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# Explaining top-down influences on lightness judgments with a computational neural model

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## Abstract

*Rudd and Zemach [1] analyzed brightness/lightness matches performed with disk/annulus stimuli under four contrast polarity conditions, in which the disk was either a luminance increment or decrement with respect to the annulus, and the annulus was either an increment or decrement with respect to the background. In all four cases, the disk brightness—measured by the luminance of a matching disk—exhibited a parabolic dependence on the annulus luminance when plotted on a log-log scale. Rudd [2] further showed that the shape of this parabolic relationship can be influenced by instructions to match the disk's brightness (perceived luminance), brightness contrast (perceived disk/annulus luminance ratio), or lightness (perceived reflectance) under different assumptions about the illumination. Here, I compare the results of those experiments to results of other, recent, experiments in which the match disk used to measure the target disk appearance was not surrounded by an annulus [3]. I model the entire body of data with a neural model involving edge integration and contrast gain control [2][4] in which top-down influences controlling the weights given to edges in the edge integration process act either before or after the contrast gain control stage of the model, depending on the stimulus configuration and the observer's assumptions about the nature of the illumination.*

## Computational Neural Model of Lightness Perception

The goal of the work reported here is to extend a recently published computational neural model of surface lightness to account for previously observed effects of top-down influences and perceptual grouping on achromatic color judgments. That goal will not be reached in full here, but I will report the progress that has been made to date in that direction. I will first describe a model of lightness that has previously been shown to account with a high degree of precision for lightness judgments in several different lightness paradigms, including classic disk/annulus brightness/lightness induction displays the Staircase Gelb illusion [5]. Then I will discuss how this model might be extended to account for top-down effects of figural organization and assumptions about the nature of the illuminant.

The neurocomputational lightness model is based on the mechanism of edge integration, first introduced by Land and McCann's retinex model of color vision [6]. The purpose of edge integration is to relate the lightnesses of all of the surfaces within a visual scent to a common lightness scale. Edge integration is achieved in the neural model by cortical receptive fields that directionally integrate local neural edge responses across space. The shape of these receptive fields is illustrated if **Figure 1**.

A key role in the model is played by fixational eye movements (FEMs): the small, random eye movements that the visual system is constantly making, even when we are fixating on a particular element of the visual scene [7][8]. In the course of these FEMs, ON and OFF cells in the early visual system are transiently activated whenever their receptive fields cross over luminance borders in the scene. The model proposes that ON and OFF cells have different characteristic neural gains, which are derived from the different exponents for their power law response to luminance contrast at the level of the lateral geniculate nucleus. The particular neural gains assumed in the model—0.27 for ON cells and 1.0 for OFF cells—combine with the fixed quantitative profile of the cortical edge integrating receptive fields mentioned above, to produce a model that accurately accounts for average lightness judgments made in several lightness matching paradigms, including the Staircase Gelb and the classic disk/annulus induction paradigm [5].

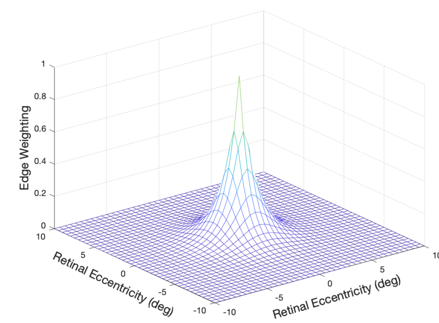


***Figure 1.*** *Spatial profile of the cortical edge integration mechanism in the neurocomputational lightness model..*

## Achromatic Color Matching Predictions for the Disk/Annulus Paradigm

In the disk/annulus lightness matching paradigm often identified with the work of the psychologist Hans Wallach, two disks are presented side by side on a visual display, each surrounded by an annulus. In Wallach's original study [9]· the disks were both luminance decrements with respect to the annuli, and the background field was dark. Following Wallach, Heinemann [10] carried out experiments in which the disks were luminance increments with respect to the annuli. The results of these classic experiments have often been described in the literature in the following way: When the disks are decrements, a match in the appearance of the two disks is achieved when the luminance ratios of the disks and annuli are equal on the two sides of the display. When the disks are increments, a match is achieved when the disk luminances are equal on the two sides of the display [11].

