Distant background information strongly affects lightness perception in dynamic displays

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Lightness perception is strongly dependent on context, including the relative luminance of the adjacent surfaces, spatial configuration, and luminance contrast. The latter, local luminance contrast, is thought to be processed in relatively early stages of visual processing and has been shown to play a crucial role in lightness perception. However, more global processing, such as perceptual grouping of surfaces, can also have an effect on lightness perception. An unresolved question, which we will address in this paper, is how global and local processes interact. We used a static gray disk embedded in a temporally modulated in luminance ring, which gives rise to a lightness effect dependent on local luminance contrast. We manipulated global image information by presenting the stimulus on backgrounds of different luminances. Surprisingly, the induction effect was greatly attenuated at a background luminance equal to that of the disk. We show that this finding cannot be explained by common lightness induction models. However, it is consistent with an effect of grouping on lightness perception and demonstrates how processes that are dependent on local edge information can be overridden by global image information.

Introduction

Lightness perception, or apparent surface reflectance, is strongly dependent on context. The study of the effects of context on lightness perception has proceeded along two paths. In one case, stimuli are made to be as simple as possible in an attempt to precisely quantify the effects of contextual information. For example, a uniform gray image patch can be made to appear darker if it is surrounded by higher luminance and lighter if it is surrounded by lower luminance. Models are then derived that characterize perception as a function of the luminance relationship between the central test surface and its surround. Indeed, there are multiple local edge integration models that can account for a variety of lightness perception phenomena in simple 2D displays (Reid & Shapley, 1988; Rudd & Arrington, 2001; Rudd & Zemach, 2004, 2005; Shapley & Reid, 1985; Vladusich, Lucassen, & Cornelissen, 2006, 2007; Zemach & Rudd, 2007).

The study of the effects of context on lightness perception has also proceeded along a second path, which has demonstrated the profound impact of larger scene properties such as overall spatial configuration and 3D interpretation. While more difficult to precisely model, these studies have shown that lightness perception in more 'natural' 3D images involves a complex interaction between estimates of surface reflectance and scene illumination (reviewed by Blakeslee, Reetz, & McCourt, 2008; Kingdom, 2003, 2008). Local edge integration models are usually unable to generalize to these more complex scenes (Kingdom, 2008). However, because of the many differences between the images used to derive local edge integration models and the more complex images used to characterize reflectance and illumination processes, it is difficult to specify the limitations of edge integration models.

In the current study, we examined the ability of local edge integration models to generalize in simple 2D lightness induction images. We reasoned that lightness perception is a process that is dominated by global scene properties, even in simple scenes. Thus, we expected that even relatively small changes to 2D images involving changes in global perceptual organization of surfaces would lead to dramatic failures of local edge integration models. Specifically, we investigated the effect of distant luminance information on lightness perception. We measured lightness induction in a static gray disk, embedded in a temporally modulated-in-luminance ring, and presented on backgrounds of different luminances. Temporally modulated-in-luminance surrounds are known to produce a strong perception of luminance flicker in static achromatic test stimuli (De Valois, Webster, De Valois, & Lingelbach, 1986; Krauskopf, Zaidi, & Mandler, 1986; Zaidi, Yoshimi, Flanigan, & Canova, 1992). The

central question of our study is the effect of the distant background luminance on the perceived flicker of the central gray disk.

We show that the lightness induction effect is greatly attenuated at a background luminance level equal to that of the disk. This finding could not be explained by any of the commonly used edge integration models (e.g. Reid & Shapley, 1988; Rudd & Arrington, 2001; Rudd & Zemach, 2004, 2005; Shapley & Reid, 1985; Vladusich et al., 2006, 2007; Zemach & Rudd, 2007). We contend that the reduced lightness induction observed in our experiment is due to a global perceptual organization of the scene—specifically a grouping between the background and the test-patch, which occurs when they are of equal luminance. This possibility is significant because it means that global perceptual grouping can override something as basic as lightness induction from local luminance edges.

Methods

Subjects

Six subjects, aged 22 to 41, participated in the experiment. All subjects had normal or corrected to normal visual acuity. All subjects gave informed written consent in accordance with the University of Washington Human Subjects Institutional Review Board.

Apparatus and stimulus specifications

The apparatus consisted of a Dell 1905FP Digital on NVIDIA Quadro FX 1400 color graphics display monitor controlled by a Dell Precision PWS380 Intel Pentium4 PC, and calibrated with a PR 650 spectroradiometer (Photo Research, CA). The monitor had a peak luminance of 210 cd/m^2 and a black level of 0.26 cd/m^2. It extended 51 × 41 deg of visual angle at a viewing distance of 43.5 cm. The stimuli (shown in Figure 1) were 8.6 deg diameter achromatic circular disks embedded in 18.4 deg diameter achromatic rings. The stimuli were centered in the respective halves of the monitor.

