The highest luminance anchoring rule in achromatic color perception: Some counterexamples and an alternative theory

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It has been hypothesized that lightness is computed in a series of stages involving: (1) extraction of local contrast or luminance ratios at borders; (2) edge integration, to combine contrast or luminance ratios across space; and (3) anchoring, to relate the relative lightness scale computed in Stage 2 to the scale of real-world reflectances. The results of several past experiments have been interpreted as supporting the highest luminance anchoring rule, which states that the highest luminance in a scene always appears white. We have previously proposed a quantitative model of achromatic color computation based on a distance-dependent edge integration mechanism. In the case of two disks surrounded by lower luminance rings, these two theories—highest luminance anchoring and distance-dependent edge integration—make different predictions regarding the luminance of a matching disk required to for an achromatic color match to a test disk of fixed luminance. The highest luminance rule predicts that luminance of the ring surrounding the test should make no difference, whereas the edge integration model predicts that increasing the surround luminance should reduce the luminance required for a match. The two theories were tested against one another in two experiments. The results of both experiments support the edge integration model over the highest luminance rule.

Keywords: achromatic color, brightness, edge integration, highest luminance rule, induction, lightness, lightness anchoring

Introduction

Over the last few decades, a large number of psychophysical studies have been published on the topic of achromatic color perception, including brightness, lightness, shading, transparency, specularity, and related subtopics. Despite the major advances that have resulted from this work, the neurophysiological mechanisms underlying achromatic color perception remain largely unknown. Various competing neural accounts coexist in the current literature, including theories based on multiscale spatial filters (Blaklee & McCourt, 1997, 1999, 2001, 2003, 2004), edge integration (Land, 1977, 1983, 1986a, 1986b; Land & McCann, 1971; Reid & Shapley, 1988; Rudd, 2001, 2003a, 2003b; Rudd & Arrington, 2001; Rudd & Zemach, 2002a, 2002b, 2003, 2004; Shapley & Reid, 1985; Zemach & Rudd, 2002, 2003), achromatic color filling-in (Arrington, 1996; Cohen & Grossberg, 1984; Grossberg & Mingolla, 1985; Grossberg & Todorovic, 1988; Grossberg, Mingolla, & Todorovic, 1989; Neumann, Pessoa, & Hansen, 2001; Ross & Pessoa, 2000; Rudd, 2001; Rudd & Arrington, 2001), and midlevel cues to lightness, such as junctions (Adelson, 1993; Anderson, 1997; Logvinenko, 2002; Todorovic, 1997; Zaidi, Spehar, & Shy, 1997).

One early and influential neurally inspired theory of achromatic color computation that continues to guide research in the field is the Retinex theory of Land and McCann (1971; Land, 1977, 1983, 1986a, 1986b). Retinex theory was devised to compute the colors—or lightness in the achromatic domain—of regions within Mondrian patterns: images made up of patches having homogeneous luminance and wavelength composition separated by sharp borders.

According to the Retinex theory, lightness computation occurs in a series of stages involving the following: (1) edge extraction, to compute local luminance ratios at luminance borders; (2) edge integration, to combine luminance ratios across space to establish a scale of relative lightness values for the regions lying between borders; and (3) anchoring, to relate the relative lightness scale computed in Stage 2 to the scale of real-world reflectances.

The results of a number of recent psychophysical experiments (Schirillo & Shevell, 1996; Bruno, Bernardis, & Schirillo, 1997; Li & Gilchrist, 1999) have been interpreted as supporting a particular lightness anchoring rule known as the highest luminance rule. The highest luminance rule states that the highest luminance in the scene appears white and the achromatic colors of all of the other regions within the scene are determined relative to the white point.
The highest luminance rule originated with the work of Wallach (1948, 1963, 1976) and was later adopted in the lightness computation algorithms of Land, McCann, and Horn (Land & McCann, 1971; McCann, 1987, 1994; Horn, 1977). In the current literature, the highest luminance rule is probably most closely identified with Gilchrist’s influential Anchoring theory of lightness perception (Gilchrist et al., 1999; Li & Gilchrist, 1999).

Anchoring theory, like Retinex, assumes the existence of separate processes that function to establish the scale of relative lightness and to map the scale of relative lightness onto the scale of perceived lightness. Gilchrist refers to these two processes as scaling and anchoring. In Retinex theory, the edge integration serves to establish the ratio scale of relative lightness. Anchoring theory does not commit to a specific mechanism for computing the ratio scale. The main focus of Anchoring theory is on the anchoring rules that map relative lightness onto absolute lightness values.

Anchoring theory extends the classical theories of lightness anchoring proposed by Wallach, Land and McCann, and others, by positing the existence of multiple anchoring frameworks. The multiple frameworks hypothesis asserts that the lightness standard applied to any given region in the image is determined by a compromise between local and global applications of the highest luminance rule. This principle was originally introduced by Kardos (1934), who referred to it as “co-determination” (see also Gilchrist et al., 1999).

Anchoring theory also postulates a new anchoring principle, relative area, which states that larger areas appear lighter and that the lightness of a target region within an image will be increased by increases in the areas, but not the luminances, of regions that are lower in luminance than the target region (Li & Gilchrist, 1999). Thus, according to Anchoring theory, anchoring is achieved by a combination of local and global applications of the highest luminance rule and the relative area rule.

The anchoring problem is central to much recent cognitive and computational theorizing about lightness perception. It is a problem that any viable neural, or mechanistic, model of achromatic color vision must address. In what follows, we will first present a model of lightness scaling based on a novel edge integration algorithm, which modifies the assumptions of Retinex. The new edge integration algorithm leads to a scaling model in which the lightness of a region depends not only on its luminance, but also on the luminances of surrounding regions. Although the rules of scaling only are changed in our edge integration model, the model generates predictions that are fundamentally at odds with the highest luminance anchoring principle. In particular, our edge integration model predicts that the lightness of the regions of highest luminance in the image will be influenced by regions of lower luminance.

In what follows, we will provide experimental demonstrations of simultaneous contrast effects obtained with incremental targets. We will show that these contrast effects violate the highest luminance anchoring principle but verify the predictions of our edge integration theory. In the Discussion section, we propose an alternative anchoring principle: one that is consistent with our edge integration model. The new anchoring principle asserts that the lightness anchor does not reliably correspond to any particular luminance value, such as the highest luminance, but instead corresponds to a particular neural activity level: the highest neural activity in the output of the edge integration process.

The experiments reported here are based on a classic achromatic color matching paradigm in which two disks, each surrounded by a ring, are presented side by side on a display. The subject’s task is to adjust the luminance of one of the disks as a function of the luminance of the ring surrounding the other disk to achieve an appearance match between the two disks. A number of past studies have investigated the conditions leading to an achromatic color match using such stimuli (Jacobsen & Gilchrist, 1988; Reid & Shapley, 1988; Rudd, 2001, 2003a, 2003b; Rudd & Arrington, 2001; Rudd & Zemach, 2002a, 2002b, 2003, 2004; Shapley & Reid, 1985; Wallach, 1948, 1963, 1976; Zemach & Rudd, 2002, 2003).

The observers in most of these studies were instructed simply to match the disks in appearance. However, Arend and Spehar (1993a, 1993b) showed that observers are able to make separate judgments of the lightness (perceived reflectance) and brightness (perceived physical intensity) of the target when viewing similar displays consisting of square-shaped targets surrounded by frames, if specifically instructed to do so. In the present paper, we will investigate the properties of both naïve matches (i.e., matches in which the observer is given to no special instructions to judge either brightness or lightness) and lightness matches, specifically. (Thanks to Prof. Davida Teller for suggesting the term “naïve match.”) Brightness matches will be studied, and their properties compared to those of lightness and naïve matches, in an upcoming paper (Rudd, Zemach, & Heredia, 2005). Ultimately, the properties of all of these types of matches—as well as the relationships between them—need to be understood if the extant literature is to be fully addressed by a theoretical model.

In what follows, we will use the term achromatic color to refer to the attribute that is matched in naïve appearance matching experiments. This term avoids the ambiguity of
the common alternative term “brightness,” which is sometimes used to refer to perceived luminance (as in the present study) and at other times used to refer to the attribute that is matched in naive matching experiments. We will also use the term achromatic color when we wish to refer to the general category of neutral color percepts that includes lightness and brightness as specific dimensions or attributes. The meaning should be clear from the context. When we wish to refer to lightness or brightness, in particular, we will be careful to use those labels.

The results of several naive appearance matching experiments performed with disk-and-ring stimuli have been successfully modeled with algorithms based on the assumption that the disk color is computed from a weighted sum of either the Michelson contrasts or the logarithms of the luminance ratios at the inner and outer ring borders (Reid & Shapley, 1988; Rudd, 2001, 2003a, 2003b; Rudd & Arrington, 2001; Rudd & Zemach, 2002a, 2002b, 2003, 2004; Shapley & Reid, 1985; Zemach & Rudd, 2002, 2003). Reid and Shapley (1988) proved mathematically that these two contrast measures are approximately equal in the low contrast limit. In a recent paper (Rudd & Zemach, 2004), we presented evidence favoring the weighted log luminance ratio edge integration model over a model based on Michelson contrast for high contrast stimuli.

The visual stimulus used in the main experiment of our previous study consisted of two disk-and-ring patterns of equal size presented side-by-side on a flat panel monitor. The luminance of each surround ring was higher than that of the disk that it surrounded and the stimuli were presented against a dark background. Our stimulus was similar to the one used in the classic “lightness constancy” experiments of Wallach (1948, 1963, 1976). The appearance of one of the disks—the test disk—was varied by manipulating the luminance $R_T$ of the ring surrounding that disk. The subject’s task was to adjust the luminance $D_M$ of the other disk—the matching disk—to match the two disks in their achromatic color. The luminance $D_T$ of the test disk and the luminance $R_M$ of the ring surrounding the matching disk were fixed, as was the background luminance $B$.