Rudd and Zemach [1][12][13] demonstrated experimentally that this description is an oversimplification at best. The effect of the annulus luminance on the disk brightness is indeed weaker in the case of increments than it is in the case of decrements, but there is some degree of contrast effect in both cases. Furthermore, in the case of decremental disks, the effect of the annulus luminance on the disk appearance is weaker than would be predicted by Wallach's ratio rule. A pictorial summary of Rudd and Zemach's quantitative disk matching results is shown in **Figure 2**, where it can be seen that the magnitude of the brightness induction produced by the annulus is about 0.7 in the case of decrements, and only about 0.3 in the case of increments, when the match luminance is plotted against the luminance of the annulus surrounding the target disk on a log-log scale. Plotting the results on a log-log scale allows for a simple quantification of induction strength as the *negative* of the slope of the plot. In what follows, I will refer to such plots as **achromatic color matching functions** (ACMFs)—using the term *achromatic color* instead of brightness because, as will be discussed below, such plots can be used to summarize the effects of the annulus on both brightness (perceived luminance) and lightness (perceived surface reflectance) judgements made to the disk.

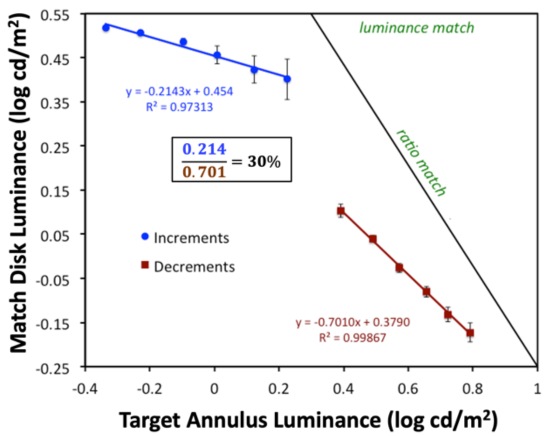


***Figure 2.** Average induction strengths for incremental and decremental disk (based on the experiments of Rudd and Zemach [12][13]).*

If the disk matches corresponded to ratio matches in the case of decremental disks, the slope of the ACMF for decrements would be exactly -1. If the disks matches corresponded to luminance matches in the case of incremental disks, the slope of the ACMF for increments would be 0. Rudd and Zemach proposed an alternative model of appearance matching for disk/annulus stimuli based on a particular edge integration model. According to their model, the match and target disks are predicted to match in appearance whenever the following mathematical equivalence holds:

$$w_1(D_M - A_M) + w_2(A_M - B) = w_1(D_T - A_T) + w_2(A_T - B), \quad (1)$$

where: $D_M$, $D_T$, $A_M$, $A_T$, and $B$ are the luminances of the match disk, target disk, the annulus surrounding the match disk, the inducing annulus surrounding the target disk, and the background (all luminances expressed in log units); and $w_1$ and $w_2$ are the perceptual weights associated with the disk/annulus and annulus/background luminance borders. The quantities on either side of Eq. (1) model the disk appearance on the two sides of the display.

According to Eq. (1), an appearance match between the two disks should obtain when

$$D_M = D_T + (1 - w_2/w_1)A_M - (1 - w_2/w_1)A_T. \quad (2)$$

It follows that the edge integration model identifies the slope of the approximately linear ACMFs in **Figure 2** with the quantity $-(1 - w_2/w_1)$, and is thus consistent with the combined assumptions that $w_2 < w_2$ and that the weight $w_1$ associated with the luminance edge between the disk and annulus is smaller in the case of incremental disks than it is in the case of decremental disks [2][4][11]. This, in turn, is consistent with the FEM-based lightness model that the gain associated with the ON cells that detect incremental luminance edges in the model is smaller than the gain of the OFF cells that detect decremental luminance edges.