On the left side of the display, a temporally static Test Disk was embedded in a temporally modulated-in-luminance Test Ring. Consistently with previous research (De Valois et al., 1986; Krauskopf et al., 1986; Zaidi et al., 1992), luminance modulation in the test ring produced a strong perception of luminance flicker in the test disk. On the right side, a temporally modulated-in-luminance Match Disk of adjustable amplitude was embedded in a temporally static ring. The disk/rings combinations were presented on temporally static backgrounds, which differed in luminance (Experiment 1); chromaticity and texture (Experiment 2).
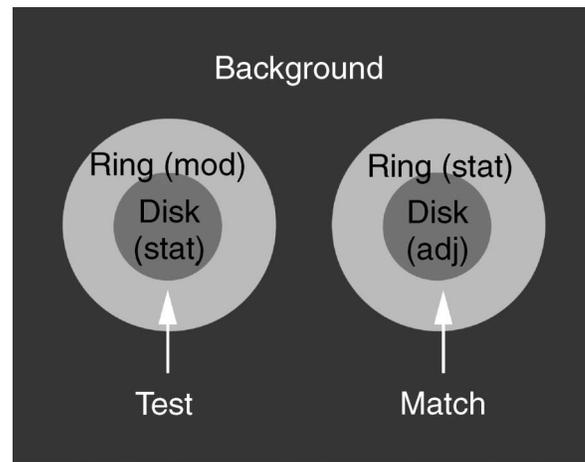
Figure 1. The stimulus. A temporally static test disk is presented on the left, surrounded by a temporally modulated ring. An adjustable disk ("match") is presented on the right, surrounded by a static ring. The amplitude of luminance modulation of the match disk can be changed by the observer to match the perceived lightness change in the test disk. The disk/surround combinations are presented on backgrounds, which differed in luminance (Experiment 1); chromaticity and texture (Experiment 2).

For simplicity, all stimulus luminances will be specified in Instrument Luminance (IL), defined as 100%*(L − Lmin)/(Lmax − Lmin), where L is the stimulus luminance, Lmin is the black level of the monitor and L max is the maximal available luminance of the display. The time-average luminances of both disks and rings were constant throughout the experiment at 50% IL. The luminance of the Test Ring was modulated sinusoidally, at 1 Hz, from 37.5 to 62.5% IL (at 25% IL). The amplitude of luminance variation of the Match Disk could be adjusted from 0 (static) up to 35% IL, at 1 Hz out-of-phase with the Test Ring modulation. Thus, the luminance of the Match Disk could be varied up to 32.5 to 67.5% IL.

In the first experiment, we manipulated the luminances of backgrounds. The stimuli were presented on temporally static backgrounds of 9 different luminance levels, evenly spanning the luminance range of the monitor from 0 to 100% IL, in steps of 12.5% IL. In the second experiment, we maintained the background at a constant 50% IL but manipulated its appearance by introducing chromaticity or texture. The backgrounds were either uniformly chromatic (yellow, CIE 1931 x, y chromaticity = (0.52, 0.44)), or had a gray-scale texture with average chromaticity of CIE 1931 x, y = (0.32, 0.34). The checkerboard texture consisted of 0.4 deg squares of 2 luminance levels: 25 and 75% IL.

Procedure

The subject's task was to adjust the amplitude of modulation of the Match Disk to make it equal in appearance to perceived lightness modulation in the Test

Disk. Subjects were asked to ignore the perception of flicker at the borders between each disk and corresponding ring and equate the overall perceived flicker at the centers of the disks. The adjustments were done in increments or decrements of luminance amplitude by 0.4% IL steps by pressing the "up" or "down" keys. Once the match was achieved, the observer would press a space bar, recording the setting and initiating a new trial. The new trial would begin with the match disk modulated at an amplitude randomly picked from the available amplitude range of 0 to 35% IL.

The trials of different backgrounds were randomly intermixed in Experiment 1 but blocked in Experiment 2, where 10 trials of each condition were presented in sequence. We blocked trials in Experiment 2 because of an observed strong aftereffect after chromatic background presentation, which we felt could potentially influence the performance in the texture condition. The block of trials with chromatic background was thus always presented after the block of trials with the textured background. An average of 12 trials per subject for each background luminance level was obtained in the first experiment, and 10 trials per subject for each background texture/chromaticity in the second experiment.

Brightness induction models

In some studies of lightness induction from static surrounds, the effect of backgrounds has been considered. In general, these models predict an additional lightness induction effect on the disk from the luminance contrast at the border between the ring and background (Reid & Shapley, 1988; Rudd & Arrington, 2001; Rudd & Zemach, 2004, 2005; Shapley & Reid, 1985; Vladusich et al., 2006, 2007; Zemach & Rudd, 2007).

Lightness induction effects in static gray fields monotonically increase with an increase in luminance contrast at the border—the greater the difference in luminance, the greater the induction. In dynamic displays it is thus reasonable to assume that the amount of lightness modulation of the central test disk will be dependent on the maximum and minimum luminance values of the surround modulation. Specifically, as the luminance of the ring peaks, the central test disk will appear the darkest, and as the luminance reaches its minimum, the disk will appear the brightest. Thus, the static models of lightness induction can be extended to account for our experimental conditions by considering the maximum and minimum values in luminance modulation. To predict the amount of lightness induction in our stimuli we will extend versions of two popular models: Weighted Log Luminance Ratio model and Weighted Michelson Contrast model (Reid & Shapley, 1988; Rudd & Zemach, 2004, 2005; Shapley & Reid, 1985).

