of bias effects occur with stimuli presented either foveally or at 7° peripheral.

3.2. Experiment 2

3.2.1. Simultaneous/Fixation and Simultaneous/Foveation Conditions

Experiment 2 had two goals. The first was to see whether or not a centering bias—two different PSEs for different luminance ranges—can be established simultaneously at two different retinal locations. To examine this question under the most favorable conditions, subjects were instructed to fixate the fixation cross, while stimuli from the two different luminance ranges were presented at the two separate locations on the video monitor in randomly interleaved trials (the *Simultaneous/Fixation* condition). The second goal was to see whether or not such a simultaneous centering bias could be maintained under conditions of foveation. In this condition, subjects were instructed to fixate the fixation cross between trials, but to foveate each stimulus when it appeared in its random left or right position on the monitor (the *Simultaneous/Foveation* condition).

The stimuli were identical to those used in Experiment 1. The stimuli from the Lo range were presented in one location on the monitor, and the stimuli from the Hi range were presented in the other. Both sets of stimuli were presented in a single randomly interleaved block of 440 trials. The locations of the two ranges were counterbalanced across subjects. Viewing was binocular.

The results of Experiment 2 are shown in Fig. 3. The five panels show psychometric functions for five subjects: AT, CBP, IKZ, MP, and SKC. The data are presented for two conditions, Simultaneous/Fixation (squares) and Simultaneous/Foveation (circles). As before, the Lo range is shown by closed symbols and solid lines, and the Hi range by open symbols, and dashed lines. Because in the Simultaneous/Foveation condition the Lo range data only encompassed the very tail of the psychometric function for the Lo stimulus set, and thus could not provide a proper PSE estimate, we stopped the data collection for this condition after testing three observers: CBP, MP, and SKC.

In the Simultaneous/Fixation condition there are again clear differences for data from the different stimulus ranges. Individual PSE values and the respective PSE differences between Hi and Lo range PSEs for five subjects are shown in Appendix Table 3. These individual PSE differences were statistically significant.

The group average data for all five subjects in the Simultaneous/Fixation condition showed similar results. The mean PSE for the Lo and Hi ranges were -0.38 ± 0.03 lu and -0.14 ± 0.03 lu, respectively, for a difference between the two mean PSEs of 0.24 ± 0.02 lu. This difference is somewhat smaller than the 0.38 lu difference seen in the successive conditions, but remains statistically significant.

The data for three subjects in the Simultaneous/Foveation condition are shown in Table 3 in Appendix. Since all three subjects judged that most or all of the stimuli presented in the Lo range were darker than the achromatic surround, in order to estimate the PSEs, we fitted the data with cumulative normal functions using a fixed slope parameter. This parameter was estimated by averaging the slope parameters over all subjects/all experimental conditions. Subject CBP judged all stimuli as darker than the surround, and thus his Lo range data could not be fitted at all. However, lower bound estimates can be derived. Given the slope of psychometric functions in the other conditions, it can be assumed this subject's PSE will be at least 0.1 lu higher than the upper limit of Lo range, or at least -0.25 lu. For the remaining two subjects the mean PSE for the Lo and Hi ranges were -0.28 ± 0.01 lu and -0.22 ± 0.02 lu, respectively, for a difference between the two mean PSEs of 0.06 ± 0.01 lu.

In sum, in the Simultaneous/Fixation condition, we have demonstrated that two different PSEs can be established simultaneously by two different stimulus sets presented in different locations. In the Simultaneous/

Foveation condition, this bias effect is reduced toward zero.

3.3. Experiment 3

3.3.1. Monocular/Fixation, Monocular/Foveation, and Dichoptic/Foveation conditions

The main purpose of Experiment 3 was to add a Dichoptic/Foveation condition to the experiments.

Two problems surfaced from the data of Experiments 1 and 2. We addressed these problems by introducing a new design in Experiment 3. First, all conditions in Experiments 1 and 2 were carried out with binocular viewing, but dichoptic viewing is more appropriately compared with monocular conditions. To address this problem, we tested three new conditions in Experiment 3: *Monocular/Fixation*, *Monocular/Foveation*, and *Dichoptic/Foveation*. An ancillary advantage of this design is that the *Monocular/Fixation* and *Monocular/Foveation* conditions provide a potential replication of Experiment 2.