It is convenient to rewrite the slope $-(1 - w_2/w_1)$ in the form $w - 1$, where $w$ stands for the ratio $w_2/w_1$ of the weights associated with the outer and inner edges of the inducing ring. This allows us to derive the weight ratios $w_{inc} = 0.7857$ and $w_{dec} = 0.2990$ corresponding to incremental and decremental disks from the linear ACMF plots shown in **Figure 2**. Since the outer edges of the annuli are luminance increments in both cases, it stands to reason that the difference in these ratios is due solely to the weights associated this the *inner* annulus edge, which is a luminance increment in the first case and a luminance decrement in the second case. In other words, it is the $w_1$, which is in the *denominator* of $w$, that differs in the two cases. That allows us to compute the weight ratio $w_{1inc}/w_{1dec} = 0.3806$. This ratio is not identical with the ratio 0.27 predicted by neurocomputational lightness model (which postulates that these weights are equivalent to the neural gains associated with ON and OFF cells [5]), but it is at least consistent with the prediction that that the weight associated with incremental edges is substantially smaller than the weight associated with decremental edges. As will be shown in the next section, there is considerable variation in the statistical estimates of the weight ratio $w_{1inc}/w_{1dec}$ obtained from different observers, so perhaps the average ratio of 0.38 calculated from only three observers should be taken with a grain of salt as being characteristic of disk/annulus matches. Nevertheless, the results are roughly consistent with the model prediction. In any case, it will be shown in what follows that the edge integration model expressed by Eq. (2) holds only approximately.

## The Problem of Parabolic ACMFs

A problem with the edge integration model described above arises from the fact that ACMFs are not, in the most general case, *linear* functions of $A_T$. As can be seen from the plots shown in **Figure 3** (a) and (b), there is often some curvature in the ACMFs of individual observers. These two plots correspond to the same matches that, when averaged across observers, produced the plots in **Figure 2**, which were fit there with linear regression models. In **Figure 3**, the plots from individual observers have instead been fit with a second-order polynomial regression model of the form

$$D_M = k_0 + k_1 A_T + k_2 A_T^2, \quad (3)$$

which I will hereafter refer to as a *parabolic* regression model, for short. Note that the ACMFs from different observers have been shifted successively upward along the y-axis to make the shapes of the individual ACMFs more easily discernable.

Rudd and Zemach [1] also studied matches made to incremental and decremental disks under conditions in which the background field was white (i.e., the highest luminance in the display), instead of dark, and showed the parabolic ACMF model was, in the most general case, superior to the linear model as a model of the ACMF. The plot shown in **Figure 3** (c) illustrates a case studied subsequently by Rudd [2], in which the background field was white (the highest luminance in the display), and the width of the inducing annulus was systematically varied. As can be seen from this figure, the matching data corresponding to each annulus width is fit well by a parabolic model, and the curvature of the parabolic fits becomes stronger as the annulus becomes narrower. It is worth noting that **Figure 3** (c) also demonstrates that a single disk/annulus display can produce **contrast** (negative ACMF slope) over one range of annulus luminances, and **assimilation** (positive ACMF slope) over another range: an effect that had not previously been reported in the literature.

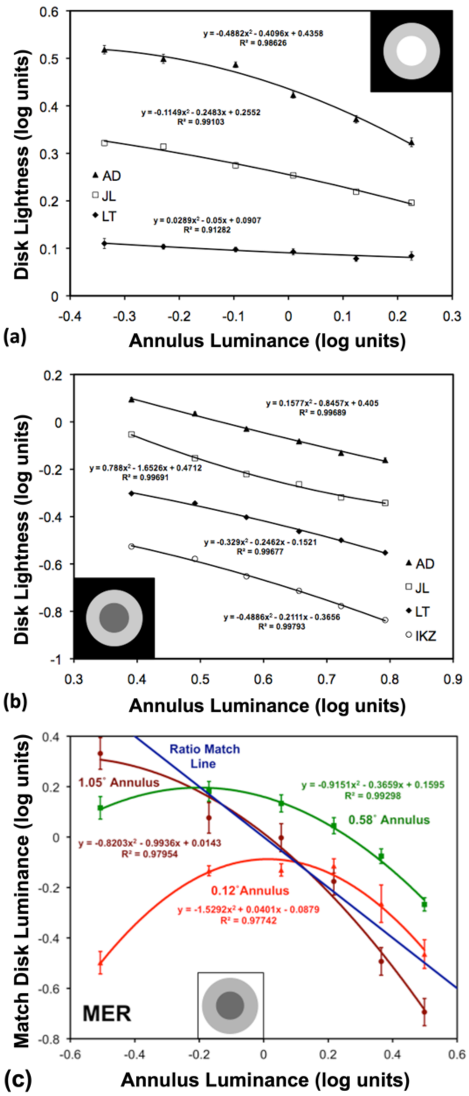


***Figure 3.*** *ACMFs corresponding to three different edge contrast polarity combinations. (a) Incremental disks, background field dark. (b) Decremental disks, background field dark. (c) Decremental disks, background field white; three different annulus widths. The ACMFs have been shifted successively upwards for two of the three observers in (a), and for three of the four observers in (b). In all three panels, the ACMF for each observer/condition has been fit with least-squares parabolic regression models (equations on the figure).*

