Contrast, constancy and measurements of perceived lightness under parametric manipulation of surface slant and surface reflectance

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For perceived surface lightness to be a useful guide to object identity, it should correlate with surface reflectance. Across illumination changes, local contrast provides a valid cue to surface reflectance. However, when the surfaces surrounding an object of interest change, local contrast is not necessarily a valid cue. To generalize beyond theories that rely on local contrast as the sole explanatory construct, we require an empirical account of which stimulus factors produce effects beyond those explainable in terms of local contrast. A fruitful approach is to hold local contrast fixed while varying other aspects of the stimulus. Here we adopted this approach to study effects of object slant in three-dimensional scenes. Observers viewed real, illuminated objects and matched the apparent lightness of a variable match spot on one surface to a fixed reference spot on another surface. We parametrically varied the surface slant and local surround reflectance of the match spot. When local contrast was a valid cue to test spot reflectance, all observers were approximately lightness constant. When local contrast was not a valid cue to test spot reflectance, observers' lightness matches were intermediate between contrast matching and lightness constancy. Quantitative model comparison showed that for most observers, surface slant exerted an effect on perceived lightness beyond that explainable by the photometric properties of the local surround.

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1. Introduction

For perceived surface color to be a useful guide to object identity, it should correlate with surface reflectance. This is difficult to achieve because the sensory signal that reaches the eye confounds surface reflectance with the illuminant. For example, the light reflected from a ripe banana under bright mid-day sunlight is very different than under cloudy, late afternoon sunlight. The ability of the visual system to maintain a stable perception of surface color across changes in viewing conditions is called color constancy.

A large body of literature confirms that human vision exhibits approximate color constancy across changes in illumination (e.g. [1], [2], [3], [4], [5], [6]). A feature of most experiments is that a test object is viewed in the context of a broader scene, and the illuminant is manipulated while the objects surrounding the test are held fixed. Under these conditions, approximate color constancy may be achieved if the brain codes color through some sort of ratio between the light reflected from the test and that reflected from nearby objects ([7], [8], [9]). For example, the ratio of cone responses to the light reflected from neighboring surfaces is approximately invariant with respect to changes in illumination ([10], [11], [12], [13]).

The notion that perceived color and lightness at an image location depends on a ratio-like comparison between the stimulus at that location and at neighboring locations is at the core of many theories of color and lightness perception ([7], [14], [15], [16], [17], [18]). We will refer to this general idea as *local contrast coding*. Local contrast coding provides an intuitive explanation for some illusions (e.g. simultaneous contrast, see [19], [20] for discussion). It is also invoked to explain data from single-unit electrophysiology in the retina, the LGN and primary visual cortex (see [21]).

If all that ever changed in a scene were the illuminant, then local contrast would always provide a valid cue to object surface reflectance. Indeed, if the surfaces in the viewed scene never vary, achieving constancy would not be a challenging computational problem. What makes constancy difficult is that fact that both the illuminant and the contextual surfaces in the scene can change. For example, bananas fall from the plant to the ground. When the objects surrounding an object of interest change, local contrast is not necessarily a valid cue to surface reflectance. And the fact that local contrast does not always predict appearance is evident in various visual illusions (e.g. Adelson's checkerboard illusion, White's Illusion, again see [19], [20]). Experimental studies that explicitly separate effects of changing the illuminant from those of changing the local surround also show that knowing contrast alone is not sufficient to predict perceived color and lightness ([22], [23], [24]).

Although it is clear that we need to generalize beyond theories that rely solely on local contrast as the explanatory construct, the empirical foundations for such generalization remain to be established. An important agenda is to understand what stimulus factors produce effects beyond those explainable in terms of local contrast. To this end, a fruitful approach is

Fig. 1. Observer's view of experimental setup. The circular stages on which the cards rested could be rotated.

to hold local contrast fixed while varying other aspects of the stimulus (e.g. [23], [24], [25]). Here we adopt this approach to study effects of object pose in three-dimensional scenes.

Hochberg and Beck ([26], see also [27], [28], [29]) showed that manipulations which changed the perceived pose of a surface relative to a directional light source, while holding the stimulus constant, also changed its perceived lightness. This allowed them to demonstrate that the lightness effect was driven by the perceived scene layout, with local contrast held constant. More recent work has studied this type of effect parametrically ([30], [31], [32]), providing data that allow development and evaluation of quantitative models (e.g. [30], [32], [33]). This parametric work does not, however, separate effects of local contrast from those of geometry. To clarify the interaction of these two factors, we report experiments that combine manipulation of surface pose and of local contrast.

2. Methods

2.A. Observers

Observers were six adults between 20 and 35. Observers FP, HB and IY were paid volunteers who were naive to the purposes of the experiment and had little experience in psychophysical observations. The other observers (SRA, DBH, RTO) were lab members with varying degrees of familiarity with experimental design and aims. Note that observer DBH is not the second author (DHB).

2.B. Apparatus

Observers looked through an aperture into an experimental chamber to view two stages, as shown in Figure 1. Observers were seated 1.3 m from the stages. Ambient illumination was provided via a single incandescent theater bulb mounted above and to the left of the observer. Light from the bulb passed through a blue filter, and the voltage to the bulb was computer-controlled. In addition, illumination to part of the booth was manipulated via a hidden projector (EPSON PowerLite 8200i), which was also computer-controlled. At RGB settings of [0,0,0], the projector cast some light, and this was included in our calculations of the ambient illuminant. With the projector at [0, 0, 0] and the incandescent light at its normal experimental settings, a white piece of paper on the left stage reflected light of CIE xyY coordinates of (0.41, 0.41, 402 cd/m^2); the same paper on the right stage reflected light with CIE xyY coordinates of (0.41, 0.41, 261 cd/m^2). A box covered with black felt was placed in the booth and mounted on four adjustable silver feet, two of which can be seen in Figure 1. A small rectangular slit was cut in the box, and the box was carefully adjusted until the edge of the light generated by the hidden projector vanished through the thin slit. This light trap served to minimize observers' awareness of the hidden projector.

2.C. Stimuli

Stimuli were constructed by printing a standard gray surface (reflectance = 0.12) of size 6 cm by 6 cm centered on a Mondrian pattern (18 reflectance values, range: 0.02 to 1). Identical Mondrians (see Figure 1) were mounted on two rotatable stages; a reference stage on the left and a match stage on the right. At standard viewing distance (1.3 meters) the central surfaces subtended 2.6 ° of visual angle.

Background surfaces of different reflectance were simulated by using the hidden projector in the following fashion.

2.C.1. Simulating surfaces

First, we created six surfaces (reflectances: 0.12, 0.20, 0.31, 0.57, 0.72, 1). With the experimental lights on and the projector at its miminum settings [0, 0, 0], we took radiometer readings (PR650) of each surface at the reference location at 0 ° slant. We then took radiometer readings of each surface at the match location at each of five different surface slants (0 °, 5 °, 10 °, 15 °, 20 °). The measured chromaticity did not change with location or surface slant. We then fit the measured CIE xyY values as a function of the reflectance of the surface under question. In each case the data were well-fit by a second order polynomial. From this function, we could calculate the predicted CIE xyY values for a surface of any reflectance. We repeated this procedure for each of the match slants. From these fits, we could predict the CIE xyY values at each surface slant for a surface of any reflectance.