A second problem arose concerning the choice of stimuli. Our original choice of a separation of 0.6 lu between the means of the stimulus ranges allowed us to maximize the bias effects in Experiments 1 and 2, but Experiment 2 showed that this separation is not well suited to further dissection of the potential sources of bias. The reason is that with the ranges spread far apart, as the bias effect gets smaller and smaller, one or both of the psychometric functions will fall between the two ranges and be unmeasurable, as did the function for the Lo range in the Simultaneous/Foveation condition of Experiment 2.

An obvious solution to this problem is to move the ranges closer together. However, a reduction of the difference in luminances between Lo and Hi ranges comes at a cost: as the ranges move closer together, the total size of the bias effect is expected to decrease. Nonetheless, absent any better solution, in Experiment 3 the means of the Lo and Hi luminance ranges were set to -0.45 and -0.2 , respectively, for a difference between the mean luminance values of only 0.25 lu. These ranges were chosen because in a series of pilot studies, they were found to span most of the psychometric functions we needed to measure, in all of the experimental conditions required by Experiment 3.

Three different viewing conditions were used in Experiment 3. In the *Monocular/Fixation* condition, subjects viewed the stimuli monocularly, with instructions to fixate the fixation cross in the middle of the screen throughout the experiment. In the *Monocular/Foveation* condition, subjects again viewed the stimuli monocularly, with instructions to foveate the test stimulus during each trial. In the *Dichoptic/Foveation* condition, the baffle separating the sides was added to the apparatus. Subjects viewed the lefthand stimuli with the left eye, and the righthand stimuli with the right

eye, with instructions to foveate the test stimulus during each trial.

The data from five subjects (AT, CBP, IKZ, MP, and SKC) in Experiment 3 are shown in Fig. 4. The data for the *Monocular/Fixation*, *Monocular/Foveation*, and *Dichoptic/Foveation* conditions are shown in respective columns of panels. The individual values of PSEs of Lo and Hi stimulus ranges, as well as the group averages are given in Table 4 in the Appendix.

The data of three subjects follow a common pattern: relatively large differences between the PSEs of Hi and Lo ranges in the *Monocular/Fixation* condition, and little or no difference between the PSEs of Hi and Lo ranges in the *Monocular/Foveation* and *Dichoptic/Foveation* conditions. Two subjects, however, deviated from this pattern. For subject SKC, there is a difference of about 0.08 lu in the *Dichoptic/Foveation* condition. For subject MP there are differences of about 0.05 lu in both *Monocular/Foveation* and *Dichoptic/Foveation* conditions.

Averaged over five observers, the mean differences were 0.14 ± 0.01 lu, 0.02 ± 0.01 , and 0.03 ± 0.02 lu for *Monocular/Fixation*, *Monocular/Foveation*, and *Dichoptic/Foveation* conditions, respectively. The only statistically reliable bias effect was found in the *Monocular/Fixation* condition. Thus, Experiment 3 shows that a bias effect occurs under *Monocular/Fixation* conditions, but is essentially eliminated under both *Monocular/Foveation* and *Dichoptic/Foveation* conditions.

3.3.2. Centering biases

A summary of the centering biases seen in all of our experiments is shown in Fig. 5. The left four bars on the graph show data taken with a mean difference in the stimulus ranges of 0.6 lu. The leftmost bar shows the *Successive/Foveation* data from Teller et al. (2003). The second bar shows the *Successive/Fixation* data from Experiment 1. Both of these conditions show a substantial centering bias. A difference of 0.6 lu between the means of the two stimulus sets results in a mean difference of 0.38 lu in the two successively measured PSEs under both fixation and foveation conditions. This finding also suggests that in heterochromatic brightness matching, the bias process is activated equally regardless of whether all of the stimuli in a block fall on the fovea, or whether half of them fall on each of two locations at $\pm 7^\circ$ peripheral.

