Title: Human lightness discrimination thresholds add linearly for independent extrinsic variations

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**ABSTRACT:**

**KEYWORDS:** Lightness, Human Psychophysics, Color Vision,

**INTRODUCTION**

Our visual system provides perceptual representation of distal properties of objects based on the proximal stimuli captured by the eyes. While object properties are intrinsic to the object (its color, shape, etc.) the proximal stimuli also depend on the properties of the scene in which the object lies (such as background objects in the scene, illumination, etc.) as well as the position and pose of the observer. The task of the visual system is to provide stable correlates of object intrinsic properties under variability of the proximal signal due to changes in object extrinsic scene properties. This work quantifies the extent to which the visual system provides such stability for the representation of the reflectance of an object under variation in spectral properties of the scene, i.e., variation in the spectra of the background objects and the light sources in the scene.

The perceptual correlate of the reflectance of an object is its perceived color. For achromatic objects, the analogous quantity is object lightness. The human visual system is known to provide a relatively stable representation of the color/lightness of an object despite variability in the proximal signal due to changes in the reflectance of the objects in the scene, the light source, geometry, and other properties of the scene [cite Foster, Brainard & Radojnik]. The degree to which such stability can be achieved is termed as color/lightness constancy [cite Adelson, earlier papers on constancy]. Several theoretical, computational, and experimental approaches have been developed to account for and measure such constancy. ADD SOME OLD AND NEW PAPERS. Recently, Singh et. al developed an equivalent noise paradigm that allows one to quantify the effect of variation in object-extrinsic task-irrelevant properties in terms of the intrinsic difficulty of a perceptual task. They measured human lightness discrimination thresholds as a function of the amount of variability in spectra of background objects in a scene. They related the discrimination thresholds to the variance in observers’ internal perceptual representation of lightness and the variance in the spectrally induced extrinsic variability, thus comparing a strength of intrinsic and extrinsic variability.

In this work, we use this paradigm to compare the variation in two spectral properties of the scene, the reflectance of background objects and the intensity of the light sources, to human observers’ representation of lightness. We measure human observers’ threshold of discriminating two images based on the lightness of an achromatic target object in the images. We measure how these discrimination thresholds change as we increase the variability in the reflectance spectra of the background objects and the intensity of the light sources, for individual and simultaneous variation of these properties. We use the equivalent noise paradigm to relate the thresholds to the variance of observers’ intrinsic noise and the extrinsic variability. These variances allow one to compare the relative effect of different sources of variability. Through the thresholds of the simultaneous variation, they also provide the rules of combination of the effect of different sources.

We show that as the variability in the extrinsic sources increases, at first the thresholds remain constant, showing that in this regime the thresholds are determined primarily by the intrinsic noise of the observer. As the variability increases, the thresholds increase. The increase in thresholds can be accounted for by model based on signal detection theory. This model shows that the effect of extrinsic variation is within a factor of two compared to the variability in the intrinsic representation of lightness. This confirms that the visual system provides a large degree of lightness constancy under object extrinsic scene variability. By comparing the increase in thresholds under individual and simultaneous variation as compared to thresholds under extrinsic variation, we also show that the effect of individual sources combines linearly under simultaneous variation.

The paper is organized as follows. Section 2, Experimental Methods, provides the details of the experimental methods, stimuli used, and model fitting. Section 3, Results, provides the results of three experiments: variation in background reflectance spectra, variation in light source intensity, and simultaneous variation in these two properties. Section 4, Discussion, provides a summary of the results and conclusive remarks.

**2 EXPERIMENTAL METHODS**

**Overview**

We followed the methodology published previously in [cite paper]. In this previous work, human lightness discrimination thresholds were measured under variability of reflectance spectra of background objects in the scene. The work presented here follows the same experimental methods, except that the stimuli used in the experiment are different. This section provides an overview of the methods, focusing on the differences from the previous work. We refer the reader to the previous work for details.

Similar to the previous work, we used a two-alternate forced-choice (2AFC) procedure to measure thresholds (Figure 1). On each trial, observers viewed two computer graphics rendering images of 3D scenes on a color calibrated monitor. Each trial contained a standard image and a comparison image. The images were viewed in sequence for 250ms with a 250ms inter-stimulus interval. Each image contained an achromatic spherical target object. The observers reported the image in which the target object was lighter. Across trials, we varied the luminous reflectance factor of the target object (LRF; American Society for Testing and Materials, 2017) in the comparison image. The LRF is the ratio of the luminance of a surface under a reference illuminant (here, the CIE D65 reference illuminant) to the luminance of the reference illuminant itself. The order of the standard and the comparison image was chosen in a pseudorandom order. We recorded the proportion of times observers chose the comparison image as having the lighter target object at 11 values of the target object LRF. Figure 2 shows a psychometric function from a typical human observer. The proportion-comparison-chosen data were fit with a cumulative normal. Threshold was defined as the difference between the LRF of the target object at proportion comparison chosen 0.76 and 0.50 (i.e., d-prime = 1.0 in a two-interval task), as determined from the cumulative normal fit.

We measured the effect of variation in object-extrinsic scene properties on human lightness discrimination thresholds. We studied two types of variations: variation in the reflectance spectra of the background objects in the scene and variation in the intensity of the light sources in the scene. We performed three experiments:

(1) Background reflectance spectra variation (preregistered Experiment 6): In this experiment, we measured human lightness discrimination thresholds as a function of the amount of variation in the background objects while the spectra of the light sources were kept fixed.

(2) Light source intensity variation (preregistered Experiment 7): In this experiment, we measured lightness discrimination thresholds as a function of the amount of variation in the intensity of the light sources while the background was fixed.

(3) Simultaneous variation (preregistered Experiment 8): In this experiment, we measured lightness discrimination thresholds as both the background object reflectance spectra and the light source intensity varied simultaneously.

The reflectance spectra of the background objects were sampled from a multivariate normal distribution. The amount of variation in the spectra was controlled by multiplying the covariance matrix of the multivariate normal distribution by a scalar. By varying the covariance scalar from 0 (no variation) to 1 (natural scene variation), we studied how background reflectance affected lightness discrimination thresholds. We measured discrimination thresholds for both chromatic and achromatic variations. In chromatic variation, the reflectance spectra could take any shape and the objects varied in their luminance and chromaticity. In achromatic variation, the reflectance spectra were spectrally flat, and the objects were gray.

The shape of the spectral power distribution function of the light source was chosen as CIE D65 reference illuminant. The intensity was varied by multiplying the spectral power distribution function by a scalar sampled from a log uniform distribution. The amount of variation was controlled by changing the range of the log uniform distribution.

The subsections below provide additional methodological detail.

**Preregistration**

The experimental design and the method for extracting thresholds from the data were preregistered before the start of the experiments. The preregistration documents are publicly available at: <https://osf.io/7tgy8/>.[[1]](#footnote-1)

We preregistered three experiments. These were preregistered as Experiment 6 (referred here as Background reflectance spectra variation), Experiment 7 (referred here as Light source intensity variation), and Experiment 8 (referred here as Simultaneous variation). Experiment 6 was a replication of previous work (preregistered as Experiment 3, cite equivalent noise paper) with three additional conditions in which the background objects were achromatic and varied only in their lightness. The experimental methods of the three experiments were same.

We followed the procedure described in the preregistration document to extract threshold from the data. The preregistration document also indicated that the primary data feature of interest was the dependence of threshold on the amount of variation in the background and the intensity of the light source. We predicted that the thresholds would increase with increase in the amount of variation. For background variation, we predicted that the thresholds of achromatic variation would be lower than chromatic variation. We also predicted that increase in thresholds could be captured by an equivalent noise model [cite]. Additionally, we predicted that the threshold for simultaneous variation would be higher than the thresholds for individual variations.

**Reflectance and Illumination Spectra**

The reflectance spectra of background objects in the scene were generated using a model of naturally occurring surface reflectance spectra, as described in previous work [cite both my papers]. Briefly, we combine two datasets of surface reflectance functions containing 632 surface reflectance measurements [cite datasets vhrel]. We then use principal component analysis (PCA) to obtain the projection of the mean centered dataset along the eigenvectors associated with the six largest eigenvalues. These eigenvalues captured more than 99.5% of the variance [cite]. We approximate the empirical distribution of the projection weights with a multivariate normal distribution. We generate pseudorandom samples from this multivariate normal distribution to get the projection weights of random samples of reflectance spectra. Reflectance spectra were constructed by using these projection weight along with the eigenvectors and adding the mean of the surface reflectance dataset. A physical realizability condition was imposed on these spectra by ensuring that the reflectance at each wavelength was between 0 and 1. If a reflectance spectrum did not meet this criterion, it was discarded.