## The Problem of Top-Down Perceptual Effects

A second problem with the edge integration model described above stems from the fact that achromatic color matches performed with disk/annulus stimuli can be strongly influenced by instructions given to the observers to match the disks on either **brightness** (perceived luminance); **brightness contrast** (the perceived disk/annulus luminance difference or ratio); or **lightness** (perceived reflectance), under different instructions regarding the nature of the illumination [2][14][15]. **Figure 4** plots the ACMFs produced by a *single* observer under these four different sets of matching instructions. When the observer matched the disks under either an instruction to match the disk *luminances*, or to match the disk *lightnesses* under the assumption that changes in the luminance of the inducing annulus signaled a change in the annulus reflectance (with illumination held constant), the ACMF exhibited the parabolic curvature that had been seen earlier in matching experiments conducted with no special instructions (hereafter referred to as **naïve** or **uninstructed** matching). However, when the observer matched the disks under either an instruction to match the disk/annulus *contrast*, or to match the disk *reflectances* under the assumption that changes in the luminance of the inducing annulus signaled changes in the *illumination* falling on the target side of the display *only* (with the reflectance of the inducing annulus held constant), the resulting ACMF was linear, and had a slope of about -0.7, similar to the slopes observed earlier for several observers who matched decremental disks presented on dark backgrounds.

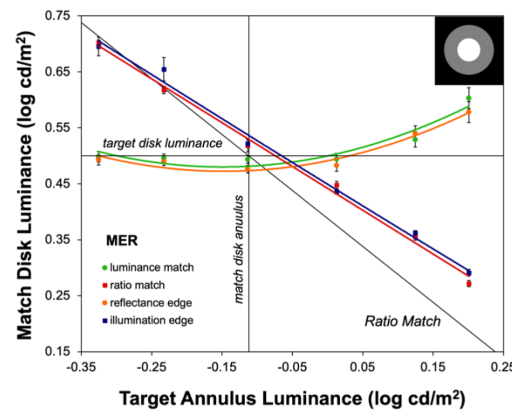


***Figure 4.*** *ACMFs for a single observer who matched the same incremental disk/annulus stimulus under four sets of matching instructions (see text for details).*

To model the full set of ACMFs obtained in this study with a signal edge integration model, Rudd [2][4] modified the original model defined by Eq. (1) by adding a contrast gain control mechanism that acts prior to the stage of edge integration to automatically adjust the edge weights—or the neural gains applied to edges—on the basis of the neural response to *neighboring* edges. For example, an increase of the magnitude of the step in log luminance at the outer annulus edge might decrease the sensory neural gain applied to the inner annulus edge, and thus automatically adjust the perceptual weight associated with the inner annulus edge. This neural gain control process can be expressed formally by substituting for the edge weights in the original edge integration model the following expressions:

$$w_{1i} = \omega_1 g_1 \big(1 - \alpha g_2 (A_i - B)\big)\,,$$

And

$$w_{2i} = \omega_2 g_2 \big(1 - \beta g_1 (D_i - A_i)\big)\,, \qquad (4)$$

where $\omega_1 g_1$ and $\omega_2 g_2$ are the total edge weights associated with the inner and outer annulus edges in the absence of neighboring edges, $g_1$and $g_2$ are the *sensory* (Stage 1; see **Figure 6**) neural gains associated with those edges (whose values are posited to differ depending on the edge contrast polarity), and $\alpha$ and $\beta$ are the strengths of the inwardly-directed and outwardly-directed contrast gain controls acting between edges. The coefficients $\alpha$ and $\beta$ are allowed to be either positive or negative in the model, corresponding to a gain control that can either increase the weight associated with an annulus edge in the presence of the other annulus edge, or decrease the weight associated with an annulus edge in the presence of the other annulus edge. It is unclear what physiological mechanism a contrast gain control with these properties might correspond to, or at what level of the visual hierarchy it occurs. In particular, it is not clear whether the contrast gain control is a low-level contrast gain control process, or some high-level or mid-level process reflecting the operation of a cortical mechanism that contributed to attentional control or perceptual organization.