The remaining bars show data taken under Simultaneous conditions. The third bar shows the data from the *Simultaneous/Fixation* condition from Experiment 2. This condition shows a reduction in the magnitude of the centering bias compared to those seen in the successive conditions; however, a substantial centering bias remains in this condition. The fourth bar shows the data for two out of three subjects in the *Simultaneous/Foveation* condition. The bias is further considerably reduced.

The right three bars show data taken with monocular or dichoptic presentation, and a difference in means of

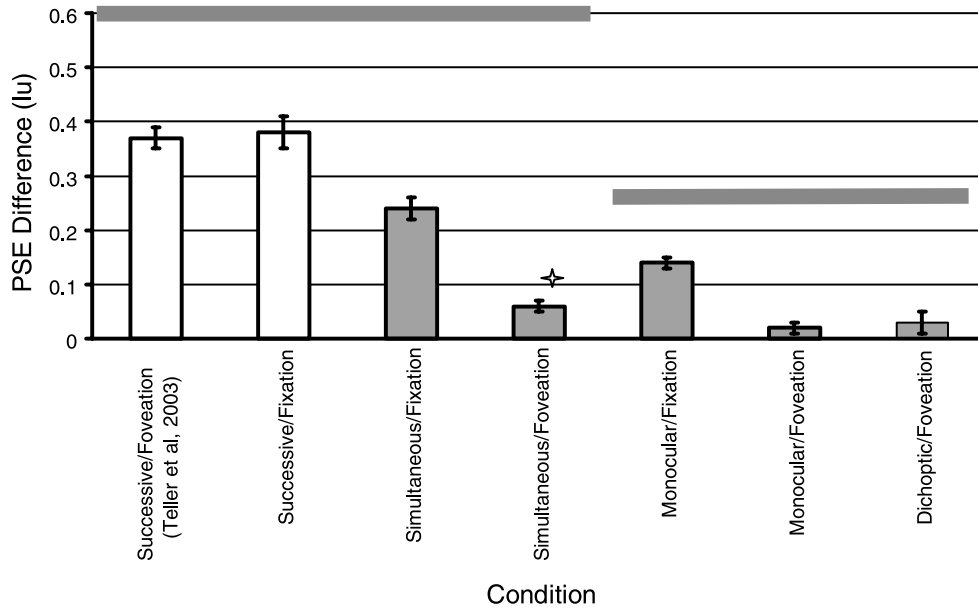


Fig. 5. Summary of results. The two open bars show group average differences in PSEs for the two Successive conditions: Successive/Foveation (Teller et al., 2003) and Successive/Fixation, respectively. The five closed bars show group average differences in PSEs for the five Simultaneous conditions: Simultaneous/Fixation (Binocular), Simultaneous/Foveation (Binocular), Monocular/Fixation, Monocular/Foveation, and Dichoptic/Foveation, respectively. The dark horizontal lines above the data show the differences between the stimulus ranges for Hi and Lo conditions; that is, the maximum expected magnitude of any centering bias. Centering biases are seen in both Successive conditions, but in Simultaneous conditions centering biases only occur in the Fixation conditions. Error bars show standard errors of the means. All bars show group average differences for 5 subjects, except for the data in Simultaneous/Foveation condition (marked by a star), which shows an average difference for two subjects.

Table 1

Properties of bias process	Experimental conditions		
	Simultaneous/Fixation (binocular) and Monocular/Fixation	Simultaneous/Foveation (binocular) and Monocular/Foveation	Dichoptic/Foveation
Retinal-retinotopic	Present	Absent	Present
Cortical-retinotopic	Present	Absent	Absent
Spatiotopic	Present	Present	Present
Results	Present	Absent	Absent

0.25 lu. A substantial centering bias remains in the Monocular/Fixation condition (bar 5), but the centering bias is nearly absent in both the Monocular/Foveation and Dichoptic/Foveation conditions (bars 6 and 7, respectively).

4. Discussion

In the present experiments, the various Simultaneous conditions (Experiments 2 and 3) explore the conditions under which two different PSEs can be established at different retinal, retinotopic, and/or physical locations. The predictions of the three hypotheses discussed in the Introduction, along with the results of all of the Simultaneous conditions (Experiments 2 and 3) are summarized in Table 1. The left-hand column of Table 1 lists the three hypotheses concerning the serial location of the bias process—retinal-retinotopic, cortical-retinotopic, and

spatiotopic. The top row of the table specifies the experimental conditions of Experiments 2 and 3, with monocular and binocular conditions that lead to the same predictions grouped together. The table entries specify the predictions—the presence or absence of a simultaneous bias effect—for each of the sets of experimental conditions, based on each of the three hypotheses. As shown in the table, the three different hypotheses predict three different patterns of outcomes for Experiments 2 and 3.