To generate achromatic surface reflectance spectra, after generating a physically realizable reflectance spectrum, its average reflectance over all wavelengths was calculated and it was replaced by a spectrum which had this average reflectance at all wavelengths.

To control the amount of variation in the reflectance spectra, the covariance matrix of the multivariate normal distribution was multiplied by a covariance scalar (). A covariance scalar of 0 corresponds to no variation in background object reflectance spectra. A covariance scalar of 1 corresponds to the full reflectance variation of the model of natural reflectance.

The power spectrum of the light source was chosen as CIE D65 reference illuminant. We normalized the D65 spectrum by its mean power to obtain its relative spectral shape. The variation in the light source intensity was introduced by multiplying the normalized D65 spectrum by a random sample generated from a log-uniform distribution in the range [1−, 1+], where determines the range of the distribution. We chose log-uniform distribution for the multiplication parameter because the spectral power distribution function of natural daylight spectra varies over three orders of magnitude and their mean over wavelength can be roughly approximated by a log-uniform distribution (cite VWCC paper). All light sources in a scene were assigned the same power spectrum.

The values of the two parameters and for the three experiments were as follows:

Background object reflectance variation (Experiment 6): In this experiment, we generated images for nine conditions. Six of these conditions were for chromatic variation at six logarithmically spaced values of the covariance scalar (): [0, 0.01, 0.03, 0.1, 0.3, 1.0]. Three conditions were for achromatic variation at covariance scalar (): 0.03, 0.3 and 1.0. The power spectrum of the light source was the same for all images. The power spectrum multiplication scalar was assigned an arbitrary value of 5. Figure 3 shows five typical images for the nine conditions.

Light source intensity variation (Experiment 7): In this experiment, we generated images for seven linearly spaced values of the range parameter (): [0.00, 0.05, 0.10, 0.15, 0.20, 0.25, 0.30]. The reflectance spectra of all background objects were the same and were equal to the mean spectrum of the reflectance database. This corresponds to covariance scalar of 0. Figure 4 shows five typical images for the seven conditions.

Simultaneous variation (Experiment 8): In this experiment we studied six conditions. These were: no variation ( = 0, = 0), chromatic background variation (covariance scalar = 1, = 0), achromatic background variation ( = 1, = 0), light source intensity variation ( = 0, = 0.3), simultaneous variation chromatic background ( = 1, = 0.3) and simultaneous variation achromatic background ( = 1, = 0.3). Figure 5 shows five typical images for these six conditions.

**Stimulus Design**

Images were generated using the software referred to as Virtual World Color Constancy (VWCC) (github.com/BrainardLab/VirtualWorldColorConstancy) as described in [cite Equivalent Noise]. To render an image, we first create a 3D model as a base scene. Next, we assign reflectance spectra and spectral power distribution function to the objects and light sources in the scene, as per the experimental condition. All light sources in a scene are assigned the same spectral power distribution function. Then we render a 2D multispectral image of the scene using Mitsuba, a physically-realistic open-source rendering system (mitsuba-renderer.org; cite Jakob, 2010). The images were rendered at 31 wavelengths equally spaced between 400nm and 700nm. The images were rendered with the camera field of view of 17° with an image resolution of 320-pixel by 240-pixels with the target object at the center. A 201-pixel by 201-pixel area, centered around the spherical target object, was cropped for display on the monitor. The cropped images were converted to LMS images using the Stockman-Sharpe 2° cone fundamentals (T\_cones\_ss2 in the Psychophysics Toolbox). Then the monitor calibration data and standard methods (Brainard, 1989; Brainard, Pelli, & Robson, 2002) were used to convert the LMS images to gamma corrected RGB images. A common scaling was applied to all images before rendering to ensure that they were within monitor gamut, so that the maximum linear channel RGB channel input was 0.9. The gamma corrected RGB images was presented on the monitor during the experiment.

For each condition described above, we generated 1100 images, 100 images each at 11 linearly spaced values of the target object LRF in the range [0.35, 0.45]. The standard image target object LRF was 0.4. The comparison image target object LRF varied in the range [0.35, 0.45]. We generated 100 images at each comparison level to avoid excessive replication of images in the experiment. For the no variation ( = 0, = 0) condition, we generated one image at each target object LRF level, as the background and light source intensity remained fixed in this case. The images were generated without secondary reflections. The geometry of the scene was also fixed.

When displayed on the experimental monitor, the average luminance of the standard image for and was 87.1 cd/m2. The average luminance of the target object for the 11 LRF levels were [120.9, 122.3, 123.8, 125.2, 126.5, 127.9, 129.2, 130.5, 131.9, 133.1, 134.4] cd/m2.

When displayed on the experimental monitor, the average luminance of the standard image for and was 87.8 cd/m2. The average luminance of the target object for the 11 LRF levels were [117.7, 119.4, 119.4, 122.3, 123.7, 123.8, 127.8, 126.9, 127.7, 129.1, 129.0] cd/m2.

**Experimental Structure:**

We define a trial as the presentation of a standard and a comparison image and the recording of the response. We define an interval as the presentation of one of the images, standard or comparison, in a trial. A block consists of recording 330 trials for one condition, 30 trials each at 11 comparison image target LRF level. A permutation consists of recording one block of data for each condition in an experiment. We recorded three permutations for each observer in each experiment. Each permutation had a random order of the conditions.

The order of the blocks in a permutation, the LRF levels of the comparison image in trials of a block, and the order of standard and comparison in a trial, was generated pseudo randomly and stored at the beginning of the experiment for each observer. Before starting a new permutation for an observer, the data for all conditions in a permutation was collected.

A session consisted of recording three blocks on a single day. An observer performed no more than one session on a day. Each block in a session was divided into three sub-blocks of 110 trials. Between these sub-blocks, the observers took a break of minimum one minute. The observers also took a small break (two to five minutes) between blocks. The observers could terminate the experiment at time during the block. If the observer terminated a block, the data was not recorded. No observer terminated a block of the experiment.

Each observer first performed a practice session where three blocks of data was recorded for the no variation (, ) condition. The observers were excluded from the experiment if their mean threshold for the last two blocks was higher than 0.03. If the observer passed this criterion, then the rest of the data was collected over several days.

At the beginning of the practice session for each observer, the experimenter explained the experimental procedure and obtained consent for the experiment. Then the observer was tested for normal visual acuity and color vision. After this, the observer went to the experimental room where they were familiarized with the experimental set-up by performing a familiarization block of 40 trials. Then the observers were dark adapted by sitting in the dark for about 5 minutes. Then the data for the three blocks of the practice session was recorded. At the end of the practice session, the observers were informed if they could continue the experiment.

If the observer was continued, their data was collected over several sessions. The data for all six observers of an experiment was collected over several weeks. The data of all six observers for preregistered Experiment 6 was collected before starting preregistered Experiment 7. The data of all six observers for preregistered Experiment 7 was collected before starting preregistered Experiment 8.

**Observer Recruitment and Exclusion**

Observers were recruited from North Carolina Agricultural and Technical State University and local Greensboro community and were compensated for their time. Observers were screened to have normal visual acuity (20/40 or better; with corrective eyewear, if applicable) and normal color vision, as assessed with pseudo-isochromatic plates (Ishihara, 1977). These exclusion criteria were specified in the preregistration document (see Methods: Preregistration).

Observers who passed the vision screening then participated in a practice session. This session also served to screen for observers’ ability to reliably perform the psychophysical task. In the practice session, the observers’ performed three blocks of the experiment for the no variation condition (, ) and the threshold was calculated for these three blocks. The observer was excluded from further participation if their mean threshold for the last two blocks in the practice session exceeded 0.030 (log T2, -3.2). This exclusion criterion was specified in our preregistered protocol (See Methods: Preregistration).

Observers who met the performance criterion participated in the rest of the experiment.

For each observer, the practice session was performed at the beginning of each of the three experiments (Experiment 6, 7, 8), irrespective of whether the observer had participated in an earlier experiment.