The data from our previous study involving decremental targets was modeled with the following achromatic color matching equation, which states the condition that should yield a match according to the edge integration model:

$$w_1 \log \frac{D_M}{R_M} + w_2 \log \frac{R_M}{B} = w_1 \log \frac{D_T}{R_T} + w_2 \log \frac{R_T}{B}.$$  

(1)

In Equation 1, $w_1$ and $w_2$ are linear weighting coefficients that determine the strengths of the induction signals originating from the inner and outer ring borders, respectively.

Solving Equation 1 for $\log D_M$ yields the following expression for the log luminance of the observer’s matching disk settings:

$$\log D_M = \log D_T + \left(1 - \frac{w_2}{w_1}\right) \log R_M - \left(1 - \frac{w_2}{w_1}\right) \log R_T.$$  

(2)

In this paper, we will be mainly interested in how the test ring luminance $R_T$ influences the matching disk luminance $D_M$. Equation 2 predicts that a log–log plot of matching disk luminance as a function of test ring luminance will be a straight line. According to the theory, the slope of the plot equals the ratio of the weight given to the outer ring edge to the weight given to the inner ring edge minus one.

A least-squares fit of Equation 2 to the achromatic color matching data from our previous study using decrements produced $r^2$ statistics in the range 0.90–0.95 for each of four psychophysical observers, with the ratio $w_2/w_1$ varying as the only free parameter of the model (Rudd & Zemach, 2004, Experiment 1). Estimates of the induction strength ratio $w_2/w_1$ were less than 1.0 for all four observers and decreased with increasing ring width (Rudd & Zemach, 2004, Experiment 2). Thus, the plots corresponding to Equation 2 in that study always exhibited negative slopes. This finding is consistent with the assumption that the edge weights $w_j$ decay with distance (Reid & Shapley, 1988; Rudd, 2001, 2003a, 2003b; Rudd & Arrington, 2001; Rudd & Zemach, 2002a, 2002b, 2003, 2004; Shapley & Reid, 1985; Zemach and Rudd, 2002, 2003). We will refer to an edge integration model that makes this ancillary assumption as the distance-dependent edge integration model. For additional ideas about the rules governing edge integration, the reader is referred to papers by Gilchrist (1988) and Ross and Pessoa (2000).

Note that our distance-dependent edge integration model predicts that the slope of the log $D_M$ versus log $R_T$ plot will lie in the range $-1 \leq$ slope $\leq 0$. The slope $-1$ corresponds to the limiting case in which the weight $w_2$ given to the outer edge is zero. The slope 0 corresponds to the limiting case in which $w_2 = w_1$; the weights given to the two edges are equal.

We next show that the distance-dependent edge integration model corresponding to Equations 1 and 2 predicts violations of the highest luminance anchoring principle, and that the predicted violations are in fact observed experimentally.

In the current study, the test and matching disks were always increments. That is, they were surrounded by rings of lower luminance. For such stimuli, according to Equation 2, it should be possible to set the luminances $D_T$ and $D_M$ of the test and matching disks to be equal, and furthermore to have both luminances be the highest luminance in the scene, and yet fail to achieve an achromatic color match, provided that $\log R_M \neq \log R_T$. This prediction of the distance-dependent edge integration
model directly contradicts the principle that the highest luminance is always perceived as white because in this case $D_M = D_T = \text{the highest luminance}$, yet $D_M$ and $D_T$ are predicted to differ in achromatic color. Not only does the distance-dependent edge integration model predict violations of the highest luminance rule; it also predicts violations of a more general principle: that any two image regions that both have the highest luminance will have the same color appearance regardless of whether that color is perceived as white or not.

It may be useful to point out that any luminance-based anchoring rule serves two different functions in a theory of lightness perception. The first function of the anchoring rule is to specify one particular luminance—the anchoring luminance—that will not vary in appearance when either the spatial structure of the image or the illuminant is varied. According to the highest luminance rule, that luminance is the highest luminance in the image. Because the appearance of the anchoring luminance is invariant with respect to changes in either the spatial image structure or the illuminant, it follows that the highest luminance regions of any two images will always match in appearance. More importantly for present purposes, the highest luminance rule also predicts that any two regions within the same image that have the highest luminance will also match.

The second function performed by any luminance-based anchoring principle is to provide a perceptual label for the invariant appearance of the anchoring luminance. According to the highest luminance rule, the anchoring luminance is seen as “white.”

Many discussions of lightness are anchoring focus on the phenomenological aspects of the problem: What is the reported appearance of a given region within the display? Thus, they focus on the second role of anchoring. For example, in an elegant study, Li and Gilchrist (1999) demonstrated that in a visual environment consisting of only two surfaces—paints having two reflectances applied to the inside of a dome inside which the observer’s head was placed—the higher reflectance always appeared white, regardless of the actual physical reflectance of the paint corresponding that had the higher reflectance. The authors interpreted their findings as supporting the highest luminance rule. But to break the highest luminance rule, it suffices to show that there exist conditions in which two patches, each having the highest luminance, do not match in appearance. In other words, it suffices to show that the appearance of the highest luminance region is not invariant with respect to changes in its spatial context. This can be accomplished using the technique of asymmetric color matching, without the need to directly address the question of phenomenology. The phenomenal appearance of the disks is important, of course, and we will revisit that topic in the Discussion.

Returning to the quantitative predictions of the distance-dependent edge integration, let us now suppose that we set $\log R_M < \log R_T$ in the disk-and-ring display. According to Equation 2, it should then be possible to choose a pair of luminance values $D_M$ and $D_T$ such that, at the match point, $D_M$ is the highest luminance in the scene, yet the achromatic color of the matching disk is determined entirely by the three luminances $D_T$, $R_M$, and $R_T$, all of which are lower than the luminance $D_M$. If the test ring luminance $R_T$, in particular, is manipulated, the distance-dependent edge integration model predicts that the test disk appearance will be subject to a contrast effect. The slope of the log $D_M$ versus log $R_T$ plot should be nonzero and negative. The highest luminance rule, on the other hand, predicts that the appearance of the highest luminance regions should be invariant with respect to changes in the test ring luminance. Thus there should be no contrast effect and the slope of the log $D_M$ versus log $R_T$ plot should be zero. If we can show that the appearance matching with increments yields a contrast effect characterized by a linear log $D_M$ versus log $R_T$ plot with a slope lying between 0 and $-1$, we will not only have provided evidence that is quantitatively consistent with the edge integration model, we will also be able to firmly reject the highest luminance anchoring rule as a general principle of achromatic color anchoring. This we do in Experiment 1.

Before presenting the details of that experiment, it is worth considering whether Gilchrist’s idea of multiple anchoring frameworks can save the highest luminance rule in the event that a contrast effect is observed. To this point, we have been assuming that the highest luminance anchoring is applied globally to the display as a whole. In other words, a single luminance serves to anchor both the test and matching disk-and-ring configurations. Another plausible hypothesis is that separate local highest luminance anchoring rules might be applied independently to the two sides of the display. Thus, a disk which is the highest luminance within its own “framework” would always appear white. We will refer to this hypothesis as local highest luminance anchoring to distinguish it from the alternative global highest luminance anchoring hypothesis.

For present purposes, we will assume that a framework comprises a single disk-and-ring configuration. The idea that achromatic color computations are made independently within the two separate disk-and-ring configurations is implicit in Wallach’s (1948, 1963, 1976) interpretation of his own achromatic color matching results. As is well known, Wallach studied achromatic color matching with disk-and-ring stimuli in which the disks were always luminance decrements with respect to their surrounds and obtained the famous result that the two disks matched in achromatic color if and only if the disk/ring luminance ratios on the two sides of the display were approximately equal (but see Rudd & Zemach, 2002a, 2002b, 2004, for evidence of systematic deviations from the ratio rule in experiments using decremental test stimuli).
Wallach explained the approximate ratio matching behavior that he observed in terms of lightness constancy. He proposed that when the disk/ring luminance ratios are equal on the two sides of the display, the observer implicitly assumes that they are two identical disk-and-ring “objects” illuminated by light sources of different intensities. The rings on the two sides of the display are seen as having equal “white” reflectances and their luminance differences are inferred by the visual system to result from unequal illumination levels on the two sides of the display. Wallach’s lightness constancy interpretation of ratio matches continues to exert a considerable influence in the contemporary lightness literature.

Applying this logic to the current experiment leads to the prediction that the two disks should both appear white regardless of whether they have the same luminance, as long as they are both increments, because they each have the highest luminance on their side of the display. Thus, if the independent frameworks hypothesis is correct and furthermore the highest luminance anchoring rule is applied strictly locally, then any incremental matching disk luminance should provide an acceptable and, in fact, equally good appearance match to the test disk. If such were the case, the subject could not reliably perform the matching task with incremental stimuli.

Whether anchoring is applied globally to the entire image, or locally within separate frameworks, the highest luminance anchoring rule predicts that the test and matching disks in the current study should, at the very least, match in achromatic color when their luminances are equal. In contrast, the distance-dependent edge integration model (Equation 2) predicts that lightness matches will be obtained if and only if the test disk luminance and the matching disk luminance are unequal, provided that the luminances of their respective surround rings are also unequal. The predictions of the distance-dependent edge integration model thus contradict those of the highest luminance anchoring theory regardless of whether the highest luminance rule is assumed to apply globally or locally within separate frameworks.

Gilchrist’s Anchoring Theory hypothesizes that individual regions of a display, such as our test and matching disks, may group to varying degrees with either local or global stimulus configurations in a way that depends on the Gestalt principle of belongingness. But as the preceding arguments demonstrate, the highest luminance principle is fundamentally at odds with the predictions of the distance-dependent edge integration theory, regardless of the degree of local or global grouping assumed by any particular instantiation of the belongingness principle. The distance-dependent edge integration model thus also contradicts Anchoring Theory. It follows that a test of the two different hypotheses—highest luminance anchoring versus distance-dependent edge integration—is possible and that the test can be made independently of assumptions about the degree to which anchoring is local versus global.