The bottom row of Table 1 provides a summary of the group average results of all of the Simultaneous conditions. The pattern of results—the presence of a simultaneous bias effect under fixation conditions, and its absence or near-absence under all foveation conditions—fits the predictions of the cortical-retinotopic hypothesis. Thus, the main conclusion of this paper is that under the conditions tested, the process that creates the observed biases in heterochromatic brightness matching is located at a post-retinal but still retinotopically organized level

of the visual system, rather than at either a retinal level or a more central, spatiotopically organized one.

4.1. Implications for the three kinds of bias processes

We now return to the three potential sources of the centering bias seen in our experiments. The first is a retinal-retinotopic bias mechanism. Interestingly, we did not observe a bias effect under Dichoptic/Foveation conditions; that is, under conditions that would have isolated and exposed any bias effect due to retinal-retinotopic adaptation. One possible reason for not observing a bias effect in this condition is that our stimulus sets were not sufficiently different to cause measurable differences in retinal adaptation. Also, the test stimuli were presented only for relatively brief periods of time (about 600 ms), and a field of the luminance of the surround filled in the stimulus locations during the rest of the inter-trial interval of about 2.5 s (Pokorny, Sun, & Smith, 2003). In addition, in the dichoptic conditions the luminance difference between the stimulus ranges was only 0.25 lu. It seems likely that stimuli presented for longer periods of time and ranges more different in luminance would create different retinal adaptation levels at the two locations, and that biases in heterochromatic brightness matching due to retinal adaptation would occur.

The second potential source of bias is a cortical-retinotopic process. In the present experiments, we have demonstrated a cortical-retinotopic location for bias effects in heterochromatic brightness matching. Two different stimulus sets presented in two different retinotopic positions can generate two different bias states simultaneously within the visual system. Even though the two stimulus sets were presented in interleaved trials, the information from the two sets must be kept separate, so that two separate brightness match points can be maintained, and used as a basis for judging the brightnesses of the stimuli in the two retinotopic positions. Yet no bias is seen under any foveation conditions, be they binocular, monocular, or dichoptic; that is, no spatiotopic bias is seen. Because the bias process is retinotopic and not spatiotopic, the use of the same retinotopic position for initiating the two sets of signals essentially eliminates the visual system's capacity to maintain two separate brightness match points for the two physical locations, i.e. abolishes the bias effect.

Finally, the third potential source of bias is a spatiotopic process. We did not observe a bias effect under either Binocular/Foveation or Monocular/Foveation conditions; that is, under conditions that would have isolated and exposed any bias effect due to spatiotopic processes. Again, the possible reason for our outcome may be the relatively small difference between the test stimulus ranges.

Speaking in cognitive terms, a spatiotopic bias effect might require the observer to notice that the test stimulus ranges at the two physical locations are different, and apply cognitive manipulations separately to left and right physical locations, even though both locations are foveated in turn. It could be that for naïve observers, the fact that the ranges are different was not immediately obvious, and so it didn't trigger spatiotopically specific "keeping track" of the stimulus ranges. We found some evidence to that effect in our pilot experiments (not shown), and also in the data from one informed observer, MP, who displayed a marginal bias (presumably due to spatiotopic processes) in the Monocular/Foveation condition (a PSE difference of $0.05 \pm .02$ lu).

4.2. Natural criterion

Not all psychophysical and perceptual judgments are equally subject to bias effects. For example, heterochromatic brightness judgments made using flicker photometry, minimally distinct border and motion nulling paradigms, are probably influenced very little by selection of the test stimulus set (cf. Teller et al., 2003).