**Observer Information**

Background reflectance variation (preregistered Experiment 6): A total of 25 observers participated in the practice sessions for background variation experiment (10 Female, 15 Male; age 19-34; mean age 22.9). To de-identify observer information in the data, observers were given pseudo-names chosen by the experimenter. Six of these observers (pseudo-names: *0003, bagel, committee, content, observer*, and *revival*) met the performance criterion set for screening (2 Female, 4 Male; age 19-28; mean age 23.33). All observers who advanced to the practice session had normal or corrected-to-normal vision (20/40 or better in both eyes, assessed using Snellen chart) and normal color vision (0 Ishihara plates read incorrectly). The visual acuities of the observers in the main experiment were: *0003*, L = 20/30, R = 20/20; *bagel*, L = 20/20, R = 20/20; *committee*, L = 20/25, R = 20/25; *content*, L = 20/20, R = 20/20; *observer*, L = 20/25, R = 20/25; *revival*, L = 20/20, R = 20/20. *Committee, content,* and *observer* wore personal corrective eyewear both during vision testing and during the experiments. Observers *0003, bagel*, and *revival* did not require or use corrective eyewear.

Light source intensity variation (preregistered Experiment 7): A total of 15 observers participated in the practice sessions for light source intensity variation experiment (9 Female, 6 Male; age 19-33; mean age 25). Six of these observers (pseudo-names: *0003*, *bagel*, *content*, *oven*, *primary*, and *revival*) met the performance criterion set for screening (3 Female, 3 Male; age 19-28; mean age 23.83). All observers who advanced to the practice session had normal or corrected-to-normal vision (20/40 or better in both eyes, assessed using Snellen chart) and normal color vision (0 Ishihara plates read incorrectly). The visual acuities of the observers in the main experiment were: *0003*, L = 20/30, R = 20/30; *bagel*, L = 20/20, R = 20/20; *content*, L = 20/20, R = 20/20; *oven*, L = 20/20, R = 20/20; *primary*, L = 20/20, R = 20/20; *revival*, L = 20/20, R = 20/20. Observer *content* and *primary* wore personal corrective eyewear both during vision testing and during the experiments. Observers *0003, bagel*, *oven,* and *revival* did not require or use corrective eyewear. Observer *oven* reported some difficulties during a few sessions of the experiment and their thresholds for two conditions did not fit the expected pattern. We removed their data from the analysis presented in this work. Their data and thresholds are provided in supplementary materials.

Simultaneous variation (preregistered Experiment 8): A total of 20 observers participated in the practice sessions for simultaneous variation experiment (9 Female, 11 Male; age 19-28; mean age 20.8). Six of these observers (pseudo-names: *0003, bagel, oven, fun, manos,* and *revival*) were retained for the experiment (2 Female, 4 Male; age 19-28; mean age 23.33). Four observers (*0003, bagel, oven* and *fun*) met the screening criteria specified in the preregistration. Due to lack of observers who met the preregistration criteria, two observers (*manos,* and *revival*), whose thresholds were close to the preregistration criteria, were also retained for the experiment. Observer *revival* had participated in previous two experiments and had met the criteria both times. Observer *manos* showed improvement in thresholds with each block, with the threshold for the final block below 0.03. This was a deviation from the preregistration. All observers who advanced to the practice session had normal or corrected-to-normal vision (20/40 or better in both eyes, assessed using Snellen chart) and normal color vision (0 Ishihara plates read incorrectly). The visual acuities of the observers in the main experiment were: *0003*, L = 20/30, R = 20/30; *bagel*, L = 20/20, R = 20/20; *oven*, L = 20/20, R = 20/20; *fun*, L = 20/20, R = 20/20; *manos*, L = 20/25, R = 20/25; *revival*, L = 20/20, R = 20/20. Observer *fun* wore personal corrective eyewear both during vision testing and during the experiments. Observers *0003, bagel*, *manos*, *oven*, and *revival* did not require or use corrective eyewear.

**Apparatus**

The stimuli were presented on a calibrated LCD color monitor (27-in. NEC MultiSync EA271U; NEC Display Solutions) in an otherwise dark room. The monitor was driven at a pixel resolution of 1920 x 1080, a refresh rate of 60Hz, and with 8-bit resolution for each RGB channel. The host computer was an Apple Macintosh with an Intel Core i7 processor. The experimental programs were written in MATLAB (MathWorks; Natick, MA) and relied on routines from the Psychophysics Toolbox (<http://psychtoolbox.org>) and mgl (<http://justingardner.net/doku.php/mgl/overview>). Responses were collected using a Logitech F310 gamepad controller.

The observer’s head position was stabilized using a chin cup and forehead rest (Headspot, UHCOTech, Houston, TX). The observer’s eyes were centered horizontally and vertically with respect to the display. The distance from observer’s eyes to the monitor was 75cm.

**Monitor Calibration**

The monitor was calibrated using a spectroradiometer (PhotoResearch PR655) as described in [cite previous paper]. The monitor was calibrated before starting each experiment. Once calibrated the same settings were used till data for all observers for that experiment was collected. The monitor was then recalibrated for the next experiment. Data was collected in the sequence Experiment 6, Experiment 7, and Experiment 8.

*The maximum absolute deviation of the x-y chromaticity between the measured values and those predicted from the calibration was 0.0028 and 0.0027 for x and y chromaticity respectively, and less than 1% for luminance.*

**Ethics Statement**

All experimental procedures were approved by North Carolina Agricultural and Technical State University Institutional Review Board and were in accordance with the World Medical Association Declaration of Helsinki.

**Code and Data Availability**

For each experiment and observer, the proportion comparison chosen data for the 3 experimental blocks of each condition as well as the thresholds are provided as supplementary information (SI). The SI also provides the MATLAB scripts to generate Figures 2, 6 – 12, supplementary figures S1-S4, and the scripts to obtain thresholds of the linear receptive field formulation of the model. The SI is available at: https://github.com/vijaysoophie/SimultaneousVariationPaper.

**Linear Receptive Field Model**

The thresholds of preregistered Experiment 6 were fit to the linear receptive field model developed in [cite]. This model consisted of a simple center surround receptive field (*R*). The receptive field was square in shape to match the images in the psychophysics experiment. Its center was a circle of radius equal to the size and the location of the target object. The central region had a spatially uniform positive sensitivity of 1. The surround had a spatially uniform negative sensitivity of . The receptive field response was computed as the dot product of the receptive field with the standard and the comparison images. A mean zero Gaussian noise was added to the response. The image with higher noise added receptive field was chosen to be lighter. The variance of the Gaussian noise () and the value of the receptive field surround sensitivity () were the two parameters of the model. These parameters provided an estimate of the internal noise () and the variance of the extrinsic properties (). The model related the thresholds (*T*) in the experiments to the variance in the intrinsic noise () of the observer and the extrinsic variance () through the relation:

*(1)*

where is the covariance scalar (see [cite] for details). The variance of the extrinsic properties () resulting from the variation in the image can be computed as , where is the covariance matrix of the variation in the images.

Background reflectance variation: To estimate the intrinsic of the observer and extrinsic variation in the images, we chose the value of the Gaussian noise variance () and the surround sensitivity to minimize mean squared difference between the model and experimental thresholds measured at the six values of the covariance scalar. provided the estimate of the intrinsic noise. The extrinsic noise was estimated using the best fit surround sensitivity () of the receptive field (*R*) and the sample covariance matrix of the images () at =1 in the relation .

Light source intensity variation: We fit a functional form similar to Eq. (1) to the thresholds of light source intensity variation experiment (Experiment 7) where we replaced covariance scalar by the range parameter . We chose the value of the Gaussian noise variance () and receptive field surround sensitivity () to minimize the mean square difference between the observer and model thresholds measured at the seven values of the range parameter. provided the estimate of the observer’s intrinsic noise. To estimate the extrinsic noise, we used the best fit surround sensitivity () and the sample covariance matrices to calculate the quantity as a function of the range parameter . We fit the resulting values with an exponential function (see Fig S5). The extrinsic noise is estimated as the value of the exponential fit at .