We then simulated surfaces by combining a standard surface with projector values calibrated to produce the expected CIE xyY values of the real surfaces. To do this, we created a standard surface (reflectance = 0.12) and took radiometer measurements of that surface at each slant under different projector settings. We repeated the measurements three times and used the average. Using algorithms from the Psychophysics Toolbox [34], we fit measured values to projector settings with cubic splines, and we used these to map between projector values and CIE xyY values.

The range and precision of surfaces that could be simulated were limited by the gamut and resolution of the projector. Because the standard surface had reflectance (0.12) we could not in principle simulate surfaces less reflective than that. Empirically, we were able to simulate adequately surfaces of reflectance 0.13 to 0.94. Because the intensity of the projector changes in discrete steps, rather than continuously, the precision with which surfaces could be simulated was limited. Because of this, we report measured CIE xyY values and reflectance values actually obtained rather than requested values. Although we could not simulate every reflectance perfectly, we could simulate changes in reflectance of about half a percent of the requested reflectance.

On each day, a geometry file determining the location of the projected light was recalibrated. The small black felt strip around the inner edge of the Mondrian (Figure 1) served to hide any residual misalignment.

In the experiments, spots of different reflectance were simulated by projecting onto the the reference and match squares. At 0 ° slant, spots were circles with a radius of 1.25 cm and at standard viewing distance they subtended 1.1 ° of visual angle. As with the geometry of the projected squares, the geometry of the projected circles was manipulated with changing slant to simulate a physically rotating circle.

Hereafter, we refer to manipulations of match and reference simply as reflectance changes rather than as simulated reflectance changes. All reported luminance values were measured in situ.

2.D. Psychophysical Task

Observers initiated a block of trials by pressing a key, after which a shutter opened to reveal the experimental booth (Figure 1). On each trial, observers performed the following 2AFC psychophysical task. Two spots were presented, one at the center of the reference surround (gray square on the left stage, Figure 1) and one at the center of the match surround (gray square on the right stage, Figure 1). Observers were instructed to move a joystick to indicate which spot appeared lighter. Reference and match spots were presented for 1500 ms, accompanied by a 250 Hz tone. Across all blocks of trials, the reference surround reflectance was fixed at 0.16 and the reference stage was fixed at 0 ° slant. Match surround reflectance and match slant were varied between blocks of trials, but remained fixed within a block of trials. Match surround reflectance took values of 0.16, 0.25, 0.34, 0.44, 0.56, and match slant took values of 0 °, 10 ° and 20 °. Match surround reflectance and slant were parametrically varied, yielding 15 possible match conditions. Within each block of trials (one match surround reflectance / slant condition), we calculated a point of subjective equality (PSE) for 5 different reference spots (reflectance values = 0.18, 0.20, 0.22, 0.26, 0.32). One match surround condition (reflectance = 0.34) was added midway through the experiment, and two subjects (IY, HB) were not tested in this condition. All reference spots were increments.

The procedure for each reference spot was as follows: On each trial, the reflectance of the match spot was determined by implementing an adaptive staircase calculated by the QUEST algorithm ([35]) as implemented in the Psychophysics Toolbox ([34]). For each of the 5 reference spots, we ran three interleaved staircases (10 trials each) with different target response probabilities (25%, 50%, 75%). In each experimental session, observers ran between four and seven blocks of 150 trials each. A block lasted approximately six minutes, and included trials for one match slant and one match surround reflectance.

Between blocks, the shutter closed while the experimenter initiated a new block of trials with a different match slant and match surround reflectance. Observers were offered the opportunity to take a break in between each block of trials, and each experimental session lasted between 35 minutes and 1 hour.

Before any experimental data were collected, each observer underwent an induction procedure designed to encourage a strategy of matching surface reflectance rather than luminance or contrast. In a separate experimental room, observers were seated in front of a plywood box that had been divided in two, with each side illuminated by a single directional light source. The right side of the box contained a paint palette, and the left side of the box contained three cubes, each of which were painted a different shade of gray. While looking at the cubes, observers were told that in the experiment, they would be matching painted surfaces or simulations of such surfaces. Observers were instructed to hold the painted cubes and view them in different orientations and locations within the plywood box. Subsequently, observers were shown fixed cubes with only one painted surface, and asked to pick the same paint from the palette.

2.E. Data Analysis and Predictions

Within a block of trials, we fit the probability of reporting that the match spot was lighter as a function of match spot reflectance with a 4-parameter cumulative Gaussian. Fits were obtained using a maximum likelihood method ([36]) implemented by the psignifit toolbox in Matlab (see http://bootstrap-software.org/psignifit/). Two parameters (α, β) determine the

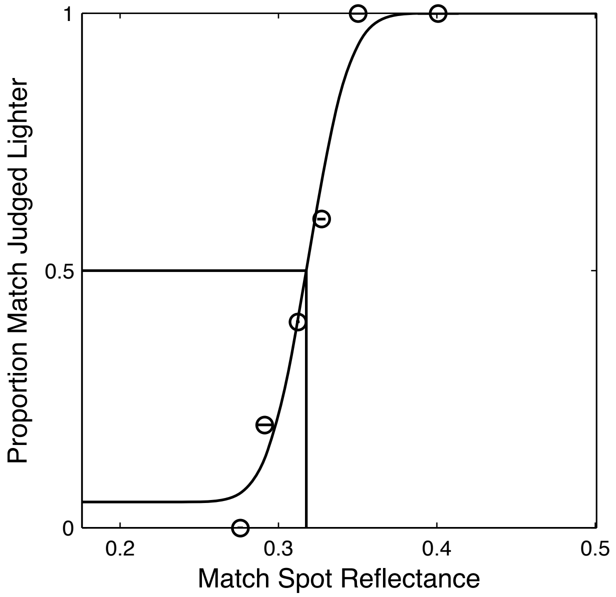

Fig. 2. Example psychometric function for observer DBH. On each trial, the reference spot reflectance was 0.32, the reference surround reflectance was 0.16, the reference slant was 0 °, the match surround reflectance was 0.16, and match slant was 0 °. The match spot reflectance was selected on each of 30 trials by the staircase procedure. For visualization purposes, the 30 trials have been divided into six bins of five trials each. In each bin, the reflectance values and responses were averaged to get the x- and y- values for each plotted data point. The horizontal bars show the variance of the match spot reflectances within that bin. The black line represents the best fit cumulative gaussian to the data. Black vertical line represents the extracted point of subjective equality (PSE), or where the best fit curve reaches 50%.

shape of the cumulative Gaussian, and there is a floor parameter (γ) and a ceiling parameter (λ). The point of subjective equality (PSE) was defined as the reflectance at which observers reported the match spot as lighter on 50% of trials. Each PSE was thus based on 30 forced-choice trials. Figure 2 shows the data and fit for one reference spot in one match condition. Pilot data indicated that within a subject, such PSEs collected on different days were highly consistent, and in fact were often identical within the reflectance resolution of our hidden projector. Because of this consistency, we collected 2 PSEs per subject per condition.

3. Results

We measured the perceived lightness of small match spots across parametric changes of slant and local surround reflectance. First, in Section 3.A we document that lightness constancy was relatively high when match surround reflectance and slant were identical to reference surround reflectance and slant. Then, in Sections 3.B and 3.C, we examine lightness constancy under manipulations of match slant (Section 3.B), where local contrast is a valid cue to reflectance, and under manipulations of match surround reflectance (Section 3.C), where local contrast is not a valid cue. Finally, in Section 3.E, we examine interactions between surround reflectance and slant.