Experiment 1. Simultaneous contrast with increments: varying the luminance of the immediate surround

The purpose of Experiment 1 was to pit the highest luminance anchoring rule against the distance-dependent edge integration model. To accomplish this, a naive matching experiment was carried out with incremental disks. The luminance of the ring surrounding the incremental test disk was manipulated as the independent variable. The observer’s task was to adjust the luminance of the matching disk to obtain an achromatic color match between the two disks. The experimental question was whether the match would be independent of surround luminance, as predicted by the highest luminance rule, or whether a contrast effect would be observed, consistent with Equation 2 and as predicted by the distance-dependent edge integration model.

General methods

The experimental stimuli in both experiments consisted of disk-and-ring patterns (Figures 1 and 3) presented side-by-side on an Apple cinema display, a 22-in. LCD computer monitor. The stimuli were viewed in a dimly lit room, the walls of which were covered with a matte black material. Stimuli were generated using the MATLAB Psychophysics Toolbox (Brainard, 1997; Pelli, 1997) running on an Apple G4 computer.

A photometer (Photo Research PR-650) was used to measure screen luminance at each of 256 achromatic RGB levels. The display was linearized through the use of a lookup table.

Figure 1. Diagram of the visual stimulus used in Experiment 1.
The displays were viewed binocularly from a distance of 0.87 m. Head position was maintained using a chin rest. The observers were otherwise allowed free viewing.

The observer’s task was to adjust the luminance of the left disk (the matching disk) to achieve an achromatic color match between that disk and the right disk (the test disk) as a function of the test ring surrounding the test disk. The luminances of the incremental test and matching disks were always higher than the luminances of their surround rings.

In Experiment 1, the luminance of the test ring was manipulated as the independent variable. In Experiment 2, the test disk was surrounded by two concentric rings. The luminance of the outer test ring was manipulated as the independent variable. The outer test ring luminance was always less than the inner test ring luminance, which was fixed throughout the experiment. The luminances of the test disk and the single matching ring also remained fixed throughout the course of each individual experiment.

The psychophysical observers were all experienced at achromatic color matching, but they were naïve with respect to the experimental hypotheses being tested, except for observers MER and IKZ, the authors of this report, who were aware of the hypotheses. Observer IKZ participated in Experiment 2 only. Observer MER participated in Experiment 3 only.

**Methods—Experiment 1**

A diagram of the stimulus is presented in Figure 1. The stimulus consisted of a test disk and a matching disk, each having a radius of 0.35°, each surrounded by a ring that was 0.35° wide. The center-to-center distance between the disks was 8.5°.

The test disk luminance \( D_T \) was fixed throughout all experiments at the value 3.16 cd/m\(^2\) (log \( D_T = 0.50 \)) and the matching ring luminance \( R_M \) was fixed at the value 1.00 cd/m\(^2\) (log \( R_M = 0 \)). The background field luminance \( B \) was 0.10 cd/m\(^2\) (log \( B = -1.00 \)).

The independent variable was the test ring luminance \( R_T \). \( R_T \) was varied from 0.501 to 1.78 cd/m\(^2\) (−0.3 to 0.25 log units) in six equal RGB unit steps. In each block of trials, each of the six \( R_T \) values was presented six times. The order of the 36 trials within a block was randomized separately for each block of trials.

Three paid psychophysical observers participated in the experiment. All three were female graduate students in their mid-20s. All three were compensated for their participation in the study, either by a financial reward or as part of a trade for psychophysical observer hours on experiments they were running. Observer LT was an experienced psychophysical observer, but she was not aware of the experimental hypotheses. Observers JL and AD were inexperienced observers and were naïve with respect to the hypotheses tested. Observers JL and LT ran three blocks of trials each. Observer AD ran two blocks.

**Results—Experiment 1**

In Figure 2, the observers’ log matching disk settings are plotted as a function of the logarithm of the test ring luminance. The solid lines in the plot correspond to the least-squares linear regression fits to the data. For all three subjects, the appearance of the test disk was influenced by the luminance of its surround ring despite the fact that the test ring luminances were always less than the luminance of the test disk. The matching disk luminance decreased with increasing test ring luminance, indicating that the appearance of the test disk was subject to a contrast effect.

The estimated intercepts \( \beta_0 \) and slopes \( \beta_1 \) obtained from the least-squares fits, along with their associated standard errors, are AD: \( \beta_0 = 0.497 ± 0.004 \) log cd/m\(^2\), \( \beta_1 = -0.358 ± 0.020 \); JL: \( \beta_0 = 0.527 ± 0.002 \) log cd/m\(^2\), \( \beta_1 = -0.237 ± 0.010 \); and LT: \( \beta_0 = 0.563 ± 0.003 \) log cd/m\(^2\), \( \beta_1 = -0.54 ± 0.014 \). The percentages of variance accounted for by the linear regression models are 82.2% (AD), 82.8% (JL), and 10.8% (LT). (Note: the small percentage of variance accounted for in the case of observer LT is due to the small slope of her log \( D_M \) versus log \( R_T \) function, which is nevertheless significantly different from zero.)

The absolute value of the slopes of the lines plotted in Figure 2 provides a measure of the magnitude of the contrast induction from the surround for each observer. A slope of zero (flat line) would indicate no contrast effect. A slope of −1 would indicate ratio matching behavior: a large contrast effect.
The global highest luminance matching predicts a luminance match for these incremental targets independent of the test ring luminance. A luminance match corresponds to a linear model having intercept \( b_0 = 0.5 \) log units and slope \( b_1 = 0 \) (dotted line in Figure 2).

The hypothesis that the true slope equals zero is rejected for all three observers (AD: Student's \( t_{0.05} = -17.966, p < 0.0001 \), two tailed; JL: \( t_{106} = -22.611, p < 0.0001 \), two tailed; LT: \( t_{106} = -3.580, p = 0.0005 \)). The hypothesis that the true intercept equals 0.5 log units is also rejected for observers JL and LT (AD: \( t_{0.05} = -0.784, p = .435 \), two tailed; JL: \( t_{106} = 13.425, p < .0001 \), two tailed; LT: \( t_{106} = 21.877, p < .0001 \), two tailed). The predictions of the global highest luminance anchoring rule are thus strongly disconfirmed by the data from Experiment 1.

The distance-dependent edge integration model predicts that the \( \log D_M \) versus \( \log R_T \) plots in Figure 2 should be straight lines having negative slopes lying between 0 and \(-1\) (Equation 2). Note that the model does not predict a specific negative slope because the ratio \( w_2/w_1 \) of the weights given to the two edges in the lightness computation is allowed to vary as a free parameter of the model.

The distance-dependent edge integration model predicts that increasing the luminance of the test surround ring should decrease the subjective intensity of the test disk, leading to a decrease in the matching disk luminance required for a match (contrast effect). This prediction is confirmed by the statistical tests, which indicate that the estimated slopes deviate from zero in the predicted direction for all three observers (AD: \( t_{0.05} = -17.966, p < 0.0001 \), one tailed; JL: \( t_{106} = -22.611, p < 0.0001 \), one tailed; LT: \( t_{106} = -3.580, p = 0.0003 \)).

According to the model (Equation 2), the slope of the \( \log D_M \) versus \( \log R_T \) plot provides an estimate of the quantity \( \frac{w_2}{w_1} - 1 \). The least-squares estimates of the induction strength ratios \( w_2/w_1 \) for the three subjects are thus \( 0.642 \pm 0.020 \) (AD), \( 0.763 \pm 0.010 \) (JL), and \( 0.946 \pm 0.015 \) (LT).

The distance-dependent edge integration model also predicts that the intercept of the least-squares linear model of the \( \log D_M \) versus \( \log R_T \) plot should equal \( \log D_T = 0.500 \) log units (because \( \log R_M = 0 \) in this experiment) (Equation 2). The best estimates of the intercepts for the three subjects were as follows: \( 0.497 \pm 0.004 \) cd/m\(^2\) (AD); \( 0.527 \pm 0.002 \) cd/m\(^2\) (AD); \( 0.563 \pm 0.003 \) cd/m\(^2\) (LT). The hypothesis that \( \log D_T = 0.500 \) cd/m\(^2\) was statistically rejected for observers JL and LT. Both of these observers set the matching disk luminance to be higher than the value predicted by the edge integration model. The percent error in \( \log D_M \) relative to the predicted value was 6.4% for observer JL and 15.6% for observer LT.

In later experiments performed with this equipment, we found that the luminances of both the matching disk and the matching ring were about 0.057 log units lower than the luminance values specified in the lookup table. The difference was due to spatial nonuniformities in the luminance of the LCD monitor and was not discovered until after the experiment was completed and our equipment had been recalibrated. Based on our later measurements, we estimate that values of both \( D_M \) and \( R_M \) were about 0.057 log units lower than the values reported above, but that the values of \( D_T, R_T \) and \( B \) were consistent with the values given above. The revised luminance estimates imply that the right side of the display was, in fact, about 14% more luminant than the left side. However, the estimates should be considered approximate. In light of this fact, an adjustment of the luminance values of about this magnitude is probably appropriate.

Importantly, decreasing the values of \( D_M \) and \( R_M \) both by 0.057 log units (or by any other amount) does not affect any of the conclusions stated above regarding the predicted or estimated slopes of the matching functions. However, the intercept predictions are affected. After making the correction, the highest luminance rule predicts that the intercept should be 0.557 log cd/m\(^2\). As a consequence, the horizontal dotted line in Figure 2, representing the prediction of the highest luminance anchoring rule, should be redrawn at a height of 0.557 log cd/m\(^2\) on the y-axis.