When cognitive processes are at play, the differing susceptibility of different perceptual judgments to a centering bias could be caused by the presence vs. absence of a *natural perceptual criterion* to underlie the judgments (Poulton, 1979). That is, one can argue that subjects can readily judge the amount of flicker, border distinctness, or motion in a display, and can therefore make settings that clearly minimize these perceptual characteristics regardless of the stimulus set (Lennie, Pokorny, & Smith, 1993; Wagner & Boynton, 1972); but that no such natural criterion occurs for brightness. It would be likely that judgments for which no natural criterion is available should be subject to bias effects, as well as to day-to-day fluctuations and to individual differences. Heterochromatic brightness matches, in particular, are well known to be subject to day-to-day fluctuations (Walsh, 1958; Wyszzecki & Stiles, 1982) and to individual differences (Ikeda, Yaguchi, & Sagawa, 1982; Ives, 1912a, 1912b; Wyszzecki & Stiles, 1982). It would be very interesting to see whether other types of judgments described in the bias literature, including perceived sweetness or saltiness (Conner et al., 1987; Lawless, 1983; Stillman, 1993), loudness (Parker & Schneider, 1994; Schneider & Parker, 1990), or contrast (Schneider et al., 1996) could also be explained by the presence vs. absence of a natural criterion.

Finally, it seems likely that the large centering biases we observed here are not confined solely to heterochromatic brightness matching. Further work is needed in understanding the influence of the choice of stimuli on PSEs measured in psychophysical and perceptual experiments, and in sorting out their causes.

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Appendix A

The Appendix provides data from all individual subjects. (see Tables 2–4).

Table 2
Data summary, Experiment 1

Subject	Hi range			Lo range			Mean PSE difference
	Left	Right	Mean left/right	Left	Right	Mean left/right	
AT	-0.02 ± 0.01	-0.02 ± 0.01	-0.02 ± na	-0.43 ± 0.03	-0.41 ± 0.04	-0.42 ± 0.01	0.40 ± 0.01***
CBP	-0.19 ± 0.04	-0.13 ± 0.02	-0.16 ± 0.03	-0.41 ± 0.03	-0.46 ± 0.02	-0.44 ± 0.02	0.28 ± 0.06 [^]
IKZ	-0.04 ± 0.01	-0.05 ± 0.01	-0.05 ± 0.01	-0.52 ± 0.01	-0.49 ± 0.02	-0.51 ± 0.02	0.47 ± 0.02**
MP	-0.16 ± 0.03	-0.16 ± 0.03	-0.16 ± na	-0.54 ± 0.01	-0.59 ± 0.01	-0.57 ± 0.03	0.41 ± 0.03**
SKC	-0.16 ± 0.03	-0.16 ± 0.03	-0.16 ± na	-0.49 ± 0.03	-0.48 ± 0.03	-0.49 ± 0.01	0.33 ± 0.01***
Mean	-0.11 ± 0.03	-0.10 ± 0.03	-0.11 ± 0.03	-0.48 ± 0.03	-0.49 ± 0.03	-0.49 ± 0.03	0.38 ± 0.03***

Columns 2–4: Hi Range. Columns 2 and 3: the PSE and the standard error of PSE estimate (standard error of the proportion) for stimuli presented in the left and the right locations. Column 4: PSE averaged over the left and right location, and the standard error of the mean. Columns 5–7: Lo Range. All conventions are as for Hi range. Column 8: The difference between the mean Hi and Lo range PSEs and the standard error of the difference. The bottom row shows the mean for 5 observers and the standard error of the mean. All units are log luminance (lu). The [^], *, **, and, *** symbols mark PSE differences significantly greater than zero: [^]*p* < 0.01, **p* < 0.05, ***p* < 0.005, ****p* < 0.0005.

