

1 Title: Characterization of human lightness discrimination thresholds for independent spectral variations

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6 **ABSTRACT:** Lightness of an object is an object intrinsic property that depends on its surface reflectance  
7 spectrum. The human visual system infers the lightness of an object from the light reflected off its  
8 surface. Since the reflected light depends also on the properties of the scene and the pose and position of  
9 the observer, to stably perceive the lightness of an object the visual system needs to discount any variation  
10 in the proximal signal due to object extrinsic factors. In this work, we characterize the extent to which the  
11 visual system can achieve this stability for variation in the reflectance spectra of objects in a scene and  
12 variations in the intensity of light sources in a scene. We measure human observers' thresholds of  
13 discriminating images based on the lightness of a spherical target object using a two alternative forced  
14 choice task. The images were computational renderings of 3D scenes. We measured how the  
15 discrimination thresholds changed as we varied the reflectance spectra of the objects and the intensity of  
16 the light sources in the scene, both individually and simultaneously. For small amounts of extrinsic  
17 variations, the thresholds of discrimination remained constant indicating that the thresholds these levels  
18 depended on the variability in the observers' intrinsic representation of lightness. As the amount of  
19 extrinsic variation increased, the thresholds started increasing indicating that the extrinsic variation started  
20 affecting observers' lightness judgement. We estimated that the variance in the lightness representation  
21 due to variation in reflectance spectra or light source intensity were within a factor of two as compared to  
22 the variation in observers' intrinsic representation of object lightness. Moreover, for simultaneous  
23 variation of both these spectral properties, the increase in threshold square compared to no variation  
24 condition was a linear sum of the corresponding increase in threshold squares for the individual  
25 properties, indicating that the variation from these independent sources combine linearly.

26 **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 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, specifically, variation in the spectra of the background objects and the intensity of light sources in the scene.

The perceptual correlate of the diffuse spectral reflectance of an object is its perceived color. For achromatic objects, the analogous perceptual 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 light source, the surface reflectance of objects in the scene, and the geometry and other properties of the scene (Foster, 2011; Brainard & Radonjic, 2004). The degree to which such stability can be achieved is termed as color/lightness constancy (Adelson, 2000; Gilchrist, 2006). Human color/lightness constancy has been measured using appearance-based approaches and discrimination-based approaches (Olkkonen & Ekroll, 2016). Appearance based approaches involve tasks in which the observer makes judgement about the appearance of stimuli. This approach includes methods such as color matching, color naming, scaling, and nulling (Foster, 2003). In color matching, observers adjust a test stimulus to match a standard stimulus. Color matching experiments show varying degrees of constancy with constancy measured between 15%-90% under conditions such as changes of illumination (Arend & Goldstein, 1987; Arend & Spehar, 1993), reflectance (Arend & Spehar, 1993; Patel, Munasinghe, & Murray, 2018), illumination gradients (Arend & Goldstein, 1990; Brainard, Brunt, & Speigle, 1997), and illumination and simulated reflectance (Rutherford & Brainard, 2002). Color naming is a more direct and arguably natural method to measure color constancy where observers are asked to categorize stimuli based on their hue, saturation, and lightness (Troost & De Weert, 1991). This method has been used with real (Uchikawa, Uchikawa, & Boynton, 1989; Olkkonen, Witzel, Hansen, & Gegenfurtner, 2010) and simulated stimuli (Olkkonen, Hansen, & Gegenfurtner, 2009) to measure constancy. Color naming methods have the limitation that there are vast number of possible discernible colors (Linhares, Pinto, & Nascimento, 2008), but there is a limit of the gamut that can be displayed. Typically, observers are asked to name from a small set of colors (Speigle & Brainard, 1996; Smithson & Zaidi, 2004; Hansen, Walter, & Gegenfurtner, 2007) which might provide an overestimate of the measured constancy. In color scaling methods, observers view a stimulus and provide a rating on a scale for a set of colors, thus allowing for a finer level of comparison for measuring constancy (Luo, et al., 1991; Schultz, Doerschner, & Maloney, 2006). Scaling methods can also be used to measure changes in stimuli, where observers provide a rating of the change between stimuli (Ennis & Doerschner, 2019). Nulling or achromatic adjustment methods involve changing a test stimulus such that it appears achromatic (Arend, 1993; Brainard, 1998; Delahunt & Brainard, 2004). This method has the limitation that it provides data only for achromatic/gray stimuli and additional assumptions about the observers' criterion needs to be made for color appearances (Speigle & Brainard, 1996).