If \( D_M \) and \( R_M \) are both decreased by 0.057 log units, the distance-dependent edge integration model (Equation 2) predicts that the intercept should differ for the three subjects: 0.537 (AD), 0.543 (JL), and 0.554 (LT) log cd/m\(^2\). Thus, the distance-dependent edge integration model predicts that the matching function intercepts should be positively correlated with the matching function slopes. This pattern is, in fact, observed in the data (\( r = .999, p = .016, n = 3 \)).

Rewriting Equation 2 to incorporate the luminance correction yields the modified matching equation

\[
\log D_M - cf = \log D_T + \left(1 - \frac{w_2}{w_1}\right)(\log R_M - cf) \\
- \left(1 - \frac{w_2}{w_1}\right)\log R_T. 
\] (2a)

Setting \( \log R_M \) equal to zero in Equation 2a, and moving the correction factor \( cf \) on the left side of the equation to the right side yields

\[
\log D_M = \log D_T + cf\left(1 - \frac{w_2}{w_1}\right) - \left(1 - \frac{w_2}{w_1}\right)\log R_T. 
\] (2b)

Note that Equation 2b predicts that, if the intercept of the \( \log D_M \) versus \( \log R_T \) function is regressed against the slope of the \( \log D_M \) versus \( \log R_T \) function, the intercept of the least-squares regression line should equal \( \log D_T + cf \) and the slope should equal \( cf \). In the present experiment, \( \log D_T = 0.5 \), so the intercept of the least-squares regression line is predicted to be 0.557 and the slope is predicted to be 0.057. Note that these predictions follow only if the
edge integration model and the correction factor are both assumed to be correct.

We performed this linear regression analysis on the data from the three observers in Experiment 1 and obtained an intercept estimate of 0.556 and a slope estimate of 0.057. This result is consistent with a correction factor of 0.056 or 0.057, as predicted. The edge integration model thus did an excellent job of predicting the relationship between the intercepts and the slopes of the log $D_M$ versus log $R_T$ function for the data from the three observers in Experiment 1 after correcting for the unequal luminances on the two sides of the display.

If the values of $D_M$ and $R_M$ are not adjusted on the basis of the estimated differences in the luminances on the two sides of the display, then the highest luminance rule and the distance-dependent edge integration model make identical predictions regarding the intercept of the log $D_M$ versus log $R_T$ plot. Thus, in the absence of a luminance adjustment the observed intercepts cannot be used to discriminate between the models. However, the slope results still support the edge integration model over the highest luminance rule.

If the luminance adjustment is not made, then the only sensible interpretation of the observed violations of the intercept predictions is in terms of a bias on the part of two of our subjects to judge the right disk as having the higher subjective intensity. Such observer bias violates both models.

Due to the uncertainties regarding the exact magnitude of any the luminance differences on the two sides of the screen, we discuss tests of the slope predictions only in our presentation of the results of Experiment 2. We evaluate intercept predictions again in Experiment 3, where we can confidently report the luminances on both sides of the display.

Experiment 2. Simultaneous contrast with increments: varying the luminance of a nonadjacent region

The results of Experiment 1 indicate that naïve appearance matches performed with incremental targets—like those performed with decremental targets—are subject to a simultaneous contrast effect (see also Bressan & Actis-Grosso, 2001, for corroborating evidence). Classical accounts of simultaneous contrast ascribe the effect either to the local contrast at the border between the target and its surround, or to some other form of spatial comparison of the target and its immediate surround. On either of these accounts, no other borders or regions in the display would be expected to influence the test disk appearance.

Edge integration theories, on the other hand, assert that the color of the test disk is determined by a sum of induction signals originating from multiple borders within the display. Thus, the contrast at the border at the outer edge of the surround ring in the disk-and-ring stimulus should also make a contribution to the achromatic color of the disk (Reid & Shapley, 1988; Rudd, 2001; Rudd & Arrington, 2001; Shapley & Reid, 1985). In our past work using decremental targets, we obtained results consistent with the idea that remote borders also influence the test disk appearance (Rudd & Arrington, 2001; Rudd & Zemach, 2004). This hypothesis has not previously been tested with incremental targets.

In Experiment 2, observers performed naïve matches with a stimulus in which the test disk was surrounded by both an inner ring, immediately adjacent to the disk, and an outer, nonadjacent, ring that surrounded the inner ring. The test disk was always an increment with respect to the inner ring and the inner ring was always an increment with respect to the outer ring.

The luminances of the test disk and the inner ring were both held constant throughout the experiment and the test disk appearance was manipulated by varying the luminance of the outer ring (i.e., the height of lowest tier of the wedding cake). To match the two disks in appearance, the observer adjusted the luminance of an identical matching disk surrounded by a single matching ring having the same radius as the outer test ring. A diagram of the stimulus configuration is presented in Figure 3.

The goal of Experiment 2, like that of Experiment 1, was to pit the predictions of the highest luminance anchoring rule against those of the distance-dependent edge integration model. According to the global highest luminance anchoring rule, the disks should match in achromatic color if and only if they both have the same global highest luminance. Thus, an achromatic color match should be equivalent to a luminance match.
According to the local highest luminance anchoring rule—that is if the disk achromatic colors are instead anchored to the local highest luminances within each of the two disk-and-ring frameworks—the disks should match as long as they are constrained to be increments, regardless of whether they match in luminance. As long as the disks are each the highest luminance within their respective frames, they should both appear “white” and therefore equal in appearance. The local highest luminance rule therefore does not make a single-valued prediction with respect to the matching disk luminance that will result in a match; an achromatic color match would result from any of an infinite number of matching disk luminances.

For present purposes, the most important conclusion is that the local highest luminance rule, like the global highest luminance rule, predicts that the observer’s matching disk settings should not be influenced by the luminance of the outer test ring as long as the luminance of the outer test ring is constrained to be lower than the luminances of the test and matching disks. This last prediction should hold if the highest luminance rule holds, regardless of whether the highest luminance rule is applied globally or locally.

According to the distance-dependent edge integration model, on the other hand, the two disks should match in achromatic color if and only if the summed contributions of the edge induction weights to the achromatic color computation are equal on the two sides of the display. For the display used in Experiment 2 (Figure 3), matches should occur when

$$w_1 \log \frac{D_M}{R_M} + w_3 \log \frac{R_M}{B} = w_1 \log \frac{D_T}{R_1T} + w_2 \log \frac{R_1T}{R_2T} + w_3 \log \frac{R_2T}{B}$$

(Rudd & Zemach, 2004), where $R_1T$ and $R_2T$ are the luminances of the inner and outer test rings, and the subscripts on the $w_i$ coefficients signify the distances between the borders with which they are associated and the corresponding test or matching disk perimeter: $w_1$ stands for $w(0^\circ)$; $w_2$ stands for $w(0.35^\circ)$; and $w_3$ stands for $w(0.70^\circ)$.

Equation 3 has been solved (Rudd & Zemach, 2004) to obtain the following expression for $\log D_M$ in terms of the other variables and parameters in the equation

$$\log D_M = \log D_T + \left(1 - \frac{w_3}{w_1}\right) \log R_M - \left(1 - \frac{w_2}{w_1}\right) \log R_1T - \left(\frac{w_2 - w_3}{w_1}\right) \log R_2T.$$  

Equation 4 predicts that a log–log plot of an observer’s matching disk settings versus the outer test ring luminance should be a straight line, having a slope equal to $-\left(\frac{w_2 - w_3}{w_1}\right)$.

Because, according to the distance-dependent edge integration model, the magnitudes of the edge induction weights $w_i$ are assumed to decay spatially with distance (Rudd, 2001, 2003a, 2003b; Rudd & Arrington, 2001; Rudd & Zemach, 2002a, 2002b, 2004; Zemach & Rudd, 2002, 2003), we expect that $w_2 > w_3$. The model therefore predicts that the slope of the log $D_M$ versus log $R_T$ plot will be negative.

Thus, in contradiction to both the global and local highest luminance anchoring hypotheses and any theory that postulates a compromise between global and local highest luminance anchoring, the distance-dependent edge integration model predicts that the observers’ matches will be influenced by the luminances of regions that are not the region of highest luminance within the image, and that in fact have lower luminances than those of either of the disks that are involved in the match. This prediction was tested in Experiment 2.

Methods—Experiment 2

A diagram of the visual stimulus used in Experiment 2 is presented in Figure 3. The test and matching disks each had a radius of 0.35°. The test disk was surrounded by two rings: an inner and an outer test ring, each of which was 0.35° wide. The matching disk was surrounded
Results—Experiment 2

In Figure 4, the observer’s log matching disk settings are plotted as a function of the logarithm of the outer test ring luminance. The colored lines in the plot correspond to the least-squares linear regression fits to the data from each of the two observers. The intercepts $\beta_0$ and slopes $\beta_1$ of the best-fit linear models, along with their associated standard errors, are IKZ: $\beta_0 = .101 \pm .012$ log cd/m$^2$, $\beta_1 = -.097 \pm .019$; KS: $\beta_0 = .124 \pm .010$ log cd/m$^2$, $\beta_1 = -.155 \pm .016$. The amount of variance accounted for by the least-squares regression models is 26.4% (IKZ) and 46.1% (KS).

According to the global highest luminance anchoring rule, for the test and matching disks to match in achromatic color, the luminances of the two disks should match. A luminance match corresponds to a linear model having slope $\beta_1 = 0$ (dotted line in Figure 4). The hypothesis that $\beta_1 = 0$ is statistically rejected for both observers (IKZ: $t_{70} = -8.372, p < .0001$ two tailed; KS: $t_{106} = -12.326, p < .0001$, two tailed). The predictions of the global highest luminance rule are thus strongly disconfirmed by the data from Experiment 2.