Table 3
Data summary, Experiment 2

Subject	Condition					
	Simultaneous/Fixation			Simultaneous/Foveation		
	PSE Hi	PSE Lo	PSE difference	PSE Hi	PSE Lo	PSE difference
AT	-0.03 ± 0.01	-0.31 ± 0.01	0.28 ± 0.01***			
CBP	-0.16 ± 0.03	-0.33 ± 0.06	0.17 ± 0.02 [^]	-0.21 ± 0.04	#	
IKZ	-0.20 ± 0.04	-0.45 ± 0.02	0.25 ± 0.04 [^]			
MP	-0.16 ± 0.03	-0.38 ± 0.04	0.22 ± 0.04*	-0.21 ± 0.04	-0.27 ± 0.02	0.06 ± na
SKC	-0.17 ± 0.03	-0.41 ± 0.03	0.24 ± 0.04*	-0.24 ± 0.06	-0.29 ± 0.02	0.05 ± na
Mean	-0.14 ± 0.03	-0.38 ± 0.03	0.24 ± 0.02***	-0.22 ± 0.02	-0.28 ± 0.01	0.06 ± 0.01

Columns 2–4: Simultaneous/Fixation Condition. PSEs for Hi and Lo range together with the standard errors of individual PSE estimates (standard errors of the proportion) are shown in columns 2 and 3, respectively. The difference in Hi and Lo range PSEs and the standard error of the difference are shown in Column 4. Columns 5–7: Simultaneous/Foveation condition. Conventions are as in columns 2–4. The symbol *na* was used when the data were not sufficient to estimate the standard error. The Lo range PSE (marked by #) could not be estimated for subject CBP. The bottom row shows the mean for all observers in each condition and the standard error of the mean. Statistical significance conventions are as in Appendix Table 2.

Table 4
Data summary, Experiment 3

Subject	Condition								
	Monocular/Fixation			Monocular/Foveation			Dichoptic/Foveation		
	PSE Hi	PSE Lo	PSE difference	PSE Hi	PSE Lo	PSE difference	PSE Hi	PSE Lo	PSE difference
AT	-0.20 ± 0.01	-0.36 ± 0.02	0.16 ± 0.02**	-0.27 ± 0.01	-0.30 ± 0.03	0.03 ± 0.03	-0.27 ± 0.01	-0.29 ± 0.03	0.02 ± 0.02
CBP	-0.28 ± 0.02	-0.43 ± 0.01	0.15 ± 0.01**	-0.28 ± 0.02	-0.31 ± 0.02	0.03 ± 0.01	-0.28 ± 0.02	-0.29 ± 0.03	0.01 ± 0.03
IKZ	-0.18 ± 0.01	-0.35 ± 0.02	0.17 ± 0.01**	-0.28 ± 0.02	-0.25 ± 0.04	-0.03 ± 0.01	-0.34 ± 0.02	-0.31 ± 0.02	-0.03 ± 0.03
MP	-0.32 ± 0.02	-0.43 ± 0.01	0.11 ± 0.02 [^]	-0.33 ± 0.02	-0.38 ± 0.01	0.05 ± 0.02*	-0.33 ± 0.02	-0.38 ± 0.01	0.05 ± 0.01*
SKC	-0.28 ± 0.02	-0.41 ± 0.01	0.13 ± 0.02*	-0.30 ± 0.02	-0.32 ± 0.02	0.02 ± 0.01	-0.32 ± 0.02	-0.40 ± 0.01	0.08 ± 0.01*
Mean	-0.25 ± 0.03	-0.40 ± 0.02	0.14 ± 0.01**	-0.29 ± 0.01	-0.31 ± 0.02	0.02 ± 0.01	-0.30 ± 0.01	-0.33 ± 0.02	0.03 ± 0.02

Columns 2–4: Monocular/Fixation condition. PSEs for Hi and Lo ranges and the standard errors of individual PSE estimates (standard errors of the proportion) are shown in columns 2 and 3, respectively. The difference in Hi and Lo range PSEs and the standard error of the difference are shown in column 4. Columns 5–7: Monocular/Foveation condition. Columns 8–10: Dichoptic/Foveation condition. Conventions are as in columns 2–4. The bottom row shows the means for 5 observers and the standard errors of the mean.