3.A. Equal Slant and Surround

Figure 3 shows average PSEs for all six observers as a function of reference spot reflectance, when the match surround reflectance was equal to the reference surround reflectance. In this condition, the background squares on the left and the right have the same reflectance (see Figure 1). Because the light source is to the left of the observer and angled across the booth, the incident illumination at the left location (reference) is about twice the incident illumination at the right location (match). If observers were lightness constant, then by definition the reflectance of each PSE would be identical to the reflectance of the reference spot. In other words:

$$R_{match\_spot}(PSE) = R_{reference\_spot} \tag{1}$$

where R indicates reflectance values. The predictions of lightness constancy are shown as the solid line in Figure 3. In general, observers exhibited good lightness constancy for this condition, with some individual variation.

To understand the deviations from constancy, it is helpful to consider the pattern that would be shown by an observer who matched the luminance of the spots rather than their reflectance. This prediction is obtained by:

$$L_{match\_spot}(PSE) = L_{reference\_spot} \tag{2}$$

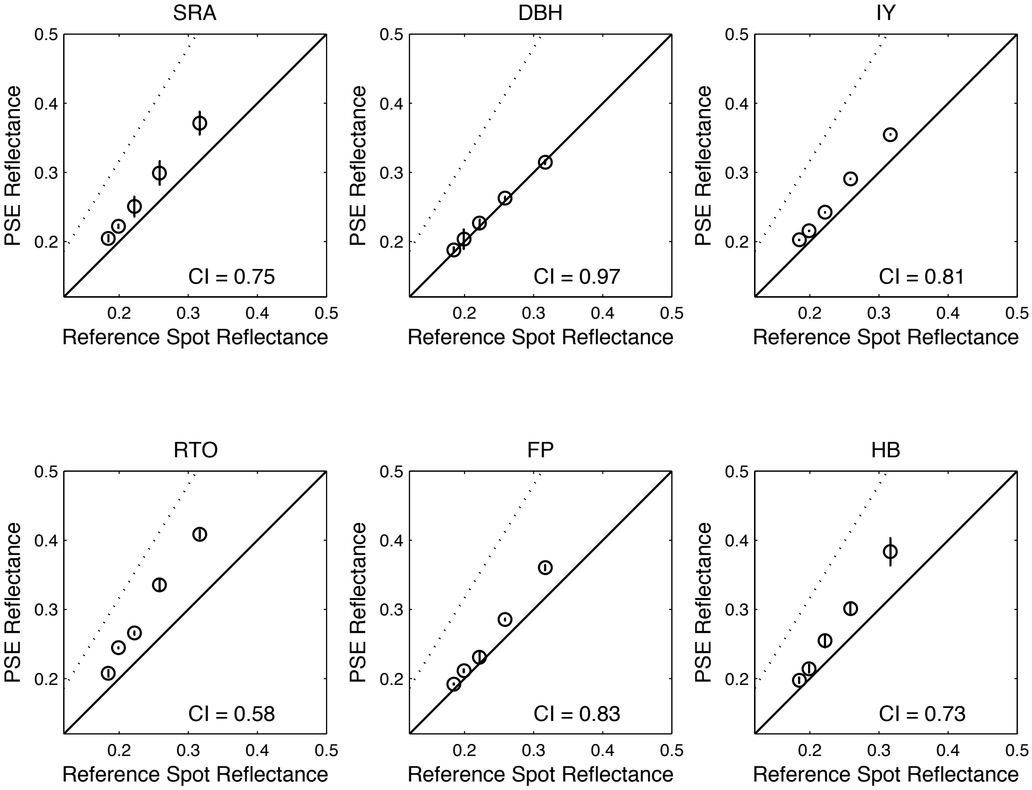

Fig. 3. PSE as a function of reference spot reflectance for all six observers in one condition (reflectance of match surround = 0.16, match slant = 0°). Error bars represent s.e.m. across sessions. Solid line represents PSE predictions for both contrast matching and lightness constancy, which coincide for this condition. Dashed line represents luminance matching predictions. The error-based constancy index is reported in the lower right corner of each panel.

where L indicates reflected luminance. Because the illuminant intensity is less at the match location than at the reference location, a much higher reflectance (PSE) is needed equate luminance of the match spot and the reference spot. The predictions of luminance matching are shown as the dashed lines in Figure 3.

When match surround reflectance and reference surround reflectance are the same, local contrast is a valid cue to the reflectance of the match spot; in other words, the predictions of local contrast matching are the same as predictions of lightness constancy (solid black line in Figure 3. That is:

$$R_{match\_spot}(PSE) = \left[\frac{R_{reference\_spot}}{R_{reference\_surround}}\right] * R_{match\_surround.} \tag{3}$$

To quantify the degree of constancy, we calculated an error-based constancy index (after [31]) for each subject by comparing the difference between the measured data point and the predictions made from both lightness constancy and luminance matching, as follows:

$$CI_{error} = \frac{\sqrt{\epsilon^2_{luminance}}}{\sqrt{\epsilon^2_{luminance}} + \sqrt{\epsilon^2_{constancy}}} \tag{4}$$

Here each ϵ^2 is calculated as the sum of the squared error between each observed PSE and the relevant prediction. The index can range from 0 to 1, where 1 represents perfect lightness constancy (data along solid black line) and 0 represents luminance matching (data along dashed black line, a failure of lightness constancy). Intuitively, the index characterizes where the data fall with respect to the two different predictions. In this condition, the CI values of observers ranged from 0.58 to 0.97, as indicated in the individual plots.

3.B. Slant Manipulation

Observers were approximately lightness constant with respect to the illumination gradient caused by the directional light source. To determine whether observers retained lightness constancy across illumination changes mediated by other scene variables, we manipulated match slant by rotating the stage on which the match card was mounted (see Figure 1). Under this manipulation, we kept the match surround reflectance the same as the reference surround reflectance. Rotating the stage changed the effective illumination incident at the match location. However, since the reflectance of the surfaces did not change, local contrast remained a valid cue to surface reflectance.

Figures 4 and 5 plot PSE as a function of reference spot reflectance when the match slant was $10\,^\circ$(Figure 4) and $20\,^\circ$ (Figure 5). If subjects were lightness constant, then the reflectance of their PSEs should be unaffected by changing the match slant. This prediction is shown by the solid line, which is unchanged across Figures 3, 4, and 5. Since rotating the stage changes