The distance-dependent edge integration model (Equation 4) predicts that the log $D_M$ versus log $R_{2T}$ plots in Figure 3 should be straight lines having negative slopes. An increase in the outer test ring luminance should darken the appearance of the test disk, leading to a decrease in the luminance of the matching disk required for a match (contrast effect). This prediction is confirmed. A statistical test indicates that the observed slopes deviate from zero in the predicted direction (IKZ: $t_{70} = -8.372, p < .0001$ one tailed; KS: $t_{106} = -12.326, p < .0001$, one tailed).

![Figure 5](https://jov.arvojournals.org/pdfaccess.ashx?url=/data/journals/jov/932833/) Figure 5. Results of Experiment 2. Matching disk settings required to achieve a lightness match to the test disk as a function of the luminance of the test ring. The horizontal black line indicates the luminance of the test disk and thus the matching disk setting corresponding to a luminance match. This is also the setting predicted by the global highest luminance rule. The vertical black line indicates the luminance of the matching ring. The diagonal line is the prediction of a ratio match. Further details of the matching procedure are provided in the text.

Experiments 1 and 2 demonstrate that achromatic color judgments carried out with incremental targets are subject to contrast effects and therefore that the highest luminance rule cannot hold for these judgments. It might be argued, however, that these experiments do not speak to the issue of whether the highest luminance rule applies to lightness perception per se because the observers in these experiments were not specifically instructed...

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by a single ring that was 0.70° wide. The center-to-center distance between the test and matching disks was 8.5°.

The test disk luminance $D_T$ was fixed throughout all experiments at the value 1.02 cd/m$^2$ (log $D_T = 0.01$). The inner test ring luminance $R_{1T}$ was fixed at the value 0.50 cd/m$^2$ (log $R_{1T} = -0.30$), that is, 0.30 log units below the luminance of the test disk. The matching ring luminance $R_M$ was fixed at the value 0.16 cd/m$^2$ (log $R_M = -0.80$). The background field luminance $B$ was 0.10 cd/m$^2$ (log $B = -1.00$).

The luminance $R_{2T}$ of the outer test ring was varied as the independent variable from 0.158 to 0.398 cd/m$^2$ (−0.8 to −0.4 log cd/m$^2$) in six equal RGB unit steps, that is, from 0.8 to 0.4 log units below the test disk luminance and from 0.5 to 0.1 log units below the inner ring luminance.

Each block of experimental trials consisted of six presentations of each of the six outer test ring luminances. The order of the 36 trials was randomized separately for each block of trials.

The observer’s task was to adjust the matching disk luminance $D_M$ to achieve an achromatic color match to the test disk as a function of the outer test ring luminance $R_{2T}$.

Two female graduate students, both in their mid-20s, served as psychophysical observers. Observer KS was an inexperienced psychophysical observer and she was also naive with respect to the experimental hypotheses. She received monetary compensation for her participation in the study. Observer IKZ, the second author of this paper, was an experienced observer and was aware of the hypotheses. Observer KS completed three blocks of trials. Observer IKZ completed two blocks of trials.
to judge lightness (i.e., perceived reflectance). Instead, they may have been judging some other attribute of achromatic color, for example brightness (i.e., perceived luminance).

Experiment 3 was carried out to pit the highest luminance anchoring principle against the distance-dependent edge integration model for judgments of lightness, specifically. The experiment was modeled after an experiment by Arend and Spehar (1993a). The observers were instructed to imagine that disks and rings were made of paper and that the disk-and-ring configuration on the test side of the display was illuminated by a light source having an intensity that varied independently of the intensity of the light source that illuminated the disk-and-ring configuration on the matching side of the display. They were further instructed to think of changes in the test ring luminance as resulting from changes in the illumination on the test side of the display; that is, the illumination falling on both the test ring and the test disk. Their task was to adjust the luminance of the matching disk to make the disk-and-ring configurations on the two sides of the display look like identical papers lit by potentially different illuminants.

As first pointed out 60 years ago by Wallach, lightness matches should ideally be equivalent to ratio matches when the observer assumes that the illuminants on the two sides of the display are independent. However, in our experiment—unlike the situation in which the target disks are decrements with respect to the surround ring—the only way that an observer who is asked to adjust the matching disk luminance could produce ratio matches when the luminances of the test and matching rings are unequal is by making the disk luminances unequal. Thus, unlike the constraints governing matches when the targets are decrements, here ratio matching is fundamentally at odds with the highest luminance anchoring rule.

Methods—Experiment 3

The methods Experiment 3 were identical to those of Experiment 1, but with changes in the ring luminances resulting from a recalibration of the equipment. The matching ring luminance \( R_T \) was fixed at the value 0.773 cd/m\(^2\) (−0.112 log units). Matches were performed at six \( R_T \) levels: 0.472, 0.585, 0.735, 1.030, 1.333, and 1.589 cd/m\(^2\) (−0.326, −0.233, −0.134, 0.013, 0.125, and 0.201 log cd/m\(^2\)). As in Experiment 1, the test disk luminance \( D_T \) was fixed at the value 3.16 cd/m\(^2\) (log \( D_T = 0.500 \)) and the background field luminance \( B \) was fixed at 0.10 cd/m\(^2\) (log \( B = −1.00 \)).

The instructions were also altered, as explained above.

Results—Experiment 3

The slopes of the log \( D_M \) versus log \( R_T \) plots in Figure 5 provide an important test of the highest luminance rule. If the highest luminance rule is a universal principle of lightness anchoring, the slopes of these plots should be zero. This prediction is strongly violated for both observers (AH: \( t_{106} = −16.542, p < .0001 \), two tailed; MER: \( t_{106} = −29.638, p < .0001 \), two tailed). The actual slopes were about −.75 for both observers (AH: \( −.725 ± .044 \); MER: \( −.780 ± .026 \)), which indicates a large magnitude contrast induction from the surround. A ratio match would be indicated by a slope of −1, as illustrated by the diagonal black line shown in the figure.

Clearly, both observers’ lightness matches were more consistent with the ratio matching behavior than with the luminance matching behavior predicted by the highest luminance rule. However, the actual slopes for both observers were shallower that the slope of −1 predicted by the ratio rule (AH: \( t_{106} = 6.275, p < .0001 \), one tailed; MER: \( t_{106} = 8.359, p < .0001 \), one tailed).

The distance-dependent edge integration model (Equation 2) predicts that the data plots in Figure 5 should consist of straight lines having negative slopes lying between 0 and −1. The observed slopes deviate from zero in the predicted direction (IKZ: \( t_{106} = −8.372, p < .0001 \) one tailed; KS: \( t_{106} = −12.326, p < .0001 \), one tailed). We thus conclude that the results of this lightness matching experiment, like those of the naive matching Experiments 1 and 2, are consistent with the distance-dependent edge integration and inconsistent with the highest luminance rule.

The least-squares estimate of the induction strength ratio \( \omega_2/\omega_1 \) is given by the quantity \( 1 + \beta_1 \), where \( \beta_1 \) is the estimated slope of the log \( D_M \) versus log \( R_T \) plot (Equation 2). The estimated value of \( \omega_2/\omega_1 \) for observer AH is \( .257 ± .044 \) and for observer JA it is \( .220 ± .026 \).

Experiment 3 was performed after we discovered and measured the discrepancies in the luminances on the two sides of the screen (as described in the Results section of Experiment 1), so we are also able to test predictions regarding the intercepts of the matching functions for this experiment. The highest luminance rule predicts that the intercepts of the plots in Figure 5 should be 0.5 and the distance-dependent edge integration model (Equation 2) predicts that the intercept for observer AH should be \( .419 ± .005 \) and for observer MER, the intercept should be \( .475 ± .003 \). The actual intercepts were \( .435 ± .009 \) (AH) and \( .450 ± .005 \) (MER).

The actual intercepts deviate from the predictions of the distance-dependent edge integration model by several times the standard error of the difference between the means, so the edge integration model is clearly violated. Nevertheless, the intercepts are much closer to the predictions of the edge integration model than they are to those of the highest luminance rule.
The results of the experiments reported here demonstrate that two regions of a visual display—in this case the test and matching disks—can both have the highest luminance in their local region, or even the highest luminance in the global display, and yet differ in achromatic color. The results of Experiment 3 furthermore demonstrate that two regions can both have the highest luminance and yet differ in lightness, specifically. The results of all three experiments violate the highest luminance anchoring principle, which asserts that the regions of highest luminance in the scene will all appear white and thus equal, independent of the spatial context in which they are viewed.

The violations of the highest luminance rule observed in our experiments resulted from differences in the luminances of the rings surrounding the disks on the two sides of the display. Because the ring luminances were always lower than the luminances of the disks they surrounded, our results demonstrate that the achromatic color of a high luminance region in an image can be influenced by contrast induction from less luminant display elements.

The results of Experiments 1 and 3 show that the achromatic color of a highest luminance region can be influenced by a lower luminance region that is directly adjacent to the highest luminance region. The results of Experiment 2 show that the achromatic color of a highest luminance region can be influenced by a lower luminance region that is not adjacent to the highest luminance region. The results of Experiment 2 not only contradict the highest luminance rule; they also cannot be accounted for by the local contrast at the disk/ring border. To explain the results of Experiment 2, a theory of long-range induction is required. If the induction effects are assumed to originate from edges, then the theory must specify a mechanism for perceptual edge integration. In any case, the results indicate the need for a better model of achromatic color anchoring.

The data from the three experiments were compared to the predictions of a quantitative edge integration model which assumes that achromatic color is computed from a weighted sum of log luminance ratios at borders. We used traditional disk-and-ring stimuli in our experiments because the use of such stimuli allowed us to pit the highest luminance rule directly against this distance-dependent edge integration model, which has previously been shown to account for achromatic color matches carried out with decremental targets (Rudd, 2001, 2003a; Rudd & Arrington, 2001; Rudd & Zemach, 2004).