Discrimination-based approaches provide an objective method to measure color constancy (Bramwell & Hurlbert, 1996; Reeves, Amano, & Foster, 2008). In these experiments, observers discriminate stimuli as to whether they are the same or different from each other. The stimuli are varied in some relevant parameter space to measure the threshold for discriminating changes in the parameter (Craven & Foster, 1992; Pearce, Crichton, Mackiewicz, Finlayson, & Hurlbert, 2014; Aston, Radonjic, Brainard, & Hurlbert, 2019). Recently, Singh et. al (Singh, Burge, & Brainard, 2022) developed an equivalent noise paradigm that relates thresholds of discrimination to the variability in observers' intrinsic representation of object properties (e.g., its lightness) and the variability due to object extrinsic properties of the scene.

They measured human lightness discrimination thresholds as a function of the amount of variability in the 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. A comparison of the strength of intrinsic and extrinsic variability provided a measure of the degree of constancy in the object intrinsic property due to the variability in object extrinsic property.

This equivalent noise paradigm can also be used to compare the effect of different sources of variabilities. The variance of multiple extrinsic properties can be characterized relative to the variance of the intrinsic variability. These in turn can be compared to each other to measure their relative effects. It can also be used to characterize how the effect of multiple sources of variability combine when presented simultaneously.

In this work, we use this paradigm to compare the variation in two spectral properties of the scene to human observers' representation of lightness. The spectral variations we study are: the surface reflectance of the background objects in the scene and the intensity of the light sources in the scene. 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. We measure discrimination thresholds 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 these spectral variations. A comparison of variance of individual and simultaneous variation condition can provide information about the combination rules of multiple sources of variation.

We show that as the variability in the extrinsic sources increases, initially for small amount of variation, the thresholds remain constant. In this region, the thresholds are determined primarily by the variation in observers' internal representation of lightness. As the variability increases further, the discrimination thresholds increase. The increase in thresholds can be accounted for by a 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 variation. By comparing the increase in thresholds of the individual and simultaneous variation condition from the no extrinsic variation condition, we show that the effects of individual sources combine 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 remarks.

## **2 EXPERIMENTAL METHODS**

### **Overview**

We followed the methodology published previously in (Singh, Burge, & Brainard, 2022). In this previous work, human lightness discrimination thresholds were measured under variability of the reflectance spectra of background objects in the scene. The work presented here follows the same experimental methods, except that the stimuli used in the experiments 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-alternative forced-choice (2AFC) procedure to measure thresholds (Figure 1). On each trial of the experiment, participants observed pairs of computer-generated 3D scenes displayed on a color calibrated monitor. These pairs consisted of a standard image and a comparison image. The images were presented sequentially for 250ms, with a 250ms inter-stimulus interval between them. Both images contained an achromatic spherical object as the target object point. Observers were required to indicate the image on which the target object was lighter. Between trials, we manipulated the luminous reflectance factor (LRF) of the target object 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 (American Society for Testing and Materials, 2017). The order of the standard and the comparison image was chosen in a pseudorandom order. We recorded the proportion of times the observer chose the comparison image to have the lighter target object at 11 values of the target object LRF. The psychometric function of one observer is shown in Figure 2. We fit the proportion-comparison-chosen data with a cumulative normal function to extract the thresholds, which was defined as the difference between the LRF of the target object at proportion comparison chosen 0.76 and 0.50 (i.e.,  $d\text{-prime} = 1.0$  in a two-interval task).

We measured the effect of variation in two types of object-extrinsic scene properties on human lightness discrimination thresholds: 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. These experiments were preregistered (see below Preregistration).

(1) Background reflectance spectra variation (preregistered as 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 as 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 as 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**

We preregistered the experiments performed in this work before collecting the data. The preregistration documents are available at: <https://osf.io/7tgy8/>.<sup>1</sup> The documentation includes information about the experimental design as well as the procedure to estimate thresholds from the collected data.

The experiments 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; Singh, Burge, & Brainard, 2022) with additional conditions in which the background objects were achromatic and varied only in their lightness. While the stimuli were different for the three experiments (preregistered Experiments 6, 7, and 8), the experimental method to measure lightness discrimination thresholds were the same.

The preregistration documents mentioned that the experiments aimed at characterizing the dependence of human lightness discrimination thresholds on the amount of variation in the background reflectance and the intensity of the light source in the scene. The method of estimating discrimination thresholds was described in the document. 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 the increase in thresholds could be captured by an equivalent noise model (Singh, Burge, & Brainard, 2022). Additionally, we predicted that the threshold for simultaneous variation would be higher than the thresholds for individual variations.