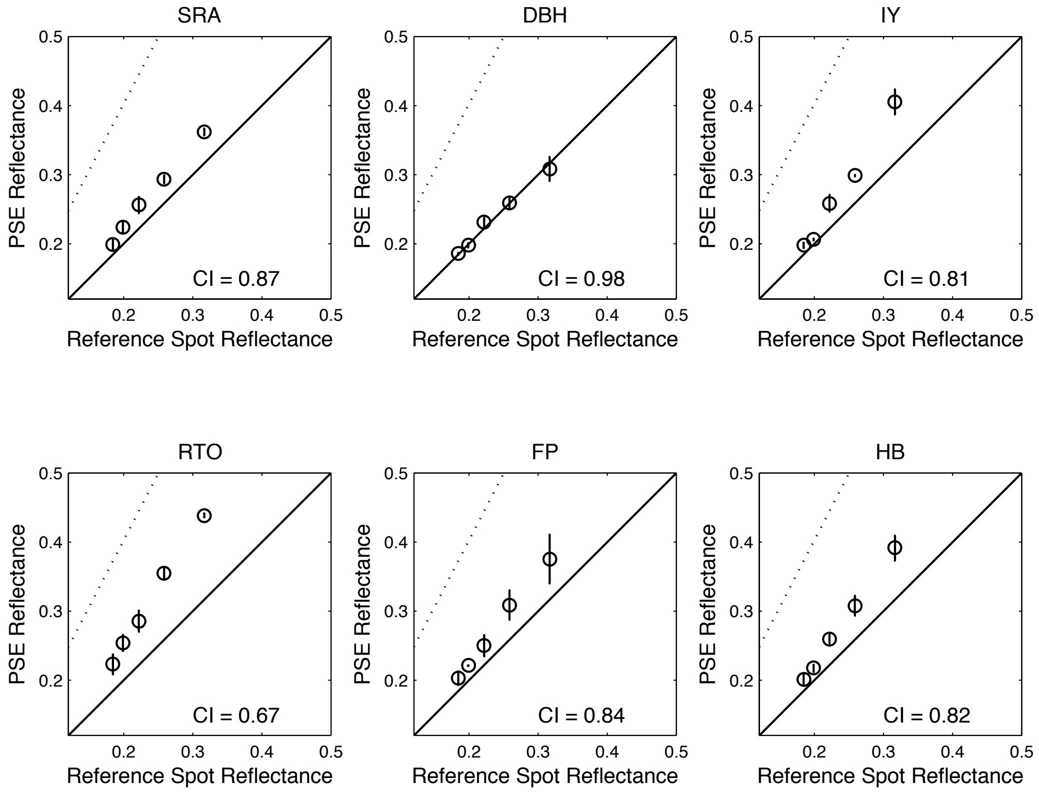

Fig. 4. PSE as a function of reference spot reflectance for all six observers in one condition (reflectance of match surround = 0.16, match slant = 10 °). Error bars represent s.e.m. across sessions. Solid lines represents PSE predictions for contrast matching and lightness constancy. Dashed lines represents luminance matching predictions. The error-based constancy index is reported in the lower right corner of each panel.

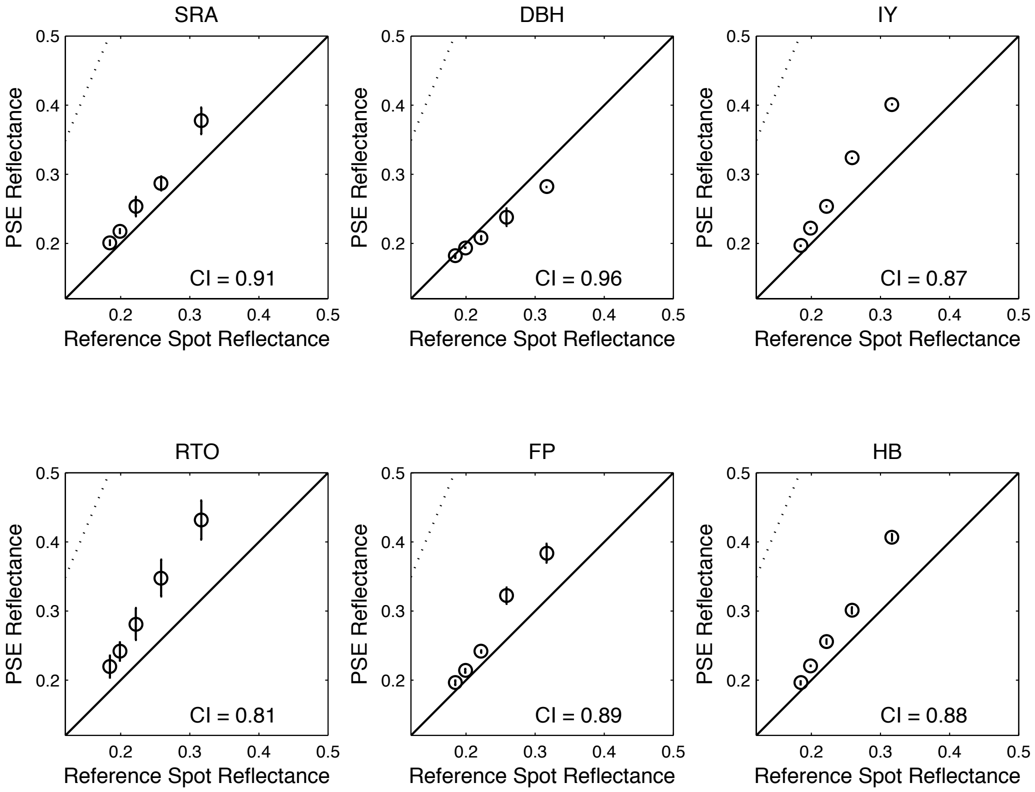

Fig. 5. PSE as a function of reference spot reflectance for all six observers in one condition (reflectance of match surround = 0.16, match slant = 20 °). Error bars represent s.e.m. across sessions. Solid lines represents PSE predictions for contrast matching and lightness constancy. Dashed lines represents luminance matching predictions. The error-based constancy index is reported in the lower right corner of each panel.

the illumination incidental on the match, however, the luminance-matching predictions do change. If perceived lightness followed luminance rather than surface reflectance, PSEs would increase with slant (dashed lines in Figures 3, 4, and 5).

Observers' PSEs were relatively constant across changes in slant; the data remain close to the solid lines rather than deviating further towards luminance matching. The CI values also reveal this constancy.

Together, Figures 3, 4 and 5 show two effects for each observer. The first (Figure 3) is how much constancy the observer shows across a spatial illumination gradient. The second (compare Figure 3 with Figures 4 and 5) is how much constancy the observer shows with respect to a change in slant, once the effect of illumination gradient has been taken into account. We can separate these two effect by normalizing the PSE at each match slant by the PSE at 0 match slant. We then plotted PSE as a function of match slant for each reference spot (Figure 6). This normalization preserves information about relative constancy across changes in slant, but discards information about absolute constancy.

Observers exhibited very high degrees of lightness constancy across changes in slant, as evidenced by the fact that for each reference spot (each different color), the normalized PSE stayed the same as slant changed (slopes of colored lines are near 0). If subjects were perfectly lightness constant, PSE should not change with slant; that is, the slope of a line through the points should be 0. However, if perceived lightness followed luminance rather than surface reflectance, PSEs would increase with match slant (dashed black line). We quantified the degree of relative constancy using the same constancy index as in Figures 3, 4, and 5, applied to the normalized PSE values. Constancy index values were close to 1 for all six observers.

3.C. Reflectance Manipulation

When match slant was manipulated and local surround reflectance held fixed, perceived lightness followed surface reflectance rather than luminance. However, local contrast under this slant manipulation remained a valid cue to surface reflectance. Next, we examined whether observers would show similar degrees of lightness constancy across a manipulation where local contrast did not predict the reflectance of the match spot.

To do so, we held match slant fixed at 0° and varied match surround reflectance. The reference surround reflectance was always 0.16. We used match surround reflectances of 0.25, 0.34, 0.44 and 0.56.