The edge integration model did a better job of accounting for the current experimental results than did the highest luminance rule. Contrary to the predictions of the highest luminance rule, the edge integration model correctly predicted that (1) matching disk luminance would decrease with increases in the test surround luminance (contrast), and more specifically, (2) the log luminance of the matching disk would decrease linearly with increases in the log luminance of the test surround. Thus, the distance-dependent edge integration model not only successfully predicted the existence of violations of the highest luminance rule that depend on the intensities of lower luminance regions in the surround, it also successfully predicted the direction of these effects and some of their mathematical properties.

Stated quantitatively, the model successfully predicted that the slopes of the empirical log $D_M$ versus log $R_T$ functions—or log $D_M$ versus log $R_2T$ functions in Experiment 2—would be negative, as was found in all three experiments and for all observers.

For two of the observers Experiment 1, statistically significant discrepancies were found between the intercept estimates obtained from the observers’ log $D_M$ versus log $R_T$ plots and the intercept predicted by the edge integration model. Both of these observers set the luminance of the matching disk to be higher on average than was predicted by the model: by 0.027 log units for one observer, and by 0.063 log units for the other. As explained in the Results section, we believe that this was the result of an actual luminance difference on the two sides of the display. After estimating the magnitude of this difference from measurements taken after the experiment was completed and making the appropriate adjustments, we obtained a revised prediction of the distance-dependent edge integration model regarding the intercepts. The model predicts that there should be a positive correlation between the intercepts and the slopes of the matching function. This pattern was, in fact, seen in the data from Experiment 1. In Experiment 3, where no luminance correction was required, the observed slopes and intercepts of the matching function were both found to be in closer agreement with the predictions of the distance-dependent edge integration model than with the predictions of the highest luminance rule.

Some mention should be made of the high between-subjects variability in the slopes of the matching functions obtained in Experiment 1 (naïve matching), and of the fact that the slopes obtained in this experiment were generally shallower than those obtained in Experiment 3, where the observers were instructed to match on lightness but the stimulus was nearly identical to the one used in the naïve matching experiment. If the results of both of these experiments are to be explained solely based on single distance-dependent edge integration, then it must be assumed that the weights given to edges in the edge integration process are variable and can be task dependent. This conclusion follows from the fact that the best estimates of the edge weight ratio $w_2/w_1$, as determined by the theoretical matching Equation 2, varied between 0.642 and 0.946 for the three observers in Experiment 1, but were about 0.25 for both observers in Experiment 3.

The implication seems to be that the weights assigned to the edges by edge integration process can be dynamically...
adjusted by a top-down attentional mechanism. Dynamical weight setting based on attentional factors makes sense from a functional point of view because different weight ratios are appropriate for different tasks. For example, in Experiment 3, our subjects were instructed to judge lightness and to think of changes in the test ring luminance as being due to changes in the illumination on the test side of the display only. Given these instructions, our subjects should ideally have performed ratio matches (Gilchrist et al., 1999; Wallach, 1948, 1963, 1976). The matches made in Experiment 3 did not conform exactly to ratio matches (i.e., slopes of -1), but the actual slopes of -0.725 and -0.780 obtained in this experiment were closer to ratio matches than were the matches made in Experiment 1 (naïve matches), where the empirical slopes were -0.54, -0.237, and -0.358. In Experiment 1, the matching instructions were ambiguous and did not necessarily call for ratio matches. We suggest that the subjects in Experiment 3 made an effort to adjust the weights assigned to edges in order to perform the implicit ratio matching task, but for some reason they could not completely discount the outer edge of the ring, which is what would be required to achieve a perfect ratio match if the edge integration model is correct.

This raises the question of what the observers thought they were supposed to be doing in Experiment 1, where their matching slopes were more variable and, on average, shallower, and their hypothetical edge weight ratios were thus more variable and closer to unity. One plausible idea is that the observers in Experiment 1, when confronted with the naïve matching task, were uncertain about the particular dimension of achromatic color that they were supposed to judgment: say, whether they were supposed to judge lightness (perceived reflectance) or brightness (perceived luminance). Brightness judgments would ideally produce flat slopes, that is, luminance matches. Thus, the variable and somewhat shallow slopes observed in Experiment 1 may have resulted from judgments that were a composite of lightness and brightness judgments.

Another possibility is that the subjects in Experiment 1 were trying to make lightness matches, but that the three subjects interpreted differently, and ambiguously, the meaning of the test ring luminance manipulations. If changes in the test ring luminance were interpreted as signifying changes in the ring reflectance instead of changes in illumination on the test side of the display, then these changes should ideally have not affected the lightness (i.e., the perceived reflectance) of the test disk. If the test ring manipulation was interpreted as a reflectance manipulation, an ideal observer would match the disks in luminance, just as they would if they were matching the disks in brightness. If the subjects in Experiment 1 were uncertain about the meaning of the ring luminance manipulations—as being due either to a reflectance change or a luminance change—then they may have stuck a compromise between luminance matching and ratio matching; hence the intermediate slopes. This latter explanation has something of the flavor of Gilchrist’s Anchoring Theory in that it assumes that the test disk can be seen as belonging either to the framework of the test ring, whose luminance signals the value of a variable illuminant on the test side of the display, or to the global framework of the display, in which the illumination is assumed to be fixed.

It follows that the intermediate and variable slopes observed in Experiment 1 may have resulted from uncertainty concerning either the achromatic color dimension that was supposed to be matched (i.e., brightness versus lightness) or the meaning of changes in the test ring luminance, as resulting from either a reflectance change on a change in the test side illuminant. These ideas are pursued experimentally and in more detail in a follow-up study, the results of which are currently being prepared for publication (Rudd et al., 2005).

Note that neither of these interpretations conflict with the hypothesis that the achromatic color judgments made in our experiments are based on a single underlying distance-dependent edge integration, as long as the weights applied to the edges in the edge integration process are assumed to be variable. Other hypotheses, such as separate neural mechanisms for brightness and edge-integration-based lightness judgments are also plausible. An important goal of future research would be to try to find a way to decide between the hypothesis of a single distance-dependent edge integration mechanism with variable weights and the alternative hypothesis of multiple underlying mechanisms using either psychophysical and neurophysiological approaches.

**Edge integration and anchoring**

If the anchoring stage of the achromatic color computation follows earlier neural stages involving edge extraction and edge integration, as proposed by ourselves and others (Arend & Goldstein, 1987; Blake, 1985; Bruno, 1994; Bruno et al., 1997; Gilchrist, 1988; Gilchrist, Delman, & Jacobsen, 1983; Horn, 1974; Hurlbert, 1986; Land, 1977, 1983, 1986a, 1986b; Land & McCann, 1971; Reid & Shapley, 1988; Shapley & Reid, 1985; Rudd, 2001; Rudd & Arrington, 2001; Rudd & Zemach, 2004; Whittle & Challands, 1969), then the anchoring stage of achromatic color computation has no direct access to information about luminance. Instead, it has access only to the neural representation of the retinal image formed as the output of the edge integration process. The original edge integration theory—the Retinex theory of Land and McCann—was designed to accurately reproduce the ratio scale of luminances seen by the retina at the output of the edge integrator. To accomplish this, Land and McCann assumed that edges were perfectly integrated across space. In mathematical terms, this means that the log luminance ratios computed at local edges are summed across space with equal weights.
To the extent that edge integration is instead imperfect, or subadditive—as our distance-dependent edge integration model proposes and our data prove that it must be if edge integration is a reality—the neural image that is formed by the output of the edge integrator, prior to anchoring, will deviate from the actual pattern of luminances impinging on the retina.

According to the distance-dependent edge integration model, regions of the retinal image that have identical luminances can produce different edge integrator outputs (Equation 2). And conversely, regions of the retinal image that have different luminances can produce identical edge integrator outputs. These model properties hold regardless of whether the region of interest is a region of highest luminance. Distortions of the retinal luminance profile occur in the edge integrator output because distance-dependent edge integration irrevocably confounds the luminances of any given region with the luminances of nearby regions. In effect, the distance-dependent edge integration mechanism strikes a compromise between the perfect achromatic color constancy with respect to spatial context that would result from perfect edge integration and the extreme susceptibility to local contrast that would result in the absence of any edge integration whatsoever (see Gilchrist, 1988, for a similar argument made in a different context). The subadditive edge integration property is alone sufficient to explain the key findings in the present study.

Because our results are explained by the mathematical properties of distance-dependent edge integration process alone, and the judgments in our study were all based on matches and not on reports of perceived achromatic color per se, one might legitimately wonder whether any insights about anchoring can be gained from our study, other than that the highest luminance rule is inadequate. Our data cannot by themselves answer the question of what is the correct anchoring rule, but we believe that they can be incorporated with data from previous experiments to help arrive at an answer to this question.

When the anchoring problem is viewed from a neural perspective, it is evident that there must be a mapping rule (Teller & Pugh, 1983; Teller, 1984) that specifies how the physiological states of the visual system underlying achromatic color vision map to perceived, or reported, achromatic colors: values such as pitch, charcoal, heather, pearl gray, or hospital white. Depending on one’s point of view, these achromatic colors might be conceptualized either as linguistic response categories or phenomenal states of awareness. In either case, the assumption that there exists a reliable mapping between particular luminance values and particular achromatic colors depends critically on the ancillary assumption that there exists a reliable mapping between particular luminances and the physiological states underlying particular achromatic colors.

The two main anchoring rules that have been proposed to date in the lightness literature—the highest luminance rule and the average-luminance-as-gray rule, or gray world hypothesis (Helson, 1943, 1964)—both rely on the implicit assumption that there exists a one-to-one mapping between at least one particular luminance and the physiological state associated with a particular lightness. According to the highest luminance rule, a one-to-one mapping exists between the highest luminance and the physiological state corresponding to white. According to the gray-world hypothesis, a one-to-one mapping exists between the average luminance and the physiological state corresponding to middle gray.