**3 RESULTS**

**Human Lightness Discrimination Thresholds Increase with Background Reflectance Variation**

We measured lightness discrimination thresholds of human observers for two types of variation in the reflectance spectra of background objects in the scene: chromatic variation and achromatic variation. In chromatic variation, the reflectance spectra could take any shape and thus the background objects varied in their chromaticity and luminance. In achromatic variation, each spectrum had the same reflectance at all wavelengths, and thus the spectra varied only in their overall luminance and the objects were gray. The amount of variation depended on the covariance matrix of the multivariate normal distribution from which the spectra were sampled. The variance was controlled by multiplying the covariance matrix by a covariance scalar (). We measured discrimination thresholds of six human observers at six values of the covariance scalar for chromatic variation and three values of covariance scalar for achromatic variation. The threshold was measured three times (three separate blocks) for each observer and each of the nine conditions. The psychometric functions for these nine conditions are shown for one observer in Figure 6 and for all observers in Figure S1. Inspection of the psychometric functions show that their slopes steadily decrease with increasing covariance scalar, corresponding to an increase in thresholds. The thresholds for chromatic and achromatic variation are comparable.

Figures 7 shows explicitly how the discrimination thresholds change with the amount of variability in the reflectance of the background objects. Here, we plot the mean log threshold squared (averaged across observers, N = 6) against the log of the covariance scalar. Table S1 provides the thresholds and SEMs from Figure 7 in tabular form. For low values of the covariance scalar, the thresholds are nearly constant. As the covariance scalar increases, log squared threshold increases. The thresholds are comparable for chromatic and achromatic variation. The p-value of the hypothesis that the mean thresholds for chromatic and achromatic variations are equal are 0.72, 0.57, and 0.16 for covariance scalar 0.03, 0.30, and 1.00 respectively.

We fit the thresholds to the linear receptive field (LINRF) model (Eq. 1) developed in [cite]. The LINRF model provides the estimate of the variance of the internal noise of the observer as and the variance of the extrinsic variability due to the reflectance of background objects as . The equivalent noise level, the ratio of the external variance and intrinsic noise, is ~ 1.5, indicating that the variability in the representation of object lightness induced by the natural variability in the reflectance of background objects is close to the internal variability of that representation. If the ratio was equal to 1, then we would have concluded that the visual system has discounted the external variability. But the ratio not significantly large compared to 1, indicating that the visual system provides a significant level of lightness constancy.

**Human Lightness Discrimination Thresholds Increase with Light Source Intensity Variation**

We measured lightness discrimination thresholds of human observers as we varied the intensity of light sources in the scene. The shape of the spectrum of the light sources was fixed to be standard daylight spectrum D65. We normalized the spectrum by its mean over wavelengths. The intensity was varied multiplying the normalized spectrum by a scalar sampled from a log-uniform distribution in the range [1- , 1+ ]. The reflectance spectra of the background objects were fixed. We measured lightness discrimination thresholds for seven values of the range parameter for five human observers. The psychometric function of one of the observers for these seven conditions are shown in Figure 8. Figure S2 shows the psychometric functions of all observers. Figure 9 shows the mean threshold of the five observers. Similar to the trend for reflectance spectra variation, lightness discrimination thresholds remain constant for small values of the range parameter and then log threshold squared increases with increase in range parameter. A fit of the mean threshold with the linear receptive field model gives the value of internal noise as . This compares well with the internal noise obtained from the background reflectance spectra variation experiment (). The variance of the extrinsic variability is . The equivalent noise level is ~ 1.8.

**Thresholds for Simultaneous Variation are Higher Than Individual Variations**

We measured lightness discrimination thresholds for simultaneous variation in the reflectance spectra of background objects and the intensity of the light sources in the scene. In this experiment, we studied six conditions: no variation, achromatic and chromatic variation in the reflectance spectra of background objects with fixed spectrum of the light source, variation in intensity of light source with fixed background, and simultaneous variation in the intensity of light source and reflectance spectra of background object for chromatic and achromatic variations. We measured lightness discrimination thresholds of six human observers for these six conditions. The psychometric function of one of the observers is shown in Figure 10. Figure S3 shows the psychometric functions of all observers. Figure 11 shows the mean threshold of all six observers for these six conditions. The threshold for simultaneous variation of light source intensity and reflectance spectra of background objects is higher than the condition with individual variations in these properties. As observed earlier, the threshold for achromatic and chromatic conditions are comparable. The p-value of the hypothesis that the mean thresholds for chromatic and achromatic variations are equal is 0.19 for background variation condition and 0.44 for simultaneous variation condition.

Figure 12 shows the increase in mean squared threshold above the no variation condition. We compare the mean square thresholds of the simultaneous variation condition with the sum of the mean square thresholds of the individual conditions for chromatic and achromatic conditions. The increase in threshold of the simultaneous variation condition is comparable to the sum of the increase in threshold for the individual variations. The p-value of the hypothesis that the mean increase in thresholds for simultaneous variation is equal to sum of the mean increase in the thresholds of light intensity variation and background object reflectance variation are 0.80 and 0.71 for chromatic and achromatic conditions respectively.

We used the linear receptive field parameters obtained from the background reflectance variation condition on the images of this experiment. Figure 12 shows the thresholds of the linear receptive model for the six conditions. As expected, the thresholds of the linear receptive model are comparable to the measured threshold of the no-variation condition and background spectra variation conditions. Also, since we have used the parameters of the background reflectance variation condition, the threshold of the linear receptive model does not match the measured average threshold of the light source intensity variation condition. Surprisingly, the threshold of the linear receptive field model for the simultaneous variation condition are comparable to the measured threshold for this condition.

**4 DISCUSSION**

The perceived lightness of an object depends on the scene in which is lies. Although the variability in object-extrinsic properties of the scene causes variability in the proximal signal to the visual system, the visual system provides a relatively stable representation of object lightness. We measured human observers’ threshold of discriminating two objects based on their lightness as a function of amount of variability in the spectra of background objects and light sources in a scene. For low level of variability, the thresholds first remained constant, showing that in this regime the performance was determined by observers’ intrinsic noise. As the variability increased, the effect of extrinsic started dominating the performance and the discrimination thresholds increased. Using a model based on signal detection theory, we related the thresholds in the low variability regime to the internal noise of the observer. The model also related the increase in threshold to amount of variability in the extrinsic property, thus providing a comparison of the variance in extrinsic property to the intrinsic noise. The effect of both types of extrinsic variation, spectra of background objects and intensity of light sources, were comparable to the effect of intrinsic noise, showing that the visual system provides a good degree of constancy to these variations.

**Chromatic v/s Achromatic Variations:** Lightness discrimination thresholds of chromatic and achromatic variation in the reflectance spectra of background objects were statistically similar. The chromatic aspect of the variation does not seem to influence lightness discrimination. Lightness and chromaticity seem to be encoded independently and do not affect each other. This hypothesis could be tested by measuring chromaticity discrimination thresholds under chromatic and achromatic variation of background objects.

**Visual system at threshold level:** The variances of extrinsic variation are within a factor of two of the intrinsic variation for the variabilities studied in this work. If the variances were equal, one could conclude that the visual system has fully compensated for the extrinsic variation. As the extrinsic variances are larger than the variance of the intrinsic noise, the visual system has not fully compensated the external variabilities. But since these variances are within a factor or two, it shows that the visual system provides a large degree of stability in the perceptual representation of lightness and seems to work at near threshold levels.

**Rules of Combination:** The increase in threshold of simultaneous variation of reflectance spectra of background object and intensity of light sources from no variation condition were equal to the linear sum of the increase in threshold of the individual variations. The effect of combined variation is the sum of the effect of the individual variations. This could be accounted assuming that the sources of noise are independent and their effect add linearly.