## Previously Verified Predictions of the Edge Integration Model with Contrast Gain Control

Rudd [2][4] proved mathematically that this modified edge integration model predicts that ACMFs will have a parabolic shape. He furthermore derived expressions for the model coefficients $k_0$, $k_1$ and $k_2$ based on the neural model. Analysis of the algebraic expression for these coefficients revealed the curious model prediction that

$$k_1 = -(D_T + B)k_2\,. \tag{5}$$

Importantly, this predicted relationship between the first- and second-order coefficients of the parabolic regression model depends only on the target disk and background luminances (expressed in log units), and is independent of any of the internal parameters of the model, such as the edge weights and contrast gain control strengths. It is thus easily tested experimentally. The prediction was shown to hold, within error, for all four of the disk/annulus contrast polarity conditions studied in the naïve matching experiments of Rudd and Zemach (incremental and decremental disk/annulus configurations presented against either a dark or while background) [2][4].

Moreover, the prediction also held for the matches made in the instructed lightness matching condition of Rudd, in which the observers were implicitly instructed to interpret the outer annulus edge as a reflectance edge, as well as for the naïve matches performed by the three observers in the earlier study of Rudd and Zemach that employed the same physical incremental disk/annulus stimulus (see **Figure 3**(a). (Since these instructional conditions were all performed with the same physical stimulus, the model predicts that the matches made by each observer in each condition should yield pairs of statistical estimates $(k_2, k_1)$ that fall on a line having a slope equal to $-(D_T + B)$, where $D_T$ and $B$ are the fixed target disk and background luminances of that stimulus.)

The fact that this thus prediction is verified for the naïve matching and reflectance edge conditions is illustrated by **Figure 5**, where the different points on the diagonal line correspond to different observers and instructional conditions. The data in the plot that does *not* fall on the line corresponds to the lightness matches for which the observers were implicitly instructed to imagine that the outer edge of the annulus instead represented an *illumination* edge. The overall pattern of results leads to the interesting—and significant—conclusion that the only edges that taking part in the edge integration process are edges that the observer *believes* to be reflectance edges. This makes sense if it is assumed that the purpose of edge integration is to relate the perceived reflectances of all of the achromatic surfaces in the scene to a single lightness scale. In that case, illumination edges should *not* be spatially integrated together with reflectance edges, because combining the two classes of edges would distort the perceived global lightness scale. In other words, illumination edges should ideally be *discounted*. If this interpretation of the results is true, then it follows that the observers in the naïve matching experiments must have imagined the outer border of the annulus to be a reflectance edge.

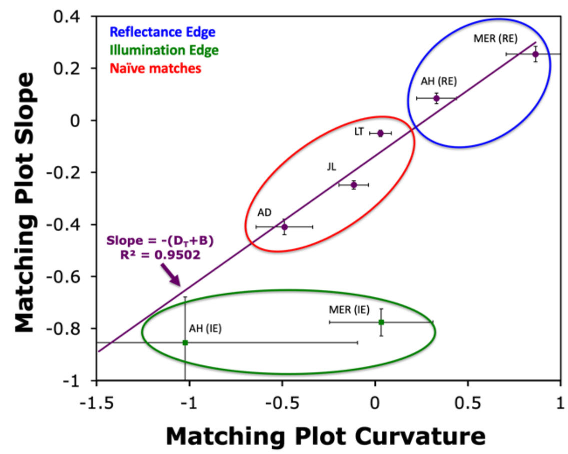


***Figure 5.*** *Plot of the statistical estimates of $k_1$ vs the corresponding estimates of $k_2$ obtained by fitting a least-squares parabolic ACMF model to the data from the naïve matching conditions whose results are plotted in Figure 3(a) and the two lightness matching conditions whose results are plotted in Figure 4.*