For a static disk of luminance D, embedded into a ring of luminance R, and presented on a background of luminance B, the Weighted Log Luminance Ratio model describes lightness induction effect in the disk as $f = w1\log\left(\frac{D}{R}\right) + w2\log\left(\frac{R}{B}\right)$ where $w1$ and $w2$ are the weights related to the respective effects of the ring and background luminance borders on the disk lightness. The weight $w1$ is always greater than $w2$; the weight $w2$ is determined by the distance of the ring/background border from the disk, and decreases with increasing distance.

The Weighted Michelson Contrast model describes lightness induction effect in the disk as $f = w1\frac{2(D-R)}{D+R} + w2\frac{2(R-B)}{R+B}$ (all conventions are the same as for the Weighted Log Luminance Ratio model above).

In the case of dynamic induction from the temporally modulated in luminance ring, the lightness induction effect can be thought of as $f_{\text{diff}} = f_{\text{min}} - f_{\text{max}}$ where f_{min} is lightness induction in the disk embedded in the ring at its trough luminance, R_{min}, and f_{max} is lightness induction in the disk from the ring at its peak luminance, R_{max}. The predictions of two extended models are illustrated in Figure 2 and briefly summarized below. For the detailed description of modeling, see Appendix A.

The Extended Weighted Log Luminance Ratio model predicts that the induction effect in the disk will be constant and independent of the background luminance (shown by solid horizontal lines in Figure 2). Because the predicted effect is independent from the background luminance, each line can be represented by multiple
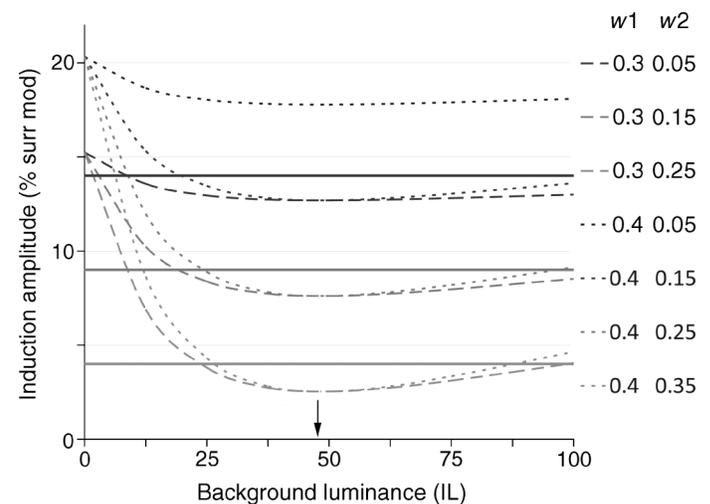
Figure 2. Predictions of two extended models. The predictions of the Extended Weighted Michelson Contrast model are shown by dashed and dotted lines. Different lines show the nested models for different $w1$ and $w2$ weight combinations (the respective weights are specified by the first and the second number in the Legend). An arrow shows predicted minimum. The predictions of the Extended Weighted Log Luminance Ratio model are shown by solid lines. Since there are multiple weight combinations resulting in the same predictions, the particular weights are not specified for this model. Background luminance is plotted along the abscissa, in instrument luminance (IL) units. Predicted induction amplitude is plotted along the ordinate, in percent of surround modulation amplitude.

combinations of $w1$ and $w2$ weights, and the unique weights cannot be determined on the basis of our experiment. The model makes two other reasonable predictions, not tested by our experiments: (1) the induction effect should increase with an increase of luminance modulation amplitude in the ring and (2) for rings of fixed amplitude, the maximal induction effect will be observed when the ring/background border is maximally removed from the disk.

The Extended Weighted Michelson Contrast model predicts an asymmetrical u-shaped induction effect as a function of background luminance, with a relatively steep drop-off at very low background luminances, and a shallow gain at high background luminances. The predicted minimum of the u-shape function is at 48% IL. Two nested groups of models for two different $w1$ values are shown by the dashed and dotted lines in Figure 2. As can be seen from the figure, the $w1$ value is mostly determined from the data collected at the lowest background luminances. This weight primarily affects the steepness of the fall-off of the predicted induction effect. The weight $w2$ determines the size of predicted effect at higher background luminances. The physical interpretation of this model is that at very low background luminances, the predicted effect of the distant background/ring luminance border is negligible, and lightness induction in the disk is determined by the proximal disk/ring luminance border. However, as the luminance of the background increases, the relative contribution of the distant background/ring border increases, peaking at background luminance near 50% IL. After the background luminance level reaches 48% IL, the relative contribution of the proximal disk/ring border starts to gradually increase again and continues to rise but never reaches the level of influence predicted for low luminance backgrounds.