We believe that the fixed luminance-to-color mapping assumption that underlies both of these anchoring principles is probably wrong. That is, there is no single luminance value that reliably maps to a particular physiological state and its associated lightness, or achromatic color more generally, independent of the spatial context in which the luminance is presented, not even an anchoring luminance (see also Rudd, 2003c). In support of this negative conclusion, we point out that our achromatic color matching equations do a good job of predicting achromatic color matches, and yet they do not depend solely on any single luminance in the image; instead they depend on a weighted sum of the logarithms of potentially many luminances in the image. Thus, the fact that the equations account for the matches made in these experiments argues against a single luminance anchor regardless of whether the equations are interpreted in terms of an underlying neural edge integration process or not.

Because it has previously been shown that the weights given to the luminance ratio at an edge also depend on the distance between the edge and the target (Reid & Shapley, 1988; Rudd, 2003a, Rudd & Zemach, 2004; Shapley & Reid, 1985), the mappings between luminance values, physiological states, and achromatic colors must be considerably more complex than the mappings implied by the simple anchoring rules proposed to date. To account for achromatic color matches in more complex real-world scenes—scenes that potentially include blurred edges, multiple depth planes, etc.—a potentially very complex theory of the mapping between luminances and the physiological states associated with particular achromatic colors is likely to be required. In fact, what is ideally needed is a physiological theory of how the retinal image is transformed along the pathway from the retina to the cortical locus or loci that deal with achromatic color processing. While a complete theory is not expected to be forthcoming any time soon, an outline of a theory that could at least deal with two-dimensional images that include blurred luminance borders is presented at the end of this paper.

Meanwhile, to account for the data from the current study, all that is needed is a distance-dependent edge integration process plus a single global anchoring principle. That is, once the edge integrator output associated with any given region of the scene is assigned an achromatic color, the rest of the entries in a putative
lookup table that maps integrated values into achromatic colors are completely determined by the mathematical properties of the distance-dependent edge integration algorithm. There are no extra degrees of freedom for a theory of achromatic color computation to account for in our matching paradigm. It is of course conceivable that additional anchoring assumptions, such as that of multiple anchoring frameworks (Gilchrist et al., 1999), will be required to account for the percepts evoked by more complex stimulus displays, but this hypothesis has yet to be proven. In fact, the observers in our Experiment 3 were explicitly instructed to assume the existence multiple frameworks of illumination; that is, they were told that the disk-and-ring configurations on the two sides of the display should be thought of as being lit by independent illuminants. Nevertheless, the assumption of separate anchors on the two sides of the display is not required to explain the results of this experiment. All that is required is the assumption of distance-dependent edge integration plus a single global anchor to relate the numerical output of the edge integration process to perceived lightness values via a lookup table.

Although our data prove conclusively that the correct anchoring rule cannot be based on the highest luminance rule, there is good reason, based on previous research, to believe that it might be based on the highest value in the output of the edge integrator. We will refer to this hypothesis as the highest integrated value rule. To the extent that the integrated values computed by our algorithm correspond to actual physiological states, the highest integrated value rule can be thought of as a neural anchoring rule.

The highest integrated values rule asserts that the region or regions associated with the highest integrated values in the output of the edge integrator is perceived as white and the achromatic colors of the other regions in the scene are determined relative to the white point based on the differences in the magnitudes of the integrated values associated each of these regions and that of the highest integrated value. This difference uniquely determines the luminance-to-achromatic-color mapping for each of the regions in the scene, which will in general be spatial context specific.

It should be noted that the data presented in this paper do not, by themselves, argue for the validity of a highest integrated value rule over any other global anchoring principle. To make the case for the highest integrated value rule convincingly, it would need to be shown that regions which are assigned the highest values by the hypothetical edge integration process always appear white, independent of the luminance profile of the image. We nevertheless favor the highest integrated value rule as a working hypothesis because the results of many previous studies have been taken to support the highest luminance rule over other single-luminance-based anchoring rules, such as the gray world hypothesis (Bruno et al., 1997; Gelb, 1929; Gilchrist et al., 1999; Li & Gilchrist, 1999). Under natural viewing conditions, the highest integrated value would be expected to correlate strongly with the highest luminance and, if the highest integrated value is the true anchor, this correlation would help to explain why the highest luminance rule often appears to hold.

Comparison with previous research on achromatic color matching with incremental targets

Previous studies of achromatic color matching that used incremental targets have produced apparently conflicting results regarding the shape of the function that relates log matching region luminance to log target surround luminance (the equivalent of our log $D_M$ versus log $R_T$ curves). Heinemann (1955, 1972) obtained inverse U-shaped matching functions: the subjective intensity of the test increased as a function of the surround luminance over the lower part of the surround luminance range—an assimilation effect—then decreased over the higher part—a contrast effect. A recent study by Bressan and Actis-Grosso (2001) found the opposite trend: a U-shaped matching function with a contrast effect at the lower end of the surround luminance range studied and an assimilation effect at the higher end.

The reasons for these disparate results are not clear. The two research groups used somewhat different stimuli and methods. Heinemann (1955) used a display consisting of test and matching disks, each surrounded by a disk, similar to the display used in the current study. However, unlike the method used in the current study, he presented the test and matching configurations binocularly, each to a separate eye and used fixation points. Bressan and Actis-Grosso (2001) presented their test and matching disks against extended surrounds of differing intensities that each filled up half of the display, as in a traditional simultaneous contrast display. There was no background field in their study other than these extended surrounds. The display was presented binocularly and free viewing was allowed, as in the present work.

The range of stimulus luminances used by Heinemann (1955) and by Bressan and Actis-Grosso (2001) also differed. All of the test disk luminances used by Heinemann were below 14 cd/m², as in our study, while Bressan and Actis-Grosso reported significant contrast effects only for increments above 20.59 cd/m². The latter authors suggested that the range of luminances investigated may be the key factor accounting for the difference in the patterns of results obtained in the two studies. But this conclusion cannot be correct because the stimulus luminances employed in the present study were within the range of those studied by Heinemann, yet the pattern of results observed in our study was consistent with the pattern obtained by Bressan and Actis-Grosso.

Importantly, both groups found evidence of a contrast effect over at least some range of surround luminances,
consistent with the finding of a contrast effect in the current study. Diamond (1953) also found evidence of a contrast effect in naïve matching experiments performed with incremental targets, as did Kozaki (1963, 1965). Gilchrist (1988), however, found no evidence of either a contrast or an assimilation effect. Bressan and Actis-Grosso speculated that a small contrast effect may actually have been present in the Gilchrist (1988) study but that it was missed because of its small magnitude. The steps in the Munsell scale that was used to quantify the match may have limited the ability to discover a small magnitude contrast effect in Gilchrist’s study. For further comparisons of the results obtained from different studies of naïve appearance matching carried out with incremental targets, the reader is directed to the discussions found in Heinemann (1972), and Bressan and Actis-Grosso (2001).

One factor that might at least partially account for the disparate results of earlier studies, as well as the variable size of the contrast effects found for different observers in the present study, is that different observers may attend to different achromatic color dimensions of the stimulus, such as lightness (perceived reflectance), brightness (perceived luminance), or brightness contrast (perceived lightness difference between the disk and its surround ring). Agostini and Bruno (1996) obtained no contrast effects with either paper stimuli or stimuli presented on a CRT when their subjects were specifically instructed to judge lightness. However, the steps in the Munsell scale used by Agostini & Bruno for reference match may have limited their ability to discover small magnitude contrast effects.

Arend and Spehar’s (1993a, 1993b) results can be qualitatively compared to ours in the following way. Through application of the distance-dependent edge integration model, it can be shown that the slopes of their data plots (but not ours) give the negative of the hypothetical edge ratio \( w_2/w_1 \). For their subjects LA and DA, this weight ratio was about 0.10. For subject BS, the estimated weight ratio was slightly larger than 0. For our two subjects, these weight ratios were a bit larger: about 0.25 for both subjects. A weight ratio of zero corresponds to ideal ratio matching behavior. The difference is likely due to the fact that the two studies employed surrounds of different widths. The surround frames used by Arend and Spehar were 1° wide, while our surround rings were only 0.35°. Previous research has shown that the weight ratio \( w_2/w_1 \) decreases monotonically with increasing surround width (Reid & Shapley, 1988; Rudd & Zemach, 2004).

It is also possible that the difference was partly due to the use of different matching procedures in the two studies. In Arend and Spehar’s (1993a, 1993b) study, the subjects adjusted the luminance of the patch whose surround luminance was varied to make the lightness match, whereas in our study the subjects adjusted the luminance of the patch on the opposite side of the display from the surround whose luminance was varied. In a study in which subjects were specifically instructed to judge brightness, Jacobsen and Gilchrist (1988) obtained either a very small contrast effect (their Experiment 5) or a moderately strong contrast effect (their Experiment 1), depending on the method used to make the judgment. In their Experiment 5, subjects adjusted the test disk to make the comparison; in their Experiment 1, they adjusted the test ring.

**Curvilinear log \( D_M \) versus log \( R_T \) plots and induction signal "blockage"**

In the studies of Heinemann (1955, 1972) and Bressan and Actis-Grosso (2001), it was found for naïve matches that the function relating matching patch luminance to test surround luminance was curvilinear (either U-shaped or inverted U-shaped). This raises the question of whether there are any signs of curvature in the plots of log \( D_M \) versus log \( R_T \) obtained from our Experiment 1 (Figure 2).