To examine how perceived lightness of the match spot changed with match surround, we again normalized PSEs by the PSEs in the condition where match surround reflectance and match slant were the same as reference surround reflectance and reference slant (data in Figure 3). The normalized PSEs as a function of match surround reflection are shown in

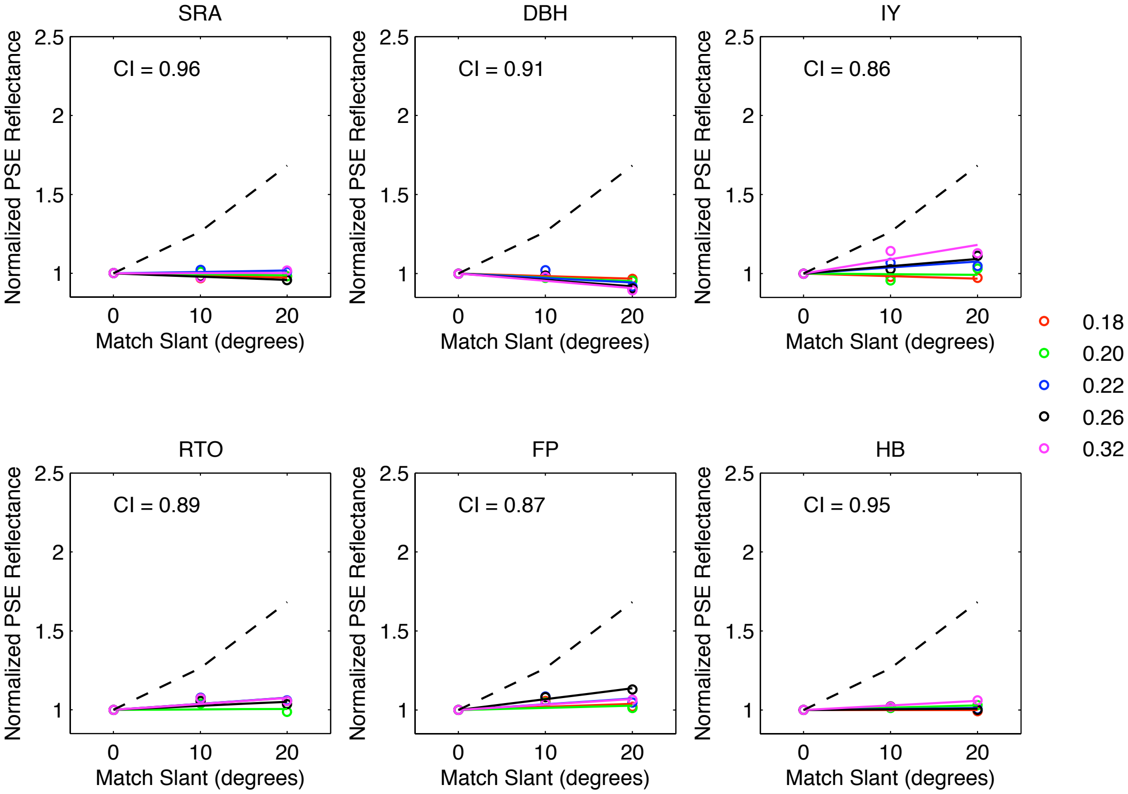

Fig. 6. Normalized PSE as a function of match slant for all six observers. Each color represents a different reference spot reflectance. Reference surround was equal to match surround (0.16). At each slant, the PSE was normalized by the PSE at slant 0. Colored lines represent the best fit line through the data points, when the line was constrained to go through the point (0, 1). Solid black lines represent predictions of lightness constancy / contrast matching. Dashed black line is predictions of luminance matching. Constancy index values are calculated using normalized PSEs.

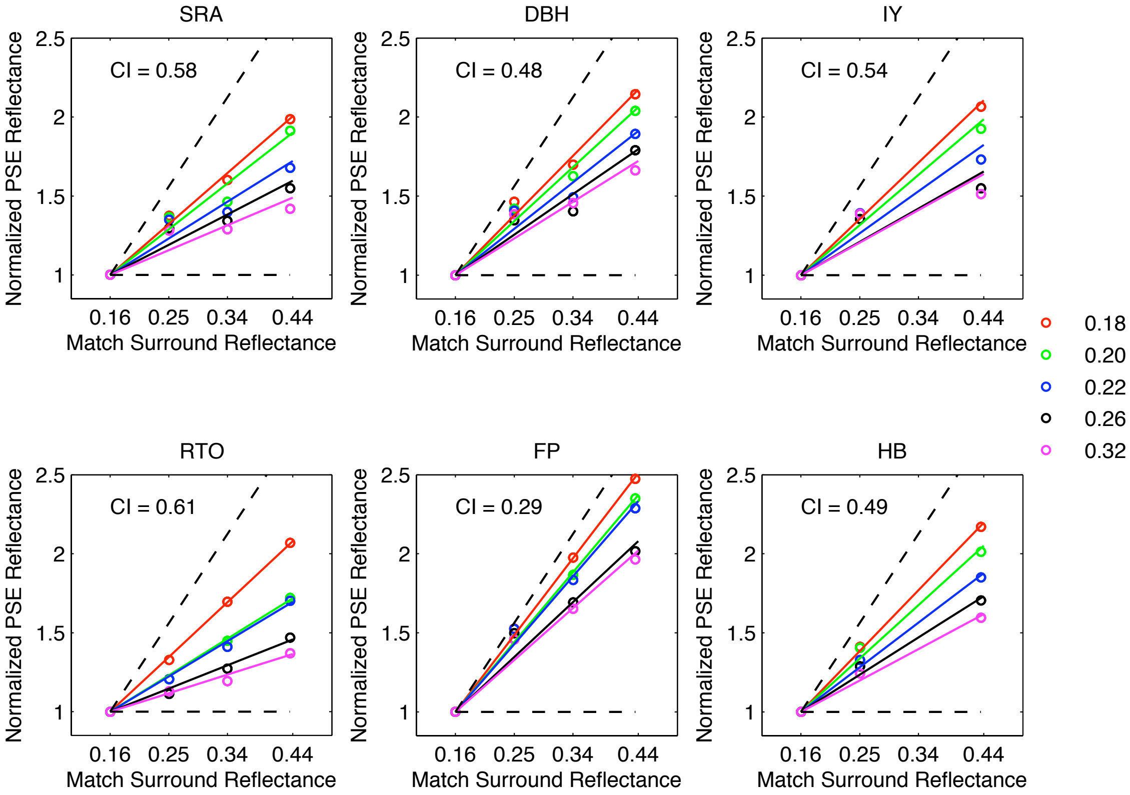

Fig. 7. Normalized PSE as a function of match surround reflectance for all six observers when match slant was equal to reference slant (0°). Each color represents a different reference spot reflectance. At each match surround, PSE was normalized by the PSE obtained in the condition where match surround and reference surround were of equal reflectance (0.16). Colored lines represent the best fit line through the data points, when the line was constrained to go through the point (0, 1). Solid black lines represent predictions of lightness constancy / luminance matching. Dashed black line shows predictions from contrast. Constancy index values are calculated using normalized PSEs.

Figure 7. If observers were lightness constant across changes in match surround reflectance, then their PSEs would not change and the data would fall along the dashed horizontal lines in Figure 7. Changing the match surround reflectance affects the local contrast of the match spot. If perceived lightness followed local contrast, then PSE would increase with increasing match surround reflectance (angled dashed line in Figure 7).

The data show that local contrast affected perceived lightness. As match surround reflectance increased, PSEs also increased. However, although PSEs were affected by local contrast, they were not completely determined by it. Normalized PSEs were significantly lower than contrast matching predictions for all observers at each match surround reflectance ($p < 0.05$, paired t-test) except one (observer fp, match surround 0.25). As in Figure 6, we calculated an error-based constancy index, where data were compared to lightness constancy predictions and contrast matching predictions. As with the previous index, 1 represents complete lightness constancy. When match surround reflectance was varied, constancy index values ranged from 0.29 (observer FP) to 0.61 (observer RTO).