Results

Experiment 1: Effect of background luminance on induction

The results of Experiment 1 for six subjects are shown in Figure 3, on the left. The graph shows the effect of the background luminance on lightness induction in the test disk. Each curve on the graph represents the matches made by one subject. The luminance of the background is plotted along the abscissa. The lightness induction effect in the test disk is plotted along the ordinate, in percent of ring modulation amplitude. The error bars represent the standard error of the mean.

As evident from the main graph, all subjects showed dramatic reduction of induction effect for stimuli presented on the background isoluminant to the test disk. Compared with that at the black background, the induction effect at the background isoluminant to the disk
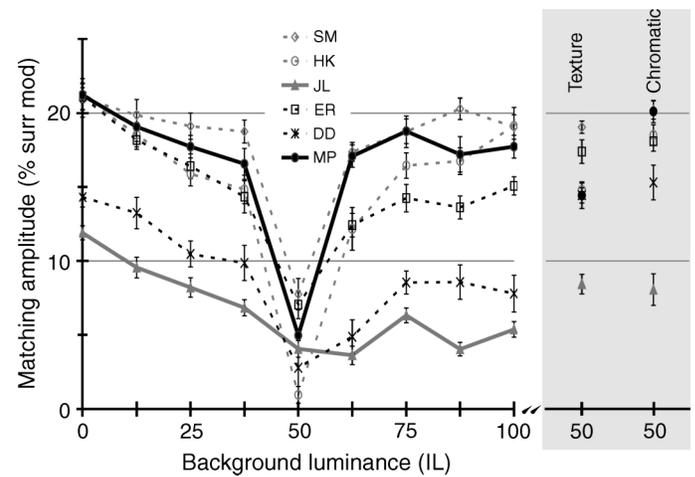
Figure 3. Main graph: Induction effect as a function of background luminance (Experiment 1). Background luminance is plotted along the abscissa, in instrument luminance (IL) units. Matching induction amplitude is plotted along the ordinate, in percent of surround modulation amplitude. Each curve in the graph represents one subject's induction effect measured on different backgrounds. The error bars show the standard error of the averaged match values. Inset on the right: Induction effect as a function of background texture and chromaticity (Experiment 2). All conventions are the same as in the main graph.

was decreased by a median 4-fold. Five of the subjects showed distinct induction minimum for stimuli presented on the background isoluminant to the test disk, resulting in the clear v-shaped functions. In addition, three of the subjects showed generalized induction attenuation at background luminances at and above that of the disk.

Between subjects, there were no significant differences in the induction effects on different luminance backgrounds of the neighboring luminance levels (e.g. 0 vs. 12.5% IL; 12.5 vs. 25% IL etc), as indicated by multiple paired comparisons with Bonferroni correction. However, the induction effect on the 50% IL background was significantly different from that at 37.5% IL ($p < 0.007$) and marginally different from the induction level at 62.5% IL ($p < 0.12$).

The observed dramatic decrease of the induction effect for stimuli presented at 50% IL backgrounds is surprising since it is at odds with multiple psychophysical observations: the effects of remote borders on target lightness usually depend on the distance to the target (Rudd & Zemach, 2004), and should be almost negligible in our case. Popular induction models (Rudd & Arrington, 2001; Rudd & Zemach, 2004, 2005; Vladusich et al., 2006) take this decline in induction into account by stipulating that the weights assigned to the border influences decrease with the increased remoteness of the border.

Thus, it appears that a process separate from simple luminance edge integration is responsible for the observed decrease in lightness induction at backgrounds isoluminant to the disk. Could it be that the appearance of background

mediates global processing of the scene, which overrides simple border integration? This question motivated Experiment 2, in which we manipulated the *appearance* of the background while keeping luminance at 50% IL.

Experiment 2: Effect of background texture/chromaticity on induction

Our second experiment was designed to test the possibility that perceptual grouping between the disk and the distant background overrides simple border integration. It is possible that when the luminances of the disk and background are equal, the disk and background are perceptually grouped to result in appearance of continuous static field over which a modulated ring is presented. However, when the luminances of the disk and the background differ, they might be no longer grouped, resulting in appearance of three separate entities: disk, ring and background. In the latter case, the disk might be more susceptible to local induction effects from the ring than when the disk in perceived to be a part of the surface.

To address this possibility, in the second experiment we kept the background and disk luminance equal but made them appear different through manipulating other dimensions (texture and chromaticity), preserving the luminance characteristics of the distant luminance edges. Thus, we expected that there would be no grouping between the disk and background, and therefore a relatively large induction effect from the ring. If it is simply the luminance of the background that is responsible for attenuation of induction, there should be no difference between the induction effect observed at 50% IL uniform gray background in the first experiment, and the induction effect at the uniform chromatic background in the second experiment. However, if changing background appearance results in the change in induction effect, induction must be affected by factors other than simple luminance border integration.