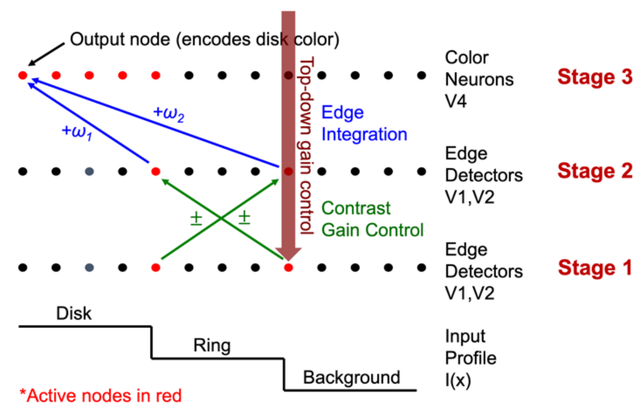


***Figure 6.*** *A neural edge integration model with a top-down feedback instantiating edge classification that accounts for the ACMFs shown in Figure 3(a) and Figure 4 (see text for details).*

This entire pattern of results can be accounted for by the neural model illustrated in **Figure 6**. According to this model, edge detectors at model Stage 1 apply a contrast polarity-dependent sensory neural gain $g_i$ to the steps in log luminance at the inner and outer borders of the annulus in the input image. At model Stage 2, the gain applied to these same edges is modified by the contrast gain control process corresponding to the system of equations (4). At model Stage 3, the gain-controlled neural edge responses are spatial integrated by the large-scale receptive fields—whose spatial profile is shown in **Figure 1**—to compute achromatic color appearance at each point in a neural representation of the image. If (and only if) the observer is explicitly or implicitly instructed to interpret the outer annulus edge as an illumination edge rather than as a reflectance edge, a top-down feedback process that reaches down to the level of the Stage 1 edge detectors will shut off the sensory gain associated with this edge.

To model this top-down feedback mechanism, the sensory gain parameter $g_i$ in the model equations needs to be rewritten as $cg_i$, where the $c$ is an edge classification parameter that equals 1 when the step in log luminance that it multiplies is interpreted by the observer as a reflectance edge, and 0 when the step is interpreted as an illumination edge. Importantly, the edge classification step must come before the contrast gain control step in the model in order to account for the fact that interpreting the outer annulus edge as an illumination edge has the effect of turning off the contrast gain control. This results in ACMFs for the fact that instructional conditions in which the outer annulus edge is interpreted as an illumination edge have zero curvature (that is, they are *linear*).

## Effect of Removing the Annulus Surrounding the Match Disk

In subsequent work, my colleagues and I have run a series of uninstructed disk matching experiments in which the annulus surrounding match disk was removed from the original Wallach-type matching display [3][16]. Our original motivation for removing the match annulus was to simplify the model equations in hopes of being able to estimate additional model parameters. We ran the experiments with both incremental and decremental target disks, and both highest luminance (white) and lowest luminance (dark) backgrounds (four edge contrast polarities combinations in total). We modeled the data from all four contrast polarity conditions with parabolic ACMFs.

We then plotted the estimates of $k_1$ obtained from the least-squares parabolic regression models against the estimates of $k_2$ obtained from the corresponding ACMFs to test the prediction of the edge integration with contrast gain control model expressed by Eq. (5). To our surprise, this prediction did not hold. The plots of $k_1$ vs $k_2$ were linear, as expected, but the slope of the plots were in no case equal to $-(D_T + B)$. Instead, we found that the slopes of the $k_1$vs $k_2$ plot corresponding to the two conditions for which the target disk was a luminance increment with respect to its surrounding annulus were both about -1.74, and the slopes of the $k_1$vs $k_2$ plots corresponding to the two conditions for which the target disk was a luminance decrement with respect to its surrounding annulus were both about -3.30.

Although this result was unexpected, we were able to show that it was, in fact, consistent with a particular parameterization of the neural edge integration model for which the weighting parameter $\omega_2 = 0$ on the target side of the display. We interpreted this finding to mean that observers tend to set the edge weight associated with the outer annulus edge on the target side to the display to zero when there is no annulus surrounding the *match* disk. Apparently, in the absence of an annulus surrounding the match disk, observers tend to match the two disks on the basis of the local luminance edge at borders of the disks only, and they ignore the luminance step at the outer border of the annulus surrounding the target disk. Thus, *observers apparently do not perform edge integration when the outer edge of the annulus does to exist on **both** sides of the display*. Importantly, this suggests a role for figural organization in the determining an observer's achromatic color matching strategy.