## **Reflectance and Illumination Spectra**

We used a statistical model of natural reflectance dataset to generate reflectance spectra of background objects (Singh, Cottaris, Heasly, Brainard, & Burge, 2018; Singh, Burge, & Brainard, 2022). We combined two datasets of surface reflectance measurements (Vrhel, Gershon, & Iwan, 1994; Kelly, Gibson, & Nickerson, 1943). These datasets contain 632 surface reflectance measurements. We mean centered the dataset by subtracting out the mean surface reflectance over the 632 measurements. Then we used 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 (Singh, Cottaris, Heasly, Brainard, & Burge, 2018). The empirical distribution of the projection weights thus obtained was approximated with a multivariate normal distribution. To get the projection weights of random samples of reflectance spectra, pseudorandom samples were generated from this multivariate normal distribution. Reflectance spectra were constructed by using these projection weights 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 ( $\sigma^2$ ). A covariance scalar of 0 indicates that there is no variation in the reflectance spectra of the background objects. On the other hand, a covariance

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<sup>1</sup> 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; Singh, Burge, & Brainard, 2022) and unreported (Experiment 4 and 5) work.

scalar of 1 corresponds to the range of reflectance variation observed in the combined natural reflectance datasets.

The light source power spectrum was chosen to be CIE D65 reference illuminant. The D65 spectrum was divided by its mean power over wavelength 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  $[1 - \delta, 1 + \delta]$ , where  $\delta$  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 (Singh, Cottaris, Heasly, Brainard, & Burge, 2018). All light sources in a scene were assigned the same power spectrum.

The values of the two parameters  $\sigma^2$  and  $\delta$  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 ( $\sigma^2$ ): [0, 0.01, 0.03, 0.1, 0.3, 1.0] (same as Singh, Burge, & Brainard, 2022). Three conditions were for achromatic variation at covariance scalar ( $\sigma^2$ ): [0.03, 0.3, 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 ( $\delta$ ): [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 ( $\sigma^2 = 0, \delta = 0$ ), chromatic background variation (covariance scalar = 1,  $\delta = 0$ ), achromatic background variation ( $\sigma^2 = 1, \delta = 0$ ), light source intensity variation ( $\sigma^2 = 0, \delta = 0.3$ ), simultaneous variation chromatic background ( $\sigma^2 = 1, \delta = 0.3$ ) and simultaneous variation achromatic background ( $\sigma^2 = 1, \delta = 0.3$ ). Figure 5 shows five typical images for these six conditions.

## Stimulus Design

The images used in this work were generated using the software Virtual World Color Constancy (VWCC) (github.com/BrainardLab/VirtualWorldColorConstancy) described in (Singh, Cottaris, Heasly, Brainard, & Burge, 2018). The initial step to generate an image involves constructing a 3D model that serves as the base scene. Then, based on the specific experimental condition, we assign reflectance spectra and spectral power distribution functions to the objects and light sources within the base scene. All light sources within a given scene were assigned identical spectral power distribution functions. Subsequently, we utilize Mitsuba, an physically-realistic open-source rendering system (mitsuba-renderer.org; Jakob, 2010) to produce a 2D multispectral image of the scene at 31 equally spaced wavelengths between 400nm and 700nm. The images had a camera field of view of  $17^\circ$  and a resolution of 320-pixel by 240-pixels and were centered at the target object. To display the images on the monitor, a 201-pixel by 201-pixel part centered at the target object was cropped out of the images. Monitor calibration data was used to convert the multispectral images to gamma corrected RGB images as described in (Singh, Burge, & Brainard, 2022). Gamma-corrected RGB images were presented on the calibrated monitor during the experiment.

For each condition described above, we generated 1100 images, 100 images each at each of the 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 ( $\sigma^2 = 0$ ,  $\delta = 0$ ) condition, we generated one image at each target object LRF level, as the background reflectance and the light source intensity remained fixed in this case. The scene geometry remained fixed during the experiment and the images did not include secondary reflections.

The standard image, when presented on the experimental monitor, had an average luminance of 87.1 cd/m<sup>2</sup> for the condition ( $\sigma^2 = 0$ ,  $\delta = 0$ ). 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/m<sup>2</sup>.

For the ( $\sigma^2 = 1.0$ ,  $\delta = 0.3$ ) condition, the average luminance of the standard image was 87.8 cd/m<sup>2</sup>. 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/m<sup>2</sup>.