The results of the second experiment, averaged for 6 subjects, are presented for comparison with the results of Experiment 1 as white bars vs. gray bars in Figure 4 (the individual data are shown in the inset in Figure 3). The figure shows a distinct induction minimum for stimuli presented on a gray, equiluminant to the disk, background. However, as evidenced by the white bars, altering the appearance (but not luminance) of the background resulted in the recovery of lightness induction in the disk. This finding is consistent with a hypothesis that lightness induction in the disk can be modified by *appearance* of the remote background, indicating contribution of mechanism other than border luminance contrast.

Model fits

We tested the degree to which two popular edge integration models could account for the dynamic induction
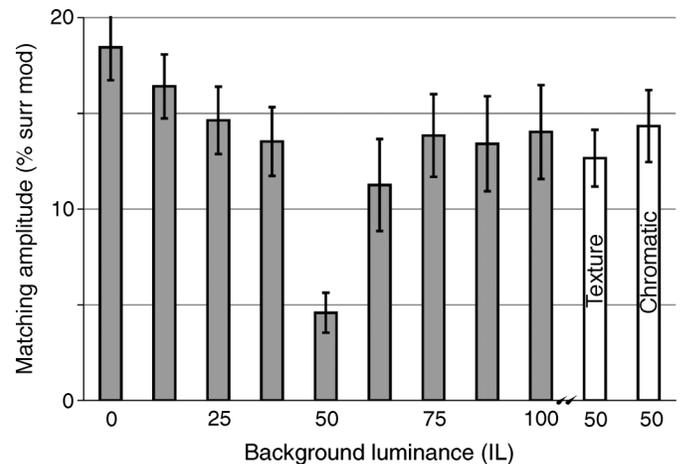
Figure 4. Average induction effects for two experiments. Background luminance is plotted along the abscissa, in instrument luminance (IL) units. Matching induction amplitude is plotted along the ordinate, in percent of surround modulation amplitude. Each bar represents the induction effect on the particular background, averaged for 6 subjects. The error bars show the standard error of the mean.

effect, by fitting the models to the data of Experiment 1. Overall, we found that both models could adequately explain the data except for the critical manipulation— when the background luminance matched the test disk luminance. To first show that extending these models to dynamic displays is effective, we fit both models to the perceptual data excluding the critical 50% IL condition (since it was apparent that the models would have difficulty with the dramatic induction decrease). The remaining data (8 data points) were then fit by the extended models, described by Equations A5 and A8 in Appendix A. For the best fit of the Extended Weighted Michelson Contrast model (as defined by the least squares method), we used a routine written in MATLAB (Math-Works, 1984–2007) to determine the weights $w1$ and $w2$. The fits by the Extended Weighted Log Luminance Ratio model were represented by horizontal lines passing through the respective mean luminance match values. Since this model's predictions were independent of background luminance level, our data are not sufficient for estimation of unique weights.

The resulting fits of the two models to the averaged data from six subjects are shown by the dotted line (Extended Weighted Michelson Contrast model) and by the dashed line (Extended Weighted Log Luminance Ratio model) in Figure 5. For comparison of the fits, we calculated the sum-of-squares error values for each model (Table 1; Columns 4 and 5).

Using the same protocol, we fit the models to individual data sets, shown in Figure 6. As evidenced by the sum-of-squares error values (Table 1; Columns 5 and 6), of the two models discussed, the Extended Weighted Michelson Contrast model provided an overall better fit to the data.
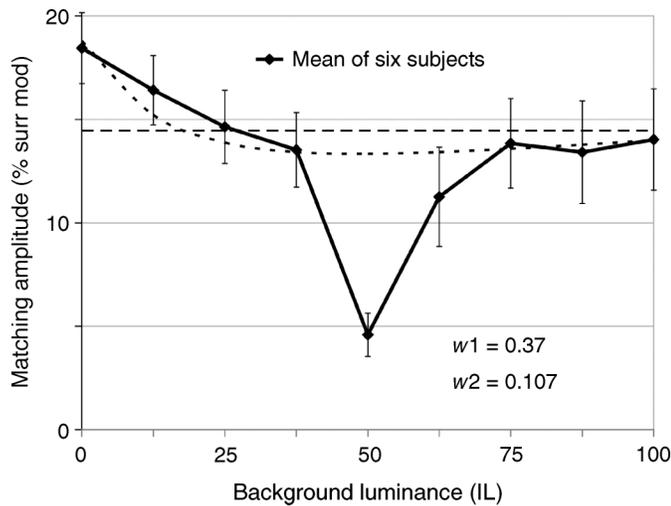
Figure 5. The averaged data of six subjects (black diamonds/solid line) are fit by Extended Weighted Michelson Contrast model (shown by the dotted lines), and by Extended Weighted Log Luminance Ratio model (shown by the dashed lines). The values of $w1$ and $w2$ represent the relative influences (or weights) of the disk/ring and the ring/background luminance borders of Extended Weighted Michelson Contrast model. All the conventions are the same as in Figure 3.