References

- Bedford, F. L., & Reinke, K. S. (1993). The McCollough effect: Dissociating retinal from spatial coordinates. *Perception and Psychophysics*, *54*, 515–526.
- Conner, M. T., Land, D. G., & Booth, D. A. (1987). Effect of stimulus range on judgments of sweetness intensity in a lime drink. *British Journal of Psychology*, *78*, 357–364.
- Finney, D. J. (1971). *Probit analysis* (3rd ed.). Cambridge: The University Press.
- Green, D. M., & Swets, J. A. (1966). *Signal detection theory and psychophysics*. New York: Wiley.
- Hahn, L. W., & Geisler, W. S. (1995). Adaptation mechanisms in spatial vision—I. Bleaches and backgrounds. *Vision Research*, *35*, 1585–1594.
- Ikeda, M., Yaguchi, H., & Sagawa, K. (1982). Brightness luminous-efficiency functions for 2 degrees and 10 degrees fields. *Journal of the Optical Society of America A*, *72*, 1660–1665.
- Irwin, D. E. (1996). Integrating information across saccadic eye movements. *Current Directions in Psychological Science*, *5*, 94–100.
- Ives, H. E. (1912a). Studies in the photometry of lights of different colours. I. Spectral luminosity curves obtained by the equality of brightness photometer and the flicker photometer under similar conditions. *Philosophical Magazine*, *24*, 149–188.
- Ives, H. E. (1912b). Studies in the photometry of lights of different colours. V. The spectral luminosity of the average eye. *Philosophical Magazine*, *24*, 853–863.
- Lawless, H. (1983). Contextual effect in category rating. *Journal of Testing and Evaluation*, *11*, 346–349.
- Lennie, P., Pokorny, J., & Smith, V. C. (1993). Luminance. *Journal of the Optical Society of America A*, *10*, 1283–1293.
- Marks, L. E. (1988). Magnitude estimation and sensory matching. *Perception and Psychophysics*, *43*, 511–525.
- Meese, T. S., & Georgeson, M. A. (1996). The tilt aftereffect in plaids and gratings: channel codes, local signs and “patchwise” transforms. *Vision Research*, *36*, 1421–1437.
- Melcher, D., & Morrone, M. C. (2003). Spatiotopic temporal integration of visual motion across saccadic eye movements. *Nature Neuroscience*, *6*, 877–881.
- Parker, S., & Schneider, B. (1994). The stimulus range effect: evidence for top-down control of sensory intensity in audition. *Perception and Psychophysics*, *56*, 1–11.
- Pokorny, J., Sun, V. C. W., & Smith, V. C. (2003). Temporal dynamics of early light adaptation. *Journal of Vision*, *3*, 423–431.
- Poulton, E. C. (1979). Models for biases in judging sensory magnitude. *Psychological Bulletin*, *86*, 777–803.
- Schneider, B., & Parker, S. (1990). Does stimulus context affect loudness or only loudness judgments? *Perception and Psychophysics*, *48*, 409–418.
- Schneider, B., Parker, S., & Moraglia, G. (1996). The effect of stimulus range on perceived contrast: Evidence for contrast gain control. *Canadian Journal of Experimental Psychology*, *50*, 347–355.
- Stillman, J. A. (1993). Context effects in judging taste intensity: A comparison of variable line and category rating methods. *Perception & Psychophysics*, *54*, 477–484.
- Teller, D. Y., Pereverzeva, M., & Civan, A. L. (2003). Adult brightness vs. luminance as models of infant photometry: Variability, biasability, and spectral characteristics for two age groups favor the luminance model. *Journal of Vision*, *3*, 333–346.
- Wade, A. R., Brewer, A. A., Rieger, J. W., & Wandell, B. A. (2002). Functional measurements of human ventral occipital cortex: Retinotopy and colour. *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, *357*, 963–973.
- Wagner, G., & Boynton, R. (1972). Comparison of four methods of heterochromatic photometry. *Journal of the Optical Society of America A*, *62*, 1508–1515.
- Walraven, J., Enroth-Cugell, C., Hood, D. C., MacLeod, D. I. A., & Schnapf, J. L. (1990). The control of visual sensitivity: receptor and postreceptor processes. In L. Spillman & J. S. Werner (Eds.), *Visual perception: The neurophysiological foundations*. San Diego: Academic Press.
- Walsh, J. W. T. (1958). *Photometry*. London: Constable.
- Wolfson, S. S., & Graham, N. (2001). Processing in the probed-sinewave paradigm is likely retinal. *Visual Neuroscience*, *18*, 1003–1010.
- Wyszecki, G., & Stiles, W. S. (1982). *Color Science*. Wiley: New York.