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**Table S1: Thresholds for Background Variation Experiment (Preregistered Experiment 6):**Mean threshold (averaged over blocks) SEM of six human observers for nine background variation conditions studied in preregistered experiment 6.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Condition | Observer | | | | | |
| 0003 | Bagel | Committee | Content | Observer | Revival |
|  | 0.02210.0010 | 0.01850.0018 | 0.03440.0027 | 0.0223 0.0012 | 0.03110.0053 | 0.02510.0023 |
|  | 0.02150.0009 | 0.01940.0020 | 0.03860.0103 | 0.01930.0012 | 0.02630.0059 | 0.02620.0048 |
|  | 0.02420.0019 | 0.02610.0020 | 0.02850.0029 | 0.02460.0046 | 0.02920.0007 | 0.02820.0016 |
| Achromatic | 0.02550.0019 | 0.02130.0024 | 0.03430.0055 | 0.02270.0023 | 0.02670.0040 | 0.02630.0016 |
|  | 0.02780.0015 | 0.02380.0010 | 0.02840.0017 | 0.02780.0035 | 0.03350.0024 | 0.02810.0013 |
|  | 0.03480.0025 | 0.02770.0024 | 0.03440.0020 | 0.02860.0002 | 0.02770.0019 | 0.03010.0038 |
| Achromatic | 0.03330.0032 | 0.02840.0028 | 0.03190.0047 | 0.03080.0015 | 0.03580.0030 | 0.02870.0022 |
|  | 0.04160.0072 | 0.03160.0008 | 0.03790.0024 | 0.03230.0022 | 0.04050.0042 | 0.03600.0055 |
| Achromatic | 0.02890.0017 | 0.03100.0015 | 0.03910.0029 | 0.03840.0058 | 0.03120.0015 | 0.03220.0009 |

**Table S2. Thresholds for Lightness Intensity Variation Experiment (Preregistered Experiment 7)**:  
Mean threshold (averaged over blocks) SEM of six human observers measured for seven lightness intensity conditions studied in preregistered experiment 7. The thresholds of observer Oven was not used in Figure 9.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Condition | Observer | | | | | |
| 0003 | Bagel | Content | Oven | Primary | Revival |
|  | 0.02170.0012 | 0.01810.0001 | 0.02080.0014 | 0.05200.0114 | 0.03290.0061 | 0.03720.0008 |
|  | 0.0228 0.0018 | 0.02290.0018 | 0.02070.0007 | 0.05800.0064 | 0.03460.0042 | 0.03640.0013 |
|  | 0.02750.0024 | 0.02170.0009 | 0.02420.0040 | 0.03250.0022 | 0.03430.0013 | 0.03760.0072 |
|  | 0.03160.0009 | 0.02380.0011 | 0.03230.0032 | 0.03330.0019 | 0.03450.0042 | 0.03260.0002 |
|  | 0.04470.0100 | 0.03810.0046 | 0.02760.0016 | 0.04930.0120 | 0.04230.0050 | 0.03920.0034 |
|  | 0.04330.0052 | 0.03930.0062 | 0.03080.0023 | 0.04610.0060 | 0.05320.0083 | 0.03870.0025 |
|  | 0.04040.0018 | 0.04290.0033 | 0.03470.0014 | 0.05800.0061 | 0.04650.0047 | 0.04210.0042 |

**Table S3. Thresholds for Simultaneous Variation Experiment (Preregistered Experiment 9)**:  
Mean threshold (averaged over blocks) SEM of six human observers measured for six conditions studied in preregistered experiment 8.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Condition | Observer | | | | | |
| 0003 | Bagel | Content | Oven | Manos | Revival |
| No Variation | 0.02610.0022 | 0.02270.0019 | 0.02460.0004 | 0.03830.0066 | 0.02580.0036 | 0.03660.0085 |
| Background Variation Chromatic | 0.04140.0036 | 0.03400.0058 | 0.03920.0083 | 0.04980.0050 | 0.03060.0013 | 0.03830.0033 |
| Background Variation Achromatic | 0.03940.0027 | 0.03190.0015 | 0.04270.0074 | 0.06830.0048 | 0.04350.0071 | 0.03890.0010 |
| Light Intensity  Variation | 0.04640.0027 | 0.06560.0208 | 0.04120.0021 | 0.05920.0091 | 0.04640.0046 | 0.04740.0069 |
| Simultaneous Variation Chromatic | 0.06350.0092 | 0.05360.0014 | 0.04370.0011 | 0.06390.0106 | 0.07680.0085 | 0.05280.0037 |
| Simultaneous Variation Achromatic | 0.06480.0103 | 0.05400.0017 | 0.04780.0049 | 0.08260.0166 | 0.07490.0082 | 0.05610.0028 |

**Figure Captions**

**Figure 1: (a) Psychophysical task.** On every trial of the experiment, human observers viewed two images, a standard image and a comparison image, and indicated the image in which the spherical target object at the center of the image was lighter. The images were computer graphics renderings of 3D scenes. They were displayed on a color calibrated monitor. This panel shows examples of standard and comparison images. The reflectance spectrum of the target object was spectrally flat, and the target object appeared gray. The reflectance of the target object in the standard image was held fixed and it changed for the comparison image. In this panel, the target object in the comparison image is lighter. We measured the fraction of times the observers chose the target object in the comparison image to be lighter as a function of the lightness of the target object in the comparison image. Fraction comparison chosen data was used to determine lightness discrimination threshold (Figure 2). We studied how the lightness discrimination thresholds changed as the trial-to-trial variability in the reflectance spectra of the background objects and the intensity of the light sources increased. **(b)** **Trial sequence:** RN-1 indicates the recording of the observer’s response for the (N-1)th trial. The Nth trial begins 250ms after the completion of the (N-1)th trial (Inter Trial Interval, ITI = 250ms). In the Nth trial, the standard and comparison images are presented for 250ms each with a 250ms inter stimulus interval (ISI) in between the two images. The order of the standard and comparison images is chosen in pseudorandom order. The observer records their choice by pressing a button on a gamepad after both images have been presented and removed from the screen. The observers could take as long as they wish before making their choice. The recording of their choice is indicated by RN in the panel. The next trial begins 250ms after the choice has been recorded.

**Figure 2: Psychometric function:** We recorded the proportion of times the observers chose the target in the comparison image to be lighter as a function of the LRF of the target object in the comparison image. We collected 30 responses each at 11 linearly spaced values of the comparison image target object LRF in the range [0.35, 0.45]. The LRF of the target object in the standard image was 0.40. The LRF of the target object in the comparison image was chosen in a pseudorandom order. The proportion comparison chosen data was fit by a cumulative normal distribution using maximum likelihood methods. The guess rate and lapse rate were constrained to be equal and restricted to be in the range [0, 0.05]. The threshold was measured as the difference between the LRF at proportion comparison chosen equal to 0.76 and 0.50 as obtained from the cumulative normal fit. This figure shows the data for observer 0003 in the second block of background reflectance variation experiment (preregistered Experiment 6) for the no variation () condition. The discrimination threshold was 0.0208. The point of subjective equality (PSE, the LRF at which proportion comparison chosen is 0.5) was 0.409. The lapse rate for this fit was 0.00.

**Figure 3: Background object reflectance variation:** We studied two types of variations in the reflectance spectra of background objects in the scene: chromatic variation and achromatic variation. In chromatic variation, the reflectance spectra could take any shape, and the objects varied in their luminance and chromaticity. In achromatic variation, the reflectance spectra were spectrally flat, and the objects appeared gray and varied only in their luminance. The spectra were chosen from a multivariate normal distribution that modeled the statistics of natural reflectance spectra. The variation in the reflectance spectra was controlled by multiplying the covariance matrix of the distribution with a scalar. We generated images at six logarithmically spaced values of the covariance scalar for chromatic variation and at three values for achromatic variations. The figure shows five typical images for each of these nine conditions. For each condition we generated 1100 images, 100 images at 11 linearly spaced value of target object LRF in the range [0.35, 0.45]. The target object in each image in the figure is at LRF = 0.4.

**Figure 4: Light intensity variation:** The shape of the power spectrum of the light sources in the scene was chosen to be CIE reference illuminant D65. The intensity of the power spectrum was varied by multiplying the normalized D65 spectrum with a scalar sampled from a log uniform distribution in the range [1- , 1+ ]. The amount of variation was controlled by changing the value of the range parameter . We generated images at seven linearly spaced values of the range parameter in the range [0.00, 0.30]. For each value of the range parameter, we generated 1100 images, 100 images at each value of the target object LRF in the range [0.35, 0.45]. The figure shows five sample images at each of the seven values of the range parameter. The target object in each image in the figure has the same LRF of 0.40.

**Figure 5: Simultaneous variation:** This figure shows five sample images for the six conditions studied in preregistered experiment 8. We generated 1100 images for each of these conditions, 100 images at each value of the target object LRF in the range [0.35, 0.45].