With an exception of 50% IL background data point, the Extended Weighted Michelson Contrast model seems to fit the data reasonably well.

Interestingly, for 4 subjects (SM, HK, ER, MP) the coefficients $w1$ of the Extended Weighted Michelson Contrast model (shown in Column 2 of Table 1) were about the same at 0.42–0.43, indicating the similarity of induction effect from the ring. Two other subjects (DD and JL) had a notably smaller induction effect, with $w1$ of .3 and .24 respectively. Because $w2$ depends on the distance from the disk, it was expected to be relatively small for all subjects.

Notably, for all subjects, with possible exception of JL, the data at 50% IL background were clearly outside the range predicted by the model ($p < 0.0005$ for SM, HK, ER and MP; $p < 0.005$ for DD; $p < 0.025$ for JL). The finding is consistent with the possibility that at 50% IL background, the lightness induction effect is modified by a mechanism other than border luminance contrast.

Discussion

The results of the experiment indicate that the lightness induction effect is strongly dependent on the appearance of the distant background. The magnitude of the induction effect increases along with the perceptual difference between the disk and background. Here, the perceptual differences were created through changes in luminance, chromaticity or surface texture. Importantly, the induction effect is greatly attenuated when the disk is presented on an isoluminant gray background.

What could cause this attenuation? In this work, we discuss an extension of a popular luminance border integration model, Weighted Michelson Contrast model (Reid & Shapley, 1988; Rudd & Zemach, 2004; Shapley & Reid, 1985). The extended model provides a reasonable fit to the data at all background luminance levels, with an exception of that isoluminant to the disk. The extended model predicts a slight decrease in the induction effect for backgrounds roughly isoluminant to the disk. The predicted decrease, however, does not nearly describe the observed attenuation.

From a strictly physiological viewpoint, it is implausible that the remote contrast border would practically eliminate the induction effects of the proximal, disk/ring luminance border. Edge integration is assumed to be mediated in early stages of visual processing (e.g. V1), where the receptive fields are small and horizontal

Subject	Extended models				
	Weighted Michelson Contrast				Log Luminance Ratio
	$w1$	$w2$	% Variance explained	SSerr	SSerr
sm	0.42	0.049	56	4.00	8.66
hk	0.43	0.127	61	23.02	53.25
jl	0.24	0.132	63	17.91	55.38
er	0.43	0.156	89	9.46	55.34
dd	0.30	0.137	59	26.07	64.09
mp	0.42	0.078	80	2.74	15.50
Mean of 6 subjects	0.37	0.107	72	7.02	32.49

Table 1. The comparative fits of the two models to individual data (rows 1–6) and group (row 7) data. Columns 2 and 3 show the model weights. Column 4 shows the percent of variance explained by the Extended Weighted Michelson Contrast model. Columns 5 and 6 present the respective sum-of-squares error terms for the Extended Weighted Michelson Contrast and Extended Weighted Log Luminance Ratio models.
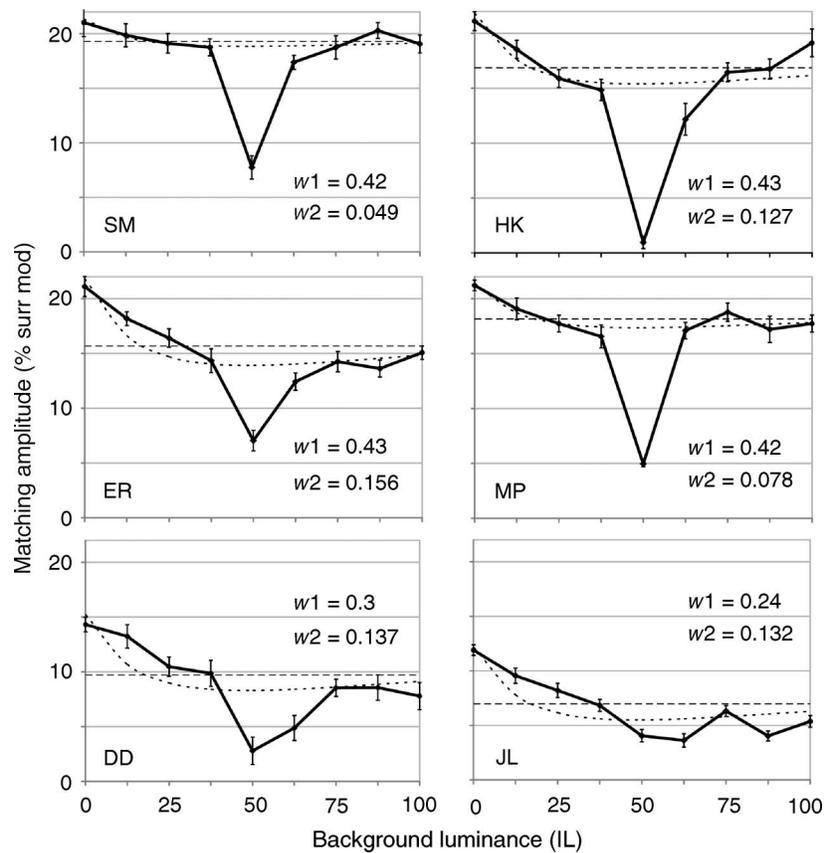
Figure 6. The individual data (black diamonds/solid lines) are fit by Extended Weighted Michelson Contrast model (dotted lines), and by Extended Weighted Log Luminance Ratio model (dashed lines). The individual weights for Extended Weighted Michelson Contrast model are given within each panel. All the conventions are the same as in Figure 5.