3.D. Intermediate Discussion

Figure 8 summarizes the data reported above. When reference slant and surround reflectance were the same as match slant and surround reflectance, observers were fairly lightness constant across the illumination gradient, as seen by the high constancy index values in the top left panel of Figure 8. Observers were also constant across changes in match slant (top right panel, Figure 8), when local contrast was a valid cue to the surface reflectance of the match spot. They were less constant across changes in match surround reflectance (bottom left panel, Figure 8), when local contrast was not a valid cue.

An additional effect may be seen by closer examination of Figure 7: the effect of local contrast depends on the reflectance of the reference spot. This is seen in Figure 7 by noting the spread in the data for the separate reference reflectances. For each observer, the magenta points (highest reflectance reference spots) are closer to lightness constancy (dashed horizontal line) than are the red points (lowest reflectance test spot).

To document this effect, we compared two different model fits to the data. We assumed that the normalized PSEs in Figure 7 could be modeled as a linear function of match surround reflectance constrained to go through the normalization point of (0.16, 1). We then compared the model predictions made when PSEs for each reference spot were fit separately (colored lines in Figure 7) to predictions made when all PSEs were modeled by one line (not shown). We used the AIC (Akaike's information criterion) [37] to compare the two models. This criterion assigns scores to different models, with a lower score meaning that a model is preferred. Briefly, the likelihood of the data (L) given a maximum-likelihood fit to the the model is calculated, and the model score decreases with increasing likelihood. The model is

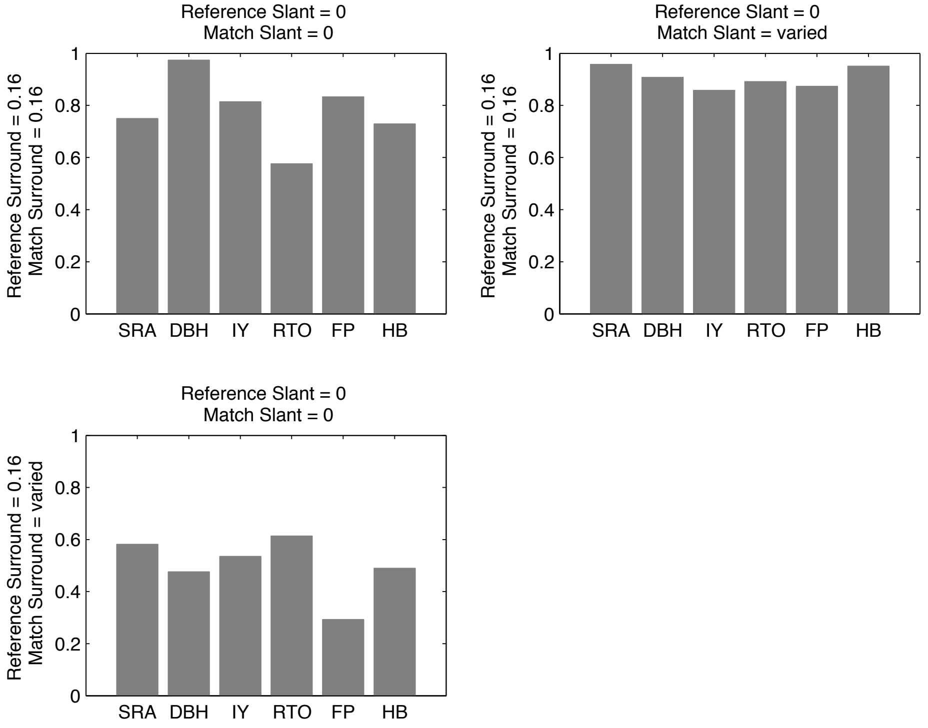

Fig. 8. Constancy Index values for each subject. Each panel represents CI values calculated in across a different condition. Top left: match slant and surround reflectance are the same as reference slant and surround reflectance. Values reported in Figure 3. Top right: match surround reflectance and reference surround reflectance are the same, match slant is varied. Values reported in Figure 6. Bottom left: match slant and reference slant are the same, match surround reflectance is varied. Values reported in Figure 7.

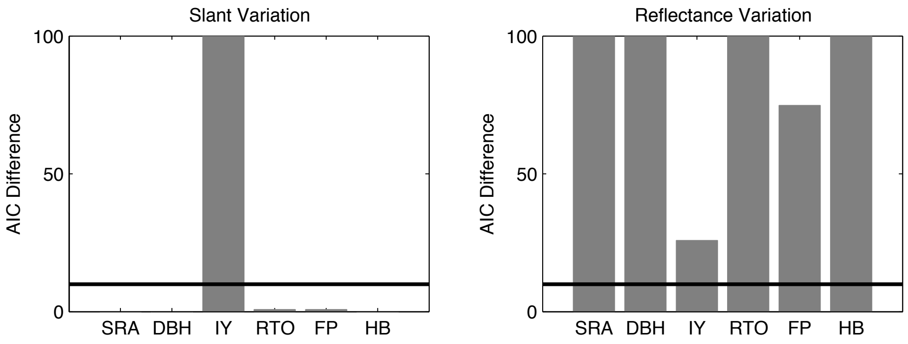

Fig. 9. Difference in the AIC score between a model in which normalized PSEs for all reference spots are predicted by one line and a model in which normalized PSEs are predicted by five lines, one for each reference spot. Each bar is a different subject. ΔAICs are shown for slant manipulation (left figure) and match surround reflectance manipulation (right figure). Horizontal black line indicates a ΔAIC of 10.

then penalized by the number of its free parameters (K).

$$AIC \ = -2ln(L(\theta \mid y) + 2K \tag{5}$$

Two models can then be pitted against each other, with the difference between AIC scores (ΔAIC) determining the extent to which one model is preferred over the other. ΔAIC values of greater than 10 are taken to indicate that one model is significantly preferred ([38]).

All subjects showed high ΔAICs in the direction of preferring the model that fit each reference reflectance separately. This means that the effect of manipulating the match surround was dependent on the reflectance of the spot to which PSEs were being made (Figure 9).

For comparison, a similar analysis revealed that the effect of match slant was not dependent on the reflectance of the reference spot (see low ΔAICs in the left panel of Figure 9 for all but one observer). These ΔAICs are also consistent with the observation that, except for observer IY, the best-fit lines for each reference spot shown in Figure 6 tend to lie on top of each other.