According to this hypothesis, the condition that should hold for a match to occur is

$$\omega_1 g_{1M}(D_M - B) = \omega_1 g_{1T}\big(1 - \alpha(A_T - B)\big)(D_T - A_T) \quad . \quad (6)$$

Note, importantly, the neural gain $g_{1M}$ applied to the border between the match disk and the background will be the same as the gain $g_{2T}$ applied to the border between the annulus surrounding the target disk and the background because these two borders have the same contrast polarity in this display. As shown in Ref. [3], Eq. (6) predicts that the plot of $k_1$ vs $k_2$ should be a straight line having a slope equal to $-\left(\frac{1}{\alpha g_{2T}} + D_T\right)$. Combining this result with the empirical findings that the slope of $k_1$ vs $k_2$ equals about -1.74 when the target disk is a luminance increment, and about -3.30 when the target disk is a luminance decrement, leads to the conclusion that $\alpha = 1/0.5g_{2T}$ when the target disk is an increment, and $\alpha = 1/2g_{2T}$ when the target disk is a decrement (see Ref. [3] for details). We are still exploring the meaning of this last finding, but it may be significant that the ratio 0.5/2 is about equal to the ratio of the neural gains for increments and decrements assumed in the neurocomputational lightness model of Rudd and Shareef [5].

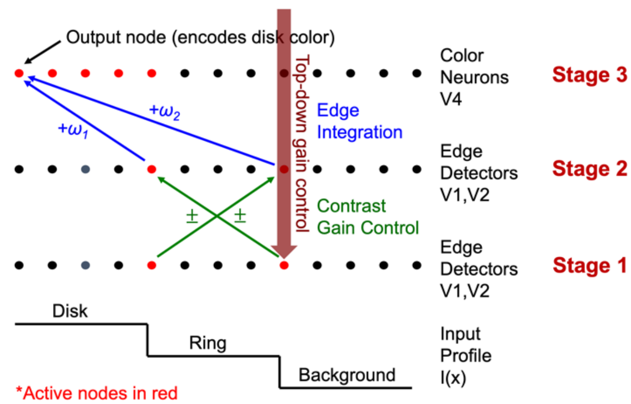


***Figure 7.*** *A neural edge integration model with top-down feedback that accounts for the ACMFs obtained from naïve matching experiments carried out with a disk/annulus stimulus in which the annulus surrounding the match disk has been removed (see text for details).*

It should be underscored that the neural edge integration model corresponding to the matching equation (6)—despite applying an edge weight of zero to the outer annulus edge—still includes contrast gain control, and, moreover, that this gain control is needed to account for the parabolic shape of the ACMFs. Since the edge integration model that we used to fit the data from these experiments also assumes that the perceptual weight associated with the outer annulus edge is zero, it follows that the top-down suppression of this edge weight must occur *after* the contrast gain control stage. A model architecture that explains the results of these experiments is illustrated in **Figure 7.** Note that the top-down gain control that we needed to assume in order to explain these results acts at a different processing stage (Stage 3) than that of the top-down gain control that accounts for the results of the effect of matching instructions (Stage 1). In words, in order to explain the *entire* pattern of results observed in all of the experiments discussed in this paper, it is necessary to assume the existence of multiple top-down feedback mechanisms that adjust the neural gains applied to edges at different stage stages of the visual hierarchy.

## Achromatic Color Matching With Disks and Annuli is Not a Low-level Visual Process

A number of interesting conclusions can be drawn from the effort made here to simultaneously model the results from several different achromatic color matching experiments carried out with stimuli consisting of disks and annuli comprised of combinations edges of different contrast polarities, annuli of various sizes, and matched under various sets of matching instructions. First, it does appear to be possible to model the data from all of these experiments in a self-consistent way with an edge integration model that includes contrast gain control and two types of top-down feedback. However, further work will be required before we can present a fully *parameterized* edge integration model that explains the results of all of these experiments in the context of a single unified model.

Perhaps more importantly, any such model must necessarily include top-down mechanisms that instantiate the effects on achromatic color of figural organization (i.e., dependence of the matching parameters on the stimulus configurations on the match and target sides of the display), and the observer's interpretation of the stimulus (i.e., assumptions about the nature of the illumination).

The disk/annulus matching paradigm was originally introduced decades ago as a means of studied the effects of an adapting field on the appearance of a target disk. The adaptation produced by the annulus was though by the psychophysicists who conducted these studies to depend solely on local contrast mechanisms, such as the center-surround mechanism of early visual neurons. On the basis of the analyses presented here, it must instead be concluded that effects that many of the effects that were previously attributed to "adaptation" instead reflect that activity of mid-level, or even high-level, neural processes by which the observer projects his or her own interpretations on the "meaning" of the visual stimulus.