In our previous study of naïve matches performed with decremental target disks, we found evidence of such curvature. In our previous study we compared the edge integration model presented here, based on a linearly weighted sum of log luminance ratios, to one based on a nonlinear summation of log luminance ratios. The nonlinear model investigated was a distance-dependent edge integration model that included an additional assumption: that the induction signal originating from the outer edge of the ring surrounding each disk is partially blocked by the inner edge of the ring (Rudd, 2001; Rudd & Arrington, 2001; Rudd & Zemach, 2004). The percentage of the
induction signal originating from the outer ring edge that is blocked by the inner ring edge was assumed to be proportional to the log luminance ratio of the inner ring edge. Rudd and Arrington (2001; see also Rudd, 2001) provided empirical support for this assumption in a naive matching experiment using a two-ring double-decrement display (i.e., a display containing a dark target disk surrounded by two rings, the outer of which had a luminance that was always either greater than or equal that of the inner ring).

The blockage model predicts that log $D_M$ will vary as a second-order polynomial function of log $R_T$ and that the coefficient that multiplies the quadratic term, log$^2R_T$, in this function will be negative; that is, the curve should be U-shaped rather than inverse U-shaped (Rudd & Zemach, 2004). For two of the four observers in our previous study, the blockage model accounted for a significantly larger proportion of the variance in the observer’s log matching disk settings than did the linear edge summation model described here. However, the magnitude of the additional variance accounted for by the blockage model was quite small, consisting of 0.6% increase for one observer and a 0.3% increase for the other.

To test whether the blockage model produces an improved statistical fit to the data from Experiment 1 of the current study, we performed a stepwise linear regression analysis of log $D_M$ in which the variable log$^2R_T$ was entered in the second step, after was first entered log $R_T$ in Step 1. An improved fit was obtained with the addition of this quadratic component for observer AD ($F_{1,69} = 19.795, p < .001$) and a borderline significant improvement was obtained for observer JL ($F_{1,105} = 3.325, p = .071$). For both observers, the least-squares estimate of the coefficient multiplying the log$^2R_T$ was term was negative, as predicted by the blockage hypothesis. The extra variance accounted for by adding the quadratic component was fairly small: about 4% in the case of AD, and 5% in the case of JL; nevertheless, the percent improvement in the amount of variance explained for these two observers was notably larger in the current study than in the previous study performed with decremental disks. For the third subject in Experiment 1—observer LT—adding the quadratic component produced no significant improvement in the regression model ($F_{1,105} = 0.102, p = .750$).

The U-shaped curvature of the log $D_M$ versus log $R_T$ function that was found in Experiment 1 for observer AD, and possibly for observer JL, is consistent with the direction of curvature found by Bressan and Actis-Grosso (2001). The blockage hypothesis thus provides a potential explanation of those authors’ data, as well.

When the same analysis was performed on the data from Experiment 3 of the present study (lightness matches), the results were mixed. An improved fit was obtained with the addition of the quadratic term in the case of observer AH ($F_{1,105} = 14.105, p = .0003$), but not in the case of observer MER ($F_{1,105} = 0.0325, p = .857$). For observer AH, the coefficient multiplying the log$^2R_T$ term was negative, consistent with the blockage hypothesis. The extra variance in her log matching disk settings accounted for by the quadratic component was 3.3%, which is roughly consistent with the percent improvement found in the case of the naive matches made by observers AD and JL in Experiment 1.

### Asymmetries in lightness and darkness induction strength

The magnitude of the contrast effect obtained in Experiment 1 of the present study is given by the absolute value of the slope of the log $D_M$ versus log $R_T$ plot. The slope estimates for the three observers ranged from −0.054 (observer LT) to −0.358 (observer AD), the average being −0.216. A 0.55 log unit increase in the surround ring luminance produced a decrease in the perceived intensity of the disk in the range 0.03–0.20 log units.

The magnitude of the contrast effect observed in Experiment 1 for naive matches carried out with incremental targets was notably smaller than the magnitude of the contrast effect observed in our previous study of naive matches using decremental targets (Rudd & Zemach, 2004). The comparison is particularly appropriate because the disk-and-ring stimuli used in the previous study were identical in size to the ones used in the current study and were presented in the same laboratory environment with the same equipment. The estimated slopes of the log $D_M$ versus log $R_T$ plots in the study employing decremental targets ranged from −0.639 to −0.791, the average being −0.703. The average size of the contrast effect in the current study, expressed in log units, was thus about 30% of that observed in the study using decrements.

While the size of the contrast effect obtained in our previous study with decrements was certainly smaller than the one obtained here with increments, the overall pattern of results differs considerably from the common statement in the literature that the strength of the contrast effect is given by Wallach’s ratio rule (slope = −1) for decrements and is nonexistent (slope = 0) for increments. Our data fail to substantiate either of these claims and suggest that the differences in magnitude of the contrast effects obtained with incremental and decremental stimuli are often exaggerated. This statement must be qualified, however, by the knowledge gleaned from Experiment 3, as well as the earlier results of Arend and Spehar (1993a, 1993b), that matching function slopes are strongly influenced by the observer’s perceptual set. When the observers in Experiment 3 were asked to match the incremental disks in lightness, and the changes in the ring luminance were interpreted as changes in the illuminant on the test side of the display, the average of the matching
function slopes for the two observers was about −0.75. This slope corresponds to a contrast effect having about the same magnitude as the one observed in our previous study of naïve matching using decremental targets. One possible interpretation of this close correspondence is that naïve observers have a tendency to match decremental targets in terms of their lightness and to use the test ring luminance to estimate the illumination, as was previously suggested by Wallach (1976).

The average magnitude of the contrast effect in Experiment 2 of the present study, in which the appearance judgments were naïve and the ring whose luminance was modulated was not directly adjacent to the test disk, was smaller than that of the contrast effect obtained in Experiment 1, where the surround ring whose luminance was modulated was contiguous with the test disk. The estimated slopes of the log $D_M$ versus log $R_{2T}$ functions in Experiment 2 were −0.097 and −0.155 for each of the two observers, the average being −0.126. Thus, the size of the contrast effect obtained when the nonadjacent ring was manipulated was about 58% of that obtained by manipulation of the adjacent ring, on average. This finding is consistent the hypothesis that the strength of contrast induction decays with distance, as assumed by the distance-dependent edge integration model (Reid & Shapley, 1988; Rudd, 2001; 2003a; Rudd & Arrington, 2001; Rudd & Zemach, 2004; Shapley & Reid, 1985).

### Generalizing the model to images that include blurred edges

We are currently exploring ways to generalize the distance-dependent edge integration model to deal with more complex stimuli. To this end, we have constructed a computer model of edge integration based on the idea that separate lightness and darkness induction signals are first generated by edges, then summed directionally across space by neural edge integration units (Reid & Popa, 2004). The model assumes that induction signals have magnitudes that are proportional to the log luminance ratios of the edge that generate them. The model further assumes that induction strength falls off linearly with distance from the signal-generating edge. These properties are consistent with the model presented here and also with the data from both the current study and our previous study using decremental targets (Rudd & Zemach, 2003). The computer model is able to compute achromatic color matches for targets embedded in any arbitrary Mondrian image.

To compute pointwise lightness values for gray-scale images containing blurred edges, that is, contrast at arbitrary spatial scales, we envision further generalizing the model in the following way (Rudd & Zemach, 2004). Log luminance ratios will be computed at a range of spatial scales by logarithmically compressing the range of pointwise luminance values in the image then con-volving the log-compressed image with spatial differencing kernels tuned to various spatial frequencies, phases, and orientations. In this way, log luminance ratios can be computed for luminance “edges” existing at many different spatial scales, phases, and orientations, including blurred edges. A natural choice for the spatial kernels would be the 2D Gabor kernels that have been used extensively to model the spatial filtering properties of simple cells in cortical area V1 (Daugman, 1985; De Valois, Albrecht, & Thorell, 1982; De Valois & De Valois, 1988; Wilson & Gelb, 1984; Wilson & Regan, 1984). The outputs of the Gabor filters would then be half-wave rectified and linearly summed over space by neural edge integration units whose receptive fields pool the outputs of the ratio-computing filters to instantiate the edge integration process.

In addition to providing a generalization of the lightness computation model that can deal with images containing blurred edges, this proposed edge integration scheme forms the basis of a plausible model of edge integration by the visual cortex.

### Summary and conclusions

In our previous work, we studied achromatic color matches using disk-and-ring stimuli in which the disks were luminance decrements with respect to their surround rings. The results of that study were modeled with an edge integration algorithm based on the assumption that achromatic colors are computed from a weighted linear combination of log luminance ratios at edges. It was further assumed that the weights given to edges decay spatial with distance from the target. Here we have shown that this algorithm can also account for both naïve appearance matches and lightness matches performed with disks that are increments with respect to their surround rings.

We have further shown here that the distance-dependent edge integration model has important implications for theories of achromatic color anchoring. Distance-dependent edge integration is not only incompatible with the highest luminance anchoring principle; it is also incompatible with any anchoring rule based on an invariant mapping between a single luminance and a particular achromatic color. The results reported here supported the distance-dependent edge integration model and failed to support the prediction of the highest luminance rule that any pair of regions having the highest luminance in the display will appear white and therefore match in achromatic color.

We suggest that approaches to the anchoring problem based on the assumption that there exists a one-to-one mapping between particular luminances and particular achromatic colors, or lightnesses more specifically, are fundamentally flawed. We propose instead that all achromatic colors, including the achromatic color associated with a region of highest luminance, depend in a potentially
A complex way on the spatial structure of the image. We advocate an alternative approach to the problem of lightness anchoring that breaks the problem into two separate subproblems. The first subproblem is to develop and test computational theories of the process by which retinal luminances map to the physiological states that support achromatic color percepts. The second is to search for a neural anchoring rule that determines how the physiological states map to perceived achromatic colors. Further insights concerning the solution to the second subproblem—neural anchoring—are likely to be gained as a by-product of progress made on the first subproblem—computation modeling of the early neural processes supporting achromatic color perception.

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