**Figure 6: Psychometric functions for observer 0003 for background reflectance variation experiment:** We measured the proportion comparison chosen data for the nine conditions separately in three blocks for each observer. The data for each block was fit with a cumulative normal to obtain the discrimination threshold (see Figure 2). Each panel plots the measured values and the cumulative fit to the proportion comparison data for each of the three blocks, for observer 0003. The data for all six observers are shown in Figure S1. The values in the legend provide the estimate of lightness discrimination threshold for each block obtained from the cumulative fit. The top row shows the data for chromatic variation conditions. The last three panels in the bottom row show the data for the three achromatic conditions. The first panel in the bottom row shows the data and threshold for the selection session. The selection session was a practice session in which the thresholds for the no variation condition was measured three times. An observer was selected for the experiment only if the average of their last two discrimination threshold measurements in the selection session was less than 0.30.

**Figure 7: Background variation increases lightness discrimination threshold.** Mean (N = 6)log squared threshold vs log covariance scalar from human psychophysics for chromatic (red circles) and achromatic conditions (gray diamonds). The error bars represent +/- 1 SEM taken between observers. The threshold of the linear receptive field (LINRF) model was estimated by simulation for the six values of the covariance scalar (blue squares). The blue error bars show +/- 1 standard deviation estimated over 10 independent simulations. The parameters of the LINRF fit are provided in the legend. The data has been jittered for ease of viewing.

**Figure 8: Psychometric functions for observer 0003 for light intensity variation experiment:** Same as Figure 6, but for the light intensity variation experiment. The figure shows the proportion comparison chosen data for the selection session and the seven condition for observer 0003. The data for all observers are shown in Figure S2.

**Figure 9: Light source intensity variation increases lightness discrimination threshold.** Mean (N = 5)log squared threshold vs range parameter from human psychophysics for the seven light source intensity variation conditions (red circles). The error bars represent +/- 1 SEM taken between observers. The threshold of the linear receptive field (LINRF) model was estimated by simulation for the seven values of the range parameters (blue squares). The blue error bars show +/- 1 standard deviation estimated over 10 independent simulations. The parameters of the LINRF fit are provided in the legend. The data has been jittered for ease of viewing.

**Figure 10: Psychometric functions for observer 0003 for simultaneous variation experiment:** Same as Figure 6 and 8, but for simultaneous variation experiment. The figure shows the proportion comparison chosen data for the selection session and the six condition for observer 0003. The data for all observers are shown in Figure S3.

**Figure 11: Discrimination thresholds for simultaneous variation of two sources are higher than individual discrimination thresholds.** Mean (N = 6)log squared threshold for the six conditions in simultaneous variation experiment. The error bars represent +/- 1 SEM taken between observers. The data for chromatic (red circles) and achromatic (gray diamonds) conditions have been plotted next to each other for visual comparison. The thresholds of the linear receptive field (LINRF) model (blue squares) were estimated using the parameters of the background variation condition (Figure 7). The blue error bars show +/- 1 standard deviation estimated over 10 independent simulations.

**Figure 12: Thresholds of independent variations add linearly for simultaneous variation:** Mean (N=6) thresholds for the six conditions in simultaneous variation experiment (black circles). The black error bars represent +/- 1 SEM taken between observers. The bars (red, gray, blue) represent the increase in threshold compared to the no variation condition (blue dotted line). For the simultaneous variation conditions, the bars on the right (bars with one color, red or gray) represent the measured thresholds for the simultaneous variation conditions and the bars on the left (stacked bars of two different colors) represent the sum of the light intensity variation threshold (blue bar) and the corresponding background variation thresholds (red or gray).

**Figure S1: Psychometric functions for all observers for background variation experiment.** Same asFigure 6, for all observers retained in background variation experiment.

**Figure S2: Psychometric functions for all observers for light intensity variation experiment.** Same asFigure 8, for all observers retained in light intensityvariation experiment.

**Figure S3:** Same asFigure 9, for all six observers in retained in light intensityvariation experiment. The parameters for the LINRF model are the same as in Figure 9.

**Figure S4: Psychometric functions for all observers for simultaneous variation experiment.** Same asFigure 10, for all observers retained in simultaneousvariation experiment.

**REFERENCES**

Abrams, A. B., Hillis, J. M., & Brainard, D. H. (2007). The relation between color discrimination and color constancy: when is optimal adaptation task dependent? *Neural Computation, 19*, 2610-2637.

Adelson, E. H. (1993). Perceptual organization and the judgment of brightness. *Science, 262(December 24)*, 2042-2044.

Adelson, E. H. (2000). Lightness perception and lightness illusions. In M. Gazzaniga (Ed.), *The New Cognitive Neurosciences, 2nd edition* (pp. 339-351). Cambridge, MA: MIT Press.

Afifi, M., Barron, J. T., LeGendre, C., Tsai, Y.-T., & Bleibel, F. (2021). *Cross-camera convolutional color constancy*. Presented at the Proceedings of the IEEE/CVF International Conference on Computer Vision,

Allred, S. R., & Brainard, D. H. (2013). A Bayesian model of lightness perception that incorporates spatial variation in the illumination. *Journal of Vision, 13(7)*, 1–18.

Alvaro, L., Linhares, J. M. M., Moreira, H., Lillo, J., & Nascimento, S. M. C. (2017). Robust colour constancy in red-green dichromats. *PLoS ONE, 12(6)*, e0180310.

American Society for Testing and Materials. (2017). Standard test method for luminous reflectance factor of acoustical materials by use of integrating-sphere reflectometers. *Renovations of Center for Historic Preservation, 98(A)*, E1477.

Arend, L., & Reeves, A. (1986). Simultaneous color constancy. *Journal Of The Optical Society Of America A, 3(10)*, 1743-1751.

Aston, S., Radonjić, A., Brainard, D. H., & Hurlbert, A. C. (2019). Illumination discrimination for chromatically biased illuminations: implications for colour constancy. *Journal of Vision, 19(30:15)*

Banks, M. S., Geisler, W. S., & Bennett, P. J. (1987). The physical limits of grating visibility. *Vision Research, 27(11)*, 1915-1924.

Barron, J. T., & Malik, J. (2012a). *Color constancy, intrinsic images, and shape estimation.* Paper presented at ECCV.

Barron, J. T., & Malik, J. (2012b). *Shape, albedo, and illumination from a single image of an unknown object.* Paper presented at IEEE Conference on Computer Vision and Pattern Recognition, 334-341.

Bloj, M., Ripamonti, C., Mitha, K., Greenwald, S., Hauck, R., & Brainard, D. H. (2004). An equivalent illuminant model for the effect of surface slant on perceived lightness. *Journal of Vision, 4(9)*, 735-746.

Boyaci, H., Maloney, L. T., & Hersh, S. (2003). The effect of perceived surface orientation on perceived surface albedo in binocularly viewed scenes. *Journal of Vision, 3(8)*, 541-553.

Brainard, D. H. (1989). Calibration of a computer controlled color monitor. *Color Research & Application, 14(1)*, 23-34.

Brainard, D. H. (1998). Color constancy in the nearly natural image. 2. achromatic loci. *Journal of the Optical Society of America A, 15(2)*, 307-325.

Brainard, D. H. (2015). Color and the cone mosaic. *Annual Review of Vision Science, 1*, 519-546.

Brainard, D. H., Brunt, W. A., & Speigle, J. M. (1997). Color constancy in the nearly natural image. 1. asymmetric matches. *Journal of the Optical Society of America A, 14(9)*, 2091-2110.

Brainard, D. H., & Freeman, W. T. (1997). Bayesian color constancy. *Journal of the Optical Society of America A, 14(7)*, 1393-1411.

Brainard, D. H., Longere, P., Delahunt, P. B., Freeman, W. T., Kraft, J. M., & Xiao, B. (2006). Bayesian model of human color constancy. *Journal of Vision, 6(11)*, 1267-1281.

Brainard, D. H., & Maloney, L. T. (2011). Surface color perception and equivalent illumination models. *Journal of Vision, 11(5)*

Brainard, D. H., Pelli, D. G., & Robson, T. (2002). Display characterization. In J. P. Hornak (Ed.), *Encylopedia of Imaging Science and Technology* (pp. 172-188). New York: Wiley.

Brainard, D. H., & Radonjić, A. (2014). Color constancy. *The New Visual Neurosciences, 1*, 545–556.

Brascamp, J. W., & Shevell, S. K. (2021). The certainty of ambiguity in visual neural representations. *Annual Review of Vision Science, in press*

Brindley, G. S. (1960). *Physiology of the Retina and the Visual Pathway*. London: Arnold.