3.E. Interactions between contrast, slant, and reflectance

Manipulations of slant and surround reflectance each change the luminance surrounding the match spot. Made independently, these luminance changes had different effects on perceived lightness. That is, subjects were more lightness constant when luminance changes were induced by manipulating slant than when luminance changes were induced by changing match

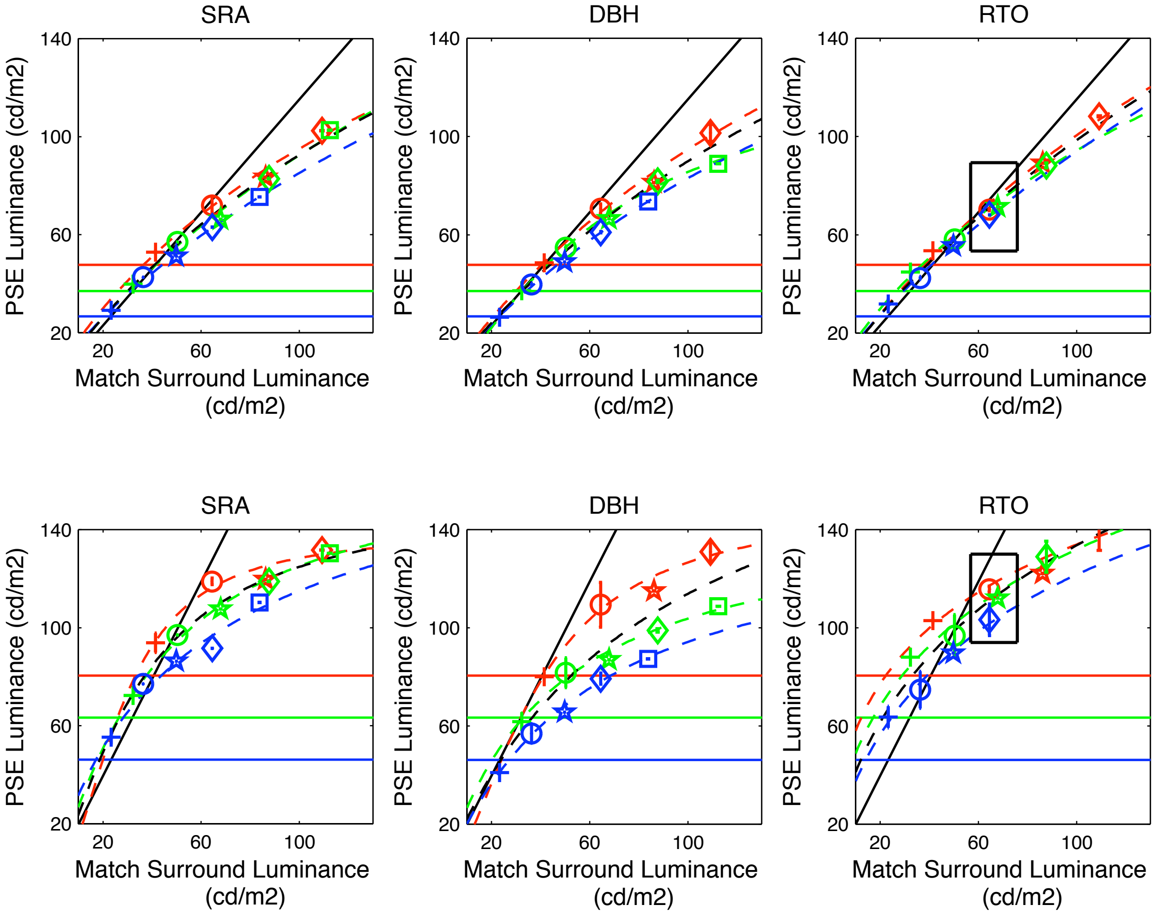

Fig. 10. PSE as a function of match surround luminance for three observers for the lowest reflectance reference spot (top panels, reference spot reflectance = 0.16) and the highest reflectance reference spot (top panel, reference spot reflectance = 0.32). Each color represents a different slant (red = 0°; blue = 10°; green = 20°) and each symbol represents a different match surround reflectance (cross = 0.16; circle = 0.25; star = 0.34; diamond = 0.44; square = 0.56). Black solid lines are predictions from contrast matching, and colored solid lines are predictions for full lightness constancy at each slant. Dashed lines represents maximum likelihood fits of the data to the modifed Naka-Rushton function. Colored dashed lines fit data separately by slant, black dashed line fit data from all slants simultaneously.

surround reflectance. To explore more completely the relationship between local contrast and perceived lightness, we varied match slant and match surround reflectance parametrically and investigated whether the effects of slant and surround reflectance could be modeled with one function.

Figure 10 presents PSEs for 3 observers as a function of match surround luminance for all 14 match conditions, for two different reference spots. Match slants are distinguished on the plot by color, and match surround reflectances are distinguished by symbol shape. All data points on a single panel were matches made to a single reference spot. Since both manipulations (slant and reflectance) change the luminance of the local surround, we characterized the PSE as a function of a single variable, the luminance of the match surround. Because the analysis presented in Figure 9 suggested that the effects of match surround reflectance were dependent on the reference spot reflectance, we considered separately PSEs made to each reference spot.

Figure 10 confirms the conclusion we drew from the data in Figure 7: the full range of data are not explainable as contrast matches (predictions shown as solid black line). It could be, however, that the deviations from contrast matching are completely accounted for by the photometric properties of the surround with no additional effect of slant. In this case, when data are plotted as a function of surround luminance, they should fall on a common curve, independent of slant. To test whether this was the case, we compared fits made to all data simultaneously (black dashed lines, Figure 10) to fits made separately at each slant (colored lines, Figure 10). This is the same type of model comparison used in the previous section to test whether or not the effect of match surround reflectance on perceived lightness was dependent on reference spot reflectance.

To fit the data in Figure 10, we used a the three-parameter Naka-Rushton function, as follows:

$$L_{match\_spot}(PSE) \ = M\frac{(gL_{match\_surround}I)^n}{(gL_{match\_surround})^n+1}. \tag{6}$$

Parameters that best-fit the data were determined using parameter search in Matlab. Of primary interest in modeling the data is whether a single function of luminance accurately described PSEs in all 14 match conditions simultaneously, or whether the PSEs must be separated into groups by slant in order to be well-fit. Our choice of parametric function was somewhat arbitrary. The Naka-Rushton function has often been used because its parameters are intuitively related to relevant psychophysical, physiological or physical variables; here its use is dictated by its utility in describing the data.

To determine whether all PSEs for a particular subject and reference spot reflectance could be well fit be a single function, we compared a model where PSEs for all 14 slant / surround conditions were fit simultaneously (1 function / 3 parameters) to a model where PSEs were

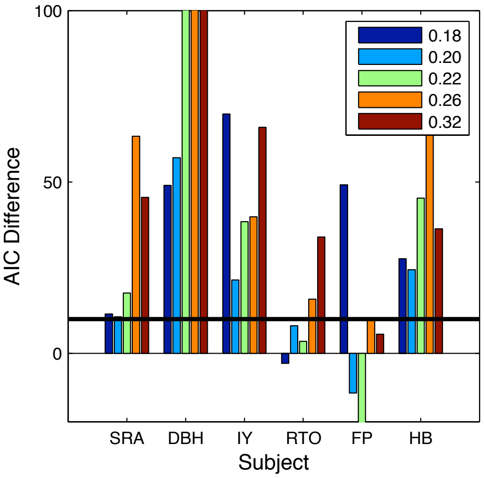

Fig. 11. Difference in AIC score between the two models for each reference spot reflectance (dark blue = 0.18, light blue = 0.20, green = 0.22, orange = 0.26, red = 0.32) and each observer. Higher bars indicate that 9 parameters were required to fit the data. Horizontal black bar represents ΔAIC of 10.

separated into three groups by slant (3 functions / 9 parameters).

For some observers and some reference spots, it was apparent that slant mattered. For example, in the lower right panel of Figure 10, the three match surrounds outlined by the black box had roughly equal luminance, though they differed in both slant and reflectance. For this reference spot, the PSEs were clearly distinct, indicating that perceived lightness was dependent on which combination of reflectance and slant determined a particular match surround luminance. However, for the same observer in the same match condition, slant played a less important role in perceived lightness when matches were made to a lower reflectance reference spot (top right panel Figure 10). Though contrast alone could explain PSEs made to this reference spot, the function of contrast that fit the data well (black, dashed line) was not a simple ratio of local luminance values (solid black line). These are two clear examples of when slant either mattered (bottom right panel) or did not (top right panel). However, the degree to which slant mattered was not as obvious for other observers and reference spot reflectances.