In his famous "War of the Ghosts" study of human memory [17], the British psychologist Frederick Bartlett proposed that the subjects in his experiments approached the to-be-remembered material by searching for its meaning. Bartlett observed that his subjects' memory of the material was based on their interpretations of the material's meaning, rather than directly on the material as presented. It appears that something similar is going on in the achromatic color matching experiments discussed here. Rather than matching a simple quantity, such as the disk/annulus luminance ratio (as Wallach proposed), observers in these experiments can match the disk/annulus stimuli in numerous ways, depending on what they believe the stimulus represents in terms of some hypothetical proximal stimulus. It follows that any neural theory of the achromatic color matches made with such stimuli properly belongs to the realm of cognitive neuroscience, rather than to the field of low-level vision. Rather than being seen as a disappointment, this finding should perhaps be viewed as a happy accident, since it implies that achromatic color matches might provide a window into the workings of visual perception more broadly, and reveal important clues regarding the nature of the computations governing mid- and high-level visual perception.

## References


[1] M. E. Rudd & I. K. Zemach, "Contrast polarity and edge integration in achromatic color perception," J. Opt. Soc. Am. A, Vol. 24, 2134-2156, 2007.

[2] M. E. Rudd, "How attention and contrast gain control interact to regulate lightness contrast and assimilation," J. Vision, Vol. 10, 40, 2010; doi:10.1167/10.14.40.

[3] M. E. Rudd, O. Kavcar, & M. A. Crognale. "Parabolic achromatic color matching functions: Dependence on incremental and decremental luminance." J. Opt. Soc. Am. A, Vol 40, No. 3, A57-A64. (2023).

[4] M. E. Rudd, "Lightness computation by the human visual system," J. Electron. Imaging, Vol. 26, No. 3, 2017.

[5] M. E. Rudd, & I. Shareef, "Fixational eye movements and edge integration in lightness perception." Vision Res., Vol. 277, 108517, 2025.

[6] E. Land & J. J. McCann, "The retinex theory of vision," J. Opt. Soc. Am., Vol. 61, 1-11, 1971.

[7] S. Martinez-Conde, S. L. MacKnik, & D. H. Hubel, "The role of fixational eye movements in visual perception," Nat. Rev. Neurosci. Vol. 5, No. 3, 229–40, 2004.

[8] M. Rucci & J. D. Victor, "The unsteady eye: an information-processing stage, not a bug," Trends Neurosci., Vol. 38, No. 4 ,195-206, 2015

[9] H. Wallach, "Brightness constancy and the nature of achromatic colors," J. Exp. Psychol., Vol. 38, No 3., 310-324**,** 1948.

[10] E. G. Heinemann, "Simultaneous brightness induction as a function of inducing- and test-field luminances. J. Exp. Psychol., Vol 50, No. 2, 89-96.

[11] A. Gilchrist, Seeing Black and White, Oxford, UK: Oxford Univ. Press, 2006.

[12] M. E. Rudd & I. K. Zemach, "Quantitative properties of achromatic color induction: An edge integration analysis," Vision Res., Vol 44, 971-981, 2004.

[13] M. E. Rudd & I. K. Zemach, "The highest luminance rule in achromatic color perception: Some counterexamples and an alternative theory," J. Vision, Vol. 5, 983-1003, 2005.

[14] L. E. Arend & B. Spehar., "Lightness, brightness, and brightness contrast: 1. Illuminance variation," Percept. Psychophys., Vol. 54, No. 2, 446-456, 1993.

[15] L. E. Arend and B. Spehar, "Lightness, brightness, and brightness contrast: 2. Reflectance variation," Percept. Psychophys., Vol. 54, No. 4, 457-468.

[16] O. Kavcar, M. E. Rudd, & M. A. Crognale, "Dependence of brightness induction on the contrast polarity of a disk/annulus stimulus," J. Opt. Soc. Am. A, Vol. 42, No. 5, 2025.

[17] B. C. Bartlett, Remembering: A Study in Experimental and Social Psychology, Cambridge, UK: Cambridge Univ. Press, 1932.


## Author Biography

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