Brown, R. O., & MacLeod, D. I. A. (1997). Color appearance depends on the variance of surround colors. *Current Biology, 7*, 844-849.

Burge, J. (2020). Image-computable ideal observers for tasks with natural stimuli. *Annual Review of Neuroscience, 6*, 491-517.

Burge, J., & Geisler, W. S. (2011). Optimal defocus estimation in individual natural images. *Proceedings of the National Academy of Sciences, 108(40)*, 16849-16854.

Burge, J., & Geisler, W. S. (2014). Optimal disparity estimation in natural stereo images. *Journal of Vision, 14(2)*

Burge, J., & Geisler, W. S. (2015). Optimal speed estimation in natural image movies predicts human performance. *Nature Communications, 6*, 7900.

Burge, J., & Jaini, P. (2017). Accuracy maximization analysis for sensory-perceptual tasks: computational improvements, filter robustness, and coding advantages for scaled additive noise. *PLoS Computational Biology, 13(2)*, e1005281.

Burnham, R. W., Evans, R. M., & Newhall, S. M. (1952). Influence on color perception of adaptation to illumination. *Journal of the Optical Society of America, 42(9)*, 597-605.

Chichilnisky, E. J., & Wandell, B. A. (1997). Increment-decrement asymmetry in adaptation. *Vision Research, 37*, 616.

Chin, B. M., & Burge, J. (2020). Predicting the partition of behavioral variability in speed perception with naturalistic stimuli. *Journal of Neuroscience, 40(4)*, 864-879.

CIE. (2007). *Fundamental chromaticity diagram with physiological axes – Parts 1 and 2. Technical Report 170-1*. Vienna: Central Bureau of the Commission Internationale de l' Éclairage.

Cohen, J. (1964). Dependency of the spectral reflectance curves of the Munsell color chips. *Psychon. Sci, 1*, 369-370.

Cohen, M. R., & Newsome, W. T. (2009). Estimates of the contribution of single neurons to perception depend on timescale and noise correlation. *J Neurosci, 29(20)*, 6635-6648.

Cottaris, N. P., Jiang, H., Ding, X., Wandell, B. A., & Brainard, D. H. (2019). A computational-observer model of spatial contrast sensitivity: Effects of wave-front-based optics, cone-mosaic structure, and inference engine. *Journal of Vision, 19(4)*, 8.

Fechner, G. T. (1860). *Elements of Psychophysics* (H. E. Adler, 1966, Trans.). New York: Holt, Rinehart and Winston.

Flachot, A., & Gegenfurtner, K. R. (2018). Processing of chromatic information in a deep convolutional neural network. *JOSA A, 35(4)*, B334-B346.

Flachot, A., & Gegenfurtner, K. R. (2021). Color for object recognition: Hue and chroma sensitivity in the deep features of convolutional neural networks. *Vision Research, 182*, 89-100.

Foster, D. H. (2011). Color constancy. *Vision Research, 51(7)*, 674-700.

Gegenfurtner, K., & Kiper, D. C. (1992). Contrast detection in luminance and chromatic noise. *Journal of the Optical Society of America A, 9(11)*, 1880-1888.

Gehler, P., Rother, C., Kiefel, M., Zhang, L., & Schölkopf, B. (2011). *Recovering intrinsic images with a global sparsity prior on reflectance.* Paper presented at Advances in Neural Information Processing Systems, 765-773.

Geisler, W. S. (2008). Visual perception and the statistical properties of natural scenes. *Annual Review of Psychology, 59*, 167-192.

Geisler, W. S., Najemnik, J., & Ing, A. D. (2009). Optimal stimulus encoders for natural tasks. *Journal of Vision, 9(13)*, 17 11-16.

Gilchrist, A. L. (1977). Perceived lightness depends on perceived spatial arrangement. *Science, 195*, 185.

Gilchrist, A. L. (2006). *Seeing Black and White*. Oxford: Oxford University Press.

Giulianini, F., & Eskew, R. T., Jr. (1998). Chromatic masking in the (DL/L, DM/M) plane of cone-contrast space reveals only two detection mechanisms. *Vision Research, 38*, 3913-3926.

Green, D. M., & Swets, J. A. (1966). *Signal Detection Theory and Psychophysics* (Vol. 1). New York: Wiley.

Heasly, B. S., Cottaris, N. P., Lichtman, D. P., Xiao, B., & Brainard, D. H. (2014). RenderToolbox3: MATLAB tools that facilitate physically based stimulus rendering for vision research. *Journal of Vision, 14(2)*

Helmholtz, H. (1896). *Physiological Optics*. New York: Dover Publications, Inc.

Helson, H., & Jeffers, V. B. (1940). Fundamental problems in color vision. II. Hue, lightness, and saturation of selective samples in chromatic illumination. *Journal of Experimental Psychology, 26(1)*, 1-27.

Helson, H., & Michels, W. C. (1948). The effect of chromatic adaptation on achromaticity. *Journal of the Optical Society of America, 38*, 1025-1032.

Henning, G. B., Hertz, B. G., & Hinton, J. L. (1981). Effects of different hypothetical detection mechanisms on the shape of spatial-frequency filters inferred from masking experiments: I. Noise masks. *Journal of the Optical Society of America, 71(5)*, 574-581.

Hillis, J. M., & Brainard, D. H. (2005). Do common mechanisms of adaptation mediate color discrimination and appearance? Uniform backgrounds. *Journal of the Optical Society of America A, 22(10)*, 2090-2106.

Hillis, J. M., & Brainard, D. H. (2007a). Distinct mechanisms mediate visual detection and identification. *Current Biology, 17(19)*, 1714-1719.

Hillis, J. M., & Brainard, D. H. (2007b). Do common mechanisms of adaptation mediate color discrimination and appearance? Contrast adaptation. *Journal of the Optical Society of America A, 24(8)*, 2122-2133.

Horn, B. K. P. (1974). Determining lightness from an image. *Computer Vision, Graphics, and Image Processing, 3*, 277-299.

Hurlbert, A. (2019). Challenges to color constancy in a contemporary light. *Current Opinion in Behavioral Sciences, 30*:186, 186-193.

Ishihara, S. (1977). Tests for colour-blindness. *Tokyo: Kanehara Shuppen Company, Ltd.*

Jaini, P., & Burge, J. (2017). Linking normative models of natural tasks to descriptive models of neural response. *Journal of Vision, 17(12)*, 16.

Jakob, W. (2010). Mitsuba Renderer.

Jameson, D., & Hurvich, L. M. (1955). Some quantitative aspects of an opponent-colors theory. I. Chromatic responses and spectral saturation. *Journal of the Optical Society of America, 45*, 546-552.

Jiang, H., Farrell, J., & Wandell, B. (2016). *A spectral estimation theory for color appearance matching*. Presented at the IS&T International Symposium on Electronic Imaging,

Kelly, K. L., Gibson, K. S., & Nickerson, D. (1943). Tristimulus specification of the Munsell book of color from spectrophoto-metric measurements. *Journal of the Optical Society of America, 33(7)*, 355-376.

Kingdom, F. A. (2011). Lightness, brightness and transparency: a quarter century of new ideas, captivating demonstrations and unrelenting controversy. *Vision Research, 51(7)*, 652-673.

Knill, D. C., & Richards, W. (1996). *Perception as Bayesian Inference*. Cambridge: Cambridge University Press.

Kraft, J. M., Maloney, S. I., & Brainard, D. H. (2002). Surface-illuminant ambiguity and color constancy: effects of scene complexity and depth cues. *Perception, 31*, 247-263.

Land, E. H., & McCann, J. J. (1971). Lightness and retinex theory. *Journal of the Optical Society of America, 61(1)*, 1-11.

Legge, G. E., Kersten, D., & Burgess, A. E. (1987). Contrast discrimination in noise. *Journal of the Optical Society of America A, 4(2)*, 391-404.

Losada, M. A., & Mullen, K. T. (1995). Color and luminance spatial tuning estimated by noise masking in the absence of off-frequency looking. *Journal of the Optical Society of America A, 12(2)*, 250-260.

Lotto, R. B., & Purves, D. (1999). The effects of color on brightness. *Nature Neuroscience, 2(11)*, 1010-1014.

Maloney, L. T. (1986). Evaluation of linear models of surface spectral reflectance with small numbers of parameters. *Journal Of The Optical Society Of America A, 3(10)*, 1673-1683.