We compared AIC scores of model fits made to all data simultaneously with AIC scores of model fits made to data at each slant separately. Figure 11 shows the ΔAIC between the model in which slant mattered, and the model in which it did not. The height of the bar represents the degree to which the model that takes into account slant was preferred. ΔAICs greater than 10 are thought to indicate statistical preference. For each observer, slant tended to play a more important role for higher reflectance reference spots. Although there was variability between observers, we found statistical support for the full model at high contrast reference spots for all observers except for one (FP).

To verify that the Naka-Rushton function characterized the data well, we also fit each PSE with its own mean, so that PSEs were described by 14 parameters. We then calculated the relevant AIC score. ΔAICs between the 14-parameter model (each point fit by its own mean) and the 9- parameter model (PSEs separated by slant and fit with Naka-Rushton function) were less than 10 for all but one reference spot for one subject (FP, data not shown). Small ΔAICs mean that moving to 14 parameters from 9 parameters does not capture any more variability in the data, indicating that 9-parameter Naka-Rushton model provided a good description of the data.

4. Discussion

We measured perceived lightness across parametric changes in match slant and match surround reflectance. These two manipulations both change the luminance of the match surround, but a perfectly lightness constant system should treat those changes differently.

We found relatively high degrees of lightness constancy in the condition where match slant and surround reflectance were equal to reference slant and surround reflectance (Figure 8, top left panel). In this condition, there was an illumination gradient across the chamber. The degree of lightness constancy we found (0.58 to 0.97) is similar to that reported in previous studies of lightness and color constancy in both simulated and real-world scenes ([23], [24], [39]).

Perceived lightness of a spot was highly constant across changes in match slant for all subjects (Figure 6, Figure 8, top right panel) when match surround reflectance was fixed. This finding stands in contrast to other studies that have shown much less lightness constancy and higher inter-observer variability under slant manipulations ([30], [31]). For example, Ripamonti et. al. [31] reported that many observers were closer to luminance matching than to constancy. Using the same constancy index, Ripamonti et al. reported CI values ranging from 0.17 to 0.54, whereas we found CI values from 0.87 to 0.96 (Figure 8).

What can account for this large discrepancy in the results? A key difference between the studies lies in what constituted the local surround of the match surface. In the Ripamonti et. al. study ([31]), the match surface was presented without an immediate coplanar surround, so that the role of local contrast in these experiments is unclear. In the present study, the match spot was immediately surrounded by another surface, as well as by the Mondrian pattern (see Figure 1). In the special case where match surround reflectance was the same as the reference surround reflectance, the local contrast between match spot and match surround provided a valid cue to surface reflectance across variations in slant (Figure 6).

Several theories of lightness perception advocate the importance of local contrast cues in determining perceived lightness, though these theories differ in their emphasis and details of how contrast cues are combined, especially for 3D scenes ([19], [40], [41]). Because of the differences in local contrast, the discrepancy between studies is not surprising. Note also that in both studies, stimuli were presented within the same natural environment. Stimuli were real, illuminated objects seen in depth in an experimental booth (see Figure 1). In both studies, global context was sufficiently complex that changing slant should have been unambiguously perceived. In fact, observers in the Ripamonti study made accurate judgments about surface slant independent of their judgments about surface lightness. Therefore, the higher lightness constancy in our study compared to the Ripamonti study is unlikely to have resulted from a more accurate representation of slant itself.

Perceived lightness was less constant across changes in match surround reflectance (Figure 7) when match slant was fixed; in this circumstance local contrast was not a valid cue to surface reflectance. Although observers exhibited less lightness constancy when match surround reflectance was varied than when match slant was varied (range of CIs under reflectance manipulation: 0.29 - 0.61; range of CIs under slant manipulation: 0.87 - 0.96), matches were still significantly different than would be expected if local contrast were the sole determinant of perceived lightness. Initially, we were surprised by this finding. Though the match surround reflectance varied in different conditions, the large Mondrian pattern enclosing the immediate match surround was identical to the large Mondrian pattern enclosing the reference surround. Mondrian patterns remained unchanged across all experimental conditions and this provided an unambiguous cue that what was varied was match surround reflectance, rather than match illumination. Thus, at first glance our findings seem at odds with compelling visual illusions and quantitative studies which demonstrate that the role of local contrast can be strongly mediated by global context or scene variable ([19], [20], [42]).

We examined this apparent discrepancy by comparing the data from one such study ([42]). Using stimuli modeled after Adelson's checkerboard illusion, ([20]) Hillis and Brainard demonstrated that even with equivalent local contrast, matches made in their "paint" conditions differed significantly from matches made in their "shadowed" conditions. This is a striking perceptual effect. However, when we compared the matches in Hillis and Brainard's "shadowed" condition to full lightness constancy predictions, we found substantial deviations. Constancy index values in the Hillis and Brainard([42]) study, computed with the index we use here, were lower than those found in our experiments (Average CI = 0.13 for "shadowed" conditions).

Our results show that local contrast has an important but not exclusive effect on perceived lightness even in rich three dimensional scenes. This is consistent with the conclusion drawn by Kraft and Brainard ([24]) for color constancy. The effect of local contrast is weakened, but not eliminated, when local contrast is not a valid cue to surface reflectance. In these cases, perceived lightness is intermediate between contrast matching and lightness constancy. However, the weakening of local contrast is a large perceptual effect, as seen by the comparison of the size of our effect with that of previously published data ([42]). We caution that finding a large perceptual effect in a study does not necessarily imply that the visual system has achieved full lightness constancy.

When both match surround and match slant were parametrically varied, most of the observers appeared to behave differently to changes in surround luminance caused by reflectance and changes in surround luminance caused by slant variation, and this tendency was greater when the reference spots were of higher reflectance. However, there was a great deal of inter-observer variability in the strength of this effect, and in its dependence in reference spot contrast (Figure 11). This inter-observer variability stands in contrast to high intra-observer reliability, where PSEs for the same condition tested on separate days was often identical within the resolution of our experimental apparatus. What can account for this inter-observer variability? Though we put substantial effort into creating experimental conditions and instructions that would elicit similar response strategies from all observers, it remains possible that observers perceived surfaces similarly, but employed different strategies in making responses. Some studies have reported that in lightness tasks, observers can make distinct judgments depending on instructions ([23], [39]), though other studies have found little dependence of responses on instructions, particularly in more realistic conditions ([31]). Our pre-experiment induction procedure was specifically designed elicit the same response strategy from all observers, and our instructions clearly directed observers towards lightness matching. In addition, we used a 2AFC task rather than an adjustment task in an attempt focus on perceptual rather than strategic processes.

If the observed inter-observer variability is perceptual rather than strategic, this would be consistent with reports that have found high inter-observer variability in the effects of geometry on various aspects visual perception ([31], [43], [44]). One potential explanation is that information about slant is encoded at a stage of visual processing that is more variable from observer-to-observer than the mechanism that encodes local contrast.

In agreement with previous studies, we found that local contrast predicts perceived lightness better when it is a valid cue to surface reflectance than when it is not. However, our findings suggest that even in a rich global context, perceived lightness never reaches full constancy when there is a strong and opposing local contrast cue.

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