connections have limited range. The effect is also at odds with the results of psychophysical studies of luminance edge effects on target lightness: these effects usually depend on the distance to the target (Rudd & Zemach, 2004), and thus are expected to be minimal in our case. Therefore, we believe that a process other than simple luminance edge integration is responsible for the observed attenuation of lightness induction at backgrounds isoluminant to the disk.

We believe that the observed attenuation in induction effects on the 50% IL achromatic background is a manifestation of perceptual grouping. It has been previously shown that surfaces are grouped on the basis of having the same perceived lightness, or surface reflectance, rather than the same luminance (Rock, Nijhawan, Palmer, & Tudor, 1992). By this logic, we can expect that in a 2D image that the parts of the image will be grouped by perceived lightness. However, the question remains: can grouping, in turn, affect lightness perception? The prospect seems improbable, since it would mean that perceptual organization can override something as basic as lightness induction from the luminance edges.

There is recent evidence in support of the role of grouping in lightness perception. For example, the "dungeon illusion" (Figure 7) can be explained by lightness

induction in large diamond shapes by their surrounds, when both the diamonds and their surrounds are amodally completed behind the "dungeon grid." The luminance-based grouping of the smaller rectangular parts of the scene
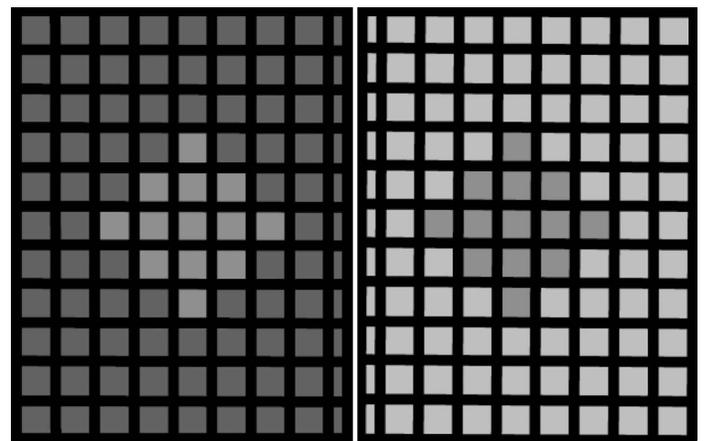
Figure 7. The dungeon illusion. The diamond-like configuration of square patches on the left-hand side appears to be lighter than that on the right-hand side, even though they have the same luminance.

into larger figures partially obstructed by the grid affects the perceived lightness of these parts (Bressan, 2001, 2006a, 2006b; Bressan & Kramer, 2008). Thus, the small rectangular patch in the very center of the left-hand panel appears to be lighter than the center patch on the right-hand panel, even though they have the same luminances and the same luminance borders.

However, the dungeon illusion presents a relatively complicated spatial configuration, and arguably involves many stages of visual processing. In contrast, our setup—with a possible exception of the temporal component—is minimalist to the extreme. Moreover, the lightness of the static versions of the similar stimulus configurations have been shown to be modeled very well by edge integration models (Rudd & Zemach, 2004, 2005). Therefore, we found the observed phenomenon surprising, as it presents evidence that higher-order visual processing can override basic lightness induction from the luminance edges.

The grouping hypothesis is substantiated by subjects' reports that at 50% IL backgrounds, the disk is perceived as part of the background, with a modulating ring superimposed over it. It is further substantiated by subjects' observations that the *ring* modulation amplitude appears to be the highest at the uniform gray, 50% IL backgrounds.

The results of Experiment 2 lend further support to the perceptual grouping hypothesis. In Experiment 2, presenting stimuli on the chromatic (yellowish) background isoluminant to the disk produced robust lightness induction effects in the disk. If just the luminance of the background was responsible for attenuation of induction, we should not have seen the difference in the induction effects between the 50% IL condition of the first experiment and the results of the second experiment. However, presenting the stimuli on either chromatic or textured backgrounds produced much larger induction effects than those observed on a 50% IL achromatic background.

To conclude, we have demonstrated the attenuation in induction effect in the disk from a distant, isoluminant to the disk background. This phenomenon cannot be explained by popular lightness induction models (Reid & Shapley, 1988; Rudd & Arrington, 2001; Rudd & Zemach, 2004, 2005; Shapley & Reid, 1985; Vladusich et al., 2006, 2007; Zemach & Rudd, 2007). However, it is consistent with an effect of perceptual grouping between the disk and remote background on lightness perception in the disk.