Maloney, L. T., & Yang, J. N. (2001). The illuminant estimation hypothesis and surface color perception. In R. Mausfeld & D. Heyer (Eds.), *Colour Perception: From Light to Object* (pp. 335–358). Oxford: Oxford University Press.

Marimont, D. H., & Wandell, B. A. (1994). Matching color images: the effects of axial chromatic aberration. *Journal of the Optical Society of America A, 11(12)*, 3113-3122.

Monaci, G., Menegaz, G., Süsstrunk, S., & Knoblauch, K. (2004). Chromatic contrast detection in spatial chromatic noise. *Visual Neuroscience, 21*, 291-294.

Morimoto, T., & Smithson, H. E. (2018). Discrimination of spectral reflectance under environmental illumination. *J Opt Soc Am A Opt Image Sci Vis, 35(4)*, B244-B255.

Murray, R. F. (2020). A model of lightness perception guided by probabilistic assumptions about lighting and reflectance. *J Vis, 20(7)*, 28.

Murray, R. F. (2021). Lightness perception in complex scenes. *Annual Review of Vision Science, 7*, 417-436.

Nachmias, J. (1999). How is a grating detected on a narrowband noise masker? *Vision Research, 39(6)*, 1133-1142.

Nachmias, J., & Sansbury, R. V. (1974). Grating contrast: discrimination may be better than detection. *Vision Research, 14(10)*, 1039–1042.

Nienborg, H., Cohen, M. R., & Cumming, B. G. (2012). Decision-related activity in sensory neurons: correlations among neurons and with behavior. *Annu Rev Neurosci, 35*, 463-483.

Olkkonen, M., Witzel, C., Hansen, T., & Gegenfurtner, K. T. (2010). Categorical color constancy for real surfaces

. *Journal of Vision, 10(9)*

Parker, A. J., & Newsome, W. T. (1998). Sense and the single neuron: probing the physiology of perception. *Annual Review of Neuroscience, 21(1)*, 227-277.

Parkkinen, J. P. S., Hallikainen, J., & Jaaskelainen, T. (1989). Characteristic spectra of Munsell colors. *Journal of the Optical Society of America, 6(2)*, 318-322.

Pearce, B., Crichton, S., Mackiewicz, M., Finlayson, G. D., & Hurlbert, A. (2014). Chromatic illumination discrimination ability reveals that human colour constancy is optimised for blue daylight illuminations. *PLoS ONE 9(2:e87989)*, e87989.

Pelli, D. G. (1990). The quantum efficiency of vision. In C. Blakemore (Ed.), *Vision: Coding and Efficiency* (pp. 3-24).

Pelli, D. G., & Farell, B. (1999). Why use noise? *Journal of the Optical Society of America A, 16(3)*, 647-653.

Prins, N., & Kingdom, F. A. A. (2018). Applying the model-comparison approach to test specific tesearch hypotheses in psychophysical research using the Palamedes toolbox. *Frontiers in Psychology, 9*, 1250.

Radonjic, A., & Brainard, D. H. (2016). The nature of instructional effects in color constancy. *J Exp Psychol Hum Percept Perform, 42(6)*, 847-865.

Radonjić, A., Cottaris, N. P., & Brainard, D. H. (2015). Color constancy supports cross-illumination color selection. *Journal of Vision, 15(6)*, 1-19.

Radonjić, A., Ding, X., Krieger, A., Aston, S., Hurlbert, A. C., & Brainard, D. H. (2018). Illumination discrimination in the absence of a fixed surface-reflectance layout. *Journal of Vision, 18(5:11)*

Radonjić, A., & Gilchrist, A. L. (2013). Depth effect on lightness revisited: the role of articulation, proximity and fields of illumination. *i-Perception, 4(6)*, 437–455.

Radonjić, A., Pearce, B., Aston, S., Krieger, A., Dubin, H., Cottaris, N. P., Brainard, D. H., & Hurlbert, A. C. (2016). Illumination discrimination in real and simulated scenes. *Journal of Vision, 16(11:2)*, 1-18.

Rodieck, R. W. (1998). *The First Steps in Seeing*. Sunderland, Mass.: Sinauer.

Rovamo, J., Franssila, R., & Nasanen, R. (1992). Contrast sensitivity as a function of spatial frequency, viewing distance and eccentricity with and without spatial noise. *Vision Research, 32(4)*, 631-637.

Rovamo, J., Raninen, A., & Donner, K. (1999). The effects of temporal noise and retinal luminance on foveal flicker sensitivity. *Vision Research, 39*, 533-539.

Ruff, D. A., Ni, A. M., & Cohen, M. R. (2018). Cognition as a window into neuronal population space. *Annual Review of Neuroscience, 41*, 77-97.

Sankeralli, M. J., & Mullen, K. T. (1997). Postreceptoral chromatic detection mechanisms revealed by noise masking in three-dimensional cone contrast space. *Journal of the Optical Society of America A, 14(10)*, 2633-2646.

Schultz, S., Doerschner, K., & Maloney, L. T. (2006). Color constancy and hue scaling. *J Vis, 6(10)*, 1102-1116.

Shadlen, M. N., Britten, K. H., Newsome, W. T., & Movshon, J. A. (1996). A computational analysis of the relationship between neuronal and behavioral responses to visual motion. *Journal of Neuroscience, 16*, 1486-1510.

Shen, L., & Yeo, C. (2011). *Intrinsic images decomposition using a local and global sparse representation of reflectance*. Presented at the IEEE Conference on Computer Vision and Pattern Recognition,

Singh, V., Cottaris, N. P., Heasly, B. S., Brainard, D. H., & Burge, J. (2018). Computational luminance constancy from naturalistic images. *Journal of Vision, 18(13)*, 19.

Smithson, H. E. (2005). Sensory, computational, and cognitive components of human color constancy. *Philosophical Transactions of the Royal Society of London. Series B, 360(1458)*, 1329-1346.

Teller, D. Y. (1984). Linking propositions. *Vision Research, 24(10)*, 1233-1246.

Thibos, L. N., Hong, X., Bradley, A., & Cheng, X. (2002). Statistical variation of aberration structure and image quality in a normal population of healthy eyes. *Journal of the Optical Society of America A, 19(12)*, 2329-2348.

von Kries, J. (1905). Influence of adaptation on the effects produced by luminous stimuli. In D. L. MacAdam (Ed.), *Sources of Color Science (1970)* (pp. 120-1126). Cambridge, MA: MIT Press.

Vrhel, M. J., Gershon, R., & Iwan, L. S. (1994). Measurement and analysis of object reflectance spectra. *Color Research & Application, 19(1)*, 4-9.

Wandell, B. A., & Brainard, D. H. (in press). Principles and consequences of the initial visual encoding. In F. G. Ashby, H. Colonius & E. Dzhafarov (Eds.), *The New Handbook of Mathematical Psychology* Cambridge: Cambridge University Press.

Webster, M. A., & Mollon, J. D. (1995). Colour constancy influenced by contrast adaptation. *Nature, 373(6516)*, 694-698.

Weiss, D., Witzel, C., & Gegenfurtner, K. (2017). Determinants of colour constancy and the blue bias. *i-Perception, 8(6)*, 204166951773963.

Whittle, P., & Challands, P. D. C. (1969). The effect of background luminance on the brightness of flashes. *Vision Research, 9(9)*, 1095-1110.

Witzel, C., & Gegenfurtner, K. R. (2018). Color perception: objects, constancy, and categories. *Annual Review of Vision Science, 4*, 475-499.

Yang, J. N., & Maloney, L. T. (2001). Illuminant cues in surface color perception: tests of three candidate cues. *Vision Research, 41*, 2581-2600.

Zhang, X., & Brainard, D. H. (2004). *Bayesian color correction method for non-colorimetric digital image sensors.* Paper presented at Color and Imaging Conference, 308-314.

Zhu, H., Yuille, A., & Kersten, D. (2021). *Three-dimensional pose discrimination in natural images of humans*. Presented at the Annual Meeting of the Vision Sciences Society, May 21-26, 2021. Poster A70.

1. The preregistration documents relevant to this work are those for Experiments 6, 7 and 8. The site also contains preregistrations for previously reported (Experiment 1, 2 and 3, [cite equivalent noise paper]) and unreported (Experiment 4 and 5) work. [↑](#footnote-ref-1)