Appendix A

Extended Weighted Log Luminance Ratio model

For a static disk of luminance D, embedded into a ring of luminance R, and presented on a background of luminance B, the Weighted Log Luminance Ratio model describes lightness induction effect in the disk as

$$f = w1\log\left(\frac{D}{R}\right) + w2\log\left(\frac{R}{B}\right) \tag{A1}$$

where $w1$ and $w2$ are the weights. The weight $w1 > w2$; the weight $w2$ is determined by the distance of the ring/background border from the disk, and will decrease with an increase of distance.

If ring luminance changes from R_{min} to R_{max}, then according to the reasoning above, f can be thought of as f_{diff}

$$f_{diff} = f_{min} - f_{max} \tag{A2}$$

where f_{min} is lightness induction in the disk embedded in the ring at its trough luminance, R_{min}, and f_{max} is a lightness induction in the disk from the ring at its peak luminance, R_{max}.

Then,

$$f_{diff} = w1\log\left(\frac{D}{R_{min}}\right) + w2\log\left(\frac{R_{min}}{B}\right)$$
$$- \left(w1\log\left(\frac{D}{R_{max}}\right) + w2\log\left(\frac{R_{max}}{B}\right)\right) \tag{A3}$$

Re-grouping

$$f_{diff} = w1\left(\log\left(\frac{D}{R_{min}}\right) - \log\left(\frac{D}{R_{max}}\right)\right)$$
$$+ w2\left(\log\left(\frac{R_{min}}{B}\right) - \log\left(\frac{R_{max}}{B}\right)\right) \tag{A4}$$

which can be simplified to

$$f_{diff} = w1\log\left(\frac{R_{max}}{R_{min}}\right) + w2\log\left(\frac{R_{min}}{R_{max}}\right) \tag{A5}$$

Thus, the predictions of the Modified Weighted Log Luminance Ratio model for our experiment are:

1. The induction effect in the disk is independent of the luminance of the background.
2. However, the induction effect should be stronger for larger ring modulation amplitudes (i.e. simultaneous decrease in R_{min} and increase in R_{max}).
3. The maximal induction effect for rings of fixed amplitude will be observed when the ring/background border is maximally removed from the disk ($w2 \rightarrow 0$).

Extended Weighted Michelson Contrast model

Weighted Michelson Contrast model describes lightness induction effect in the disk as

$$f = w1 \frac{2(D-R)}{D+R} + w2 \frac{2(R-B)}{R+B} \tag{A6}$$

$$f_{\text{diff}} = f_{\text{min}} - f_{\text{max}} \tag{A7}$$

(all the conventions are the same as in Equations A1 and A2 of the Weighted Log Luminance Ratio model). Then

$$f_{\text{diff}} = w1 \frac{2(D-R_{\text{min}})}{D+R_{\text{min}}} + w2 \frac{2(R_{\text{min}}-B)}{R_{\text{min}}+B} - \left(w1 \frac{2(D-R_{\text{max}})}{D+R_{\text{max}}} + w2 \frac{2(R_{\text{max}}-B)}{R_{\text{max}}+B} \right) \tag{A8}$$

Re-grouping,

$$f_{\text{diff}} = 2w1 \left(\frac{D-R_{\text{min}}}{D+R_{\text{min}}} - \frac{D-R_{\text{max}}}{D+R_{\text{max}}} \right) + 2w2 \left(\frac{R_{\text{min}}-B}{R_{\text{min}}+B} - \frac{R_{\text{max}}-B}{R_{\text{max}}+B} \right) \tag{A9}$$

The first part of the Equation A9, $2w1 \left(\frac{D-R_{\text{min}}}{D+R_{\text{min}}} - \frac{D-R_{\text{max}}}{D+R_{\text{max}}} \right)$, is independent of background luminance. Let's take a closer look at the second part, which we'll call $F(B)$

$$F(B) = 2w2 \left(\frac{R_{\text{min}}-B}{R_{\text{min}}+B} - \frac{R_{\text{max}}-B}{R_{\text{max}}+B} \right) \tag{A10}$$

For black backgrounds, i.e. when $B = 0$, $F(B) = 0$. Thus, since $F(B) < = 0$ for all background luminance levels B, we can infer that when the background luminance equals zero, the induction effect in the disk will be maximal. In order to find the background luminance, at which the induction effect is minimal, we'll differentiate the Equation A10 with respect to B. By solving the resulting Equation A11, we'll determine the minimum of $F(B)$, and the minimum of our model described by Equation A9.

$$2w2 \left(\frac{2R_{\text{max}}}{(R_{\text{max}}+B)^2} - \frac{2R_{\text{min}}}{(R_{\text{min}}+B)^2} \right) = 0 \tag{A11}$$

The solution is

$$B = \sqrt{R_{\text{max}}R_{\text{min}}} \tag{A12}$$

Thus, the predicted minimal induction effect in our experiment should occur at background luminance of 48% IL, which is very close to the observed minimum at 50% IL.

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