## **Experimental Structure:**

In this study, a trial is defined as the display of a standard and a comparison image on the monitor and the recording of the observer's response. An interval is defined as the presentation of either the standard image or the comparison image within a trial. A block consists of recording 330 trials for one condition, 30 trials each at 11 comparison image target LRF levels. 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 images in a trial was generated pseudorandomly 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 (nearly two to five minutes) between blocks. The observers were informed that they could stop the experiment at any time. 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 ( $\sigma^2 = 0$ ,  $\delta = 0$ ) 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.

The experimental procedure was explained to each observer at the beginning of the practice session. The experimenter then obtained the consent for the experiment. Vision tests were performed on the observer to ensure normal visual acuity normal 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

The study recruited observers from North Carolina Agricultural and Technical State University and the local Greensboro community. The participants were compensated for their time. The observers underwent a screening process to meet criteria such as a normal visual acuity of 20/40 or better (with corrective eyewear if necessary) and normal color vision, which was assessed using pseudo-isochromatic plates (Ishihara, 1977). The preregistration documents outlined these exclusion criteria (see Methods: Preregistration).

We further conducted a practice session to identify observers who could reliably perform the psychophysical task. In the practice session, the observers' performed three blocks of the experiment for the no variation condition ( $\sigma^2 = 0.00$ ,  $\delta = 0.00$ ) and the threshold was calculated for these three blocks. If the mean threshold of the observer for the last two blocks in the practice session was larger than 0.030 ( $\log T^2$ , -3.2), the observer was discontinued. The preregistration document specified this exclusion criteria (See Methods: Preregistration).

If the observers met these criteria, they were continued with 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 reflectance variation experiment (10 Female, 15 Male; age 19-34; mean age 22.9). Observers were given pseudo-names to deidentify their personal information from the data. 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 as supplementary information (SI).

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*, *content*, *oven*, *manos*, and *revival*) were retained for the experiment (2 Female, 4 Male; age 19-28; mean age 23.33). Four observers (*0003*, *bagel*, *content*, and *oven*) 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; *content*, L = 20/20, R = 20/20; *oven*, L = 20/20, R = 20/20; *manos*, L = 20/25, R = 20/25; *revival*, L = 20/20, R = 20/20. Observer *content* 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 experiments were performed in a dark room and the stimuli were presented on a color calibrated LCD monitor (27-in. NEC MultiSync EA271U; NEC Display Solutions). The monitor operated at a pixel resolution of 1920 x 1080, with a refresh rate of 60Hz, and 8-bit resolution for each RGB channel. The setup utilized an Apple Macintosh computer with an Intel Core i7 processor. The experimental programs were written in MATLAB (MathWorks; Natick, MA). The programs utilized the Psychophysics Toolbox (<http://psychtoolbox.org>) and mgl (<http://justingardner.net/doku.php/mgl/overview>) libraries. A Logitech F310 gamepad controller was used to collect observers' response.

The distance between the observers' eyes and the monitor was set at 75cm. To ensure stability and proper alignment, a chin cup and forehead rest (Headspot, UHCOTech, Houston, TX) were used to stabilize the observers' head position. The observers' eyes were centered both horizontally and vertically in relation to the display.

## Monitor Calibration

The monitor was calibrated using a spectroradiometer (PhotoResearch PR655) as described in (Singh, Burge, & Brainard, 2022). 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.

## Ethics Statement

All experiments 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

The data for each experiment and observer is provided as supplementary information (SI). The SI is available at: <https://github.com/vijaysoophie/SimultaneousVariationPaper>. The SI contains the proportion comparison chosen data as well as the thresholds for the 3 experimental blocks of each condition, for each experiment and observer. The MATLAB scripts to generate Figures 2, 6 – 12, supplementary Figures S1-S7, and the scripts to obtain thresholds of the linear receptive field formulation of the model are also provided in the SI.

## Linear Receptive Field Model

The thresholds of preregistered Experiment 6 were fit to the linear receptive field model developed in (Singh, Burge, & Brainard, 2022). 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  $v_s$ . 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 the higher noise added receptive field response was chosen to be lighter. The variance of the Gaussian noise ( $\sigma_{ri}^2$ ) and the value of the receptive field surround sensitivity ( $v_s$ ) were the two parameters of the model. These parameters provided an estimate of the internal noise ( $\sigma_{ri}^2$ ) and the variance of the extrinsic properties ( $\sigma_{e0}^2$ ). The model related the thresholds ( $T$ ) in the experiments to the variance in the intrinsic noise ( $\sigma_{ri}^2$ ) of the observer and the extrinsic variance ( $\sigma_{e0}^2$ ) through the relation:

$$T = \sqrt{\sigma_{ri}^2 + \sigma^2 \sigma_{e0}^2} \quad (1)$$

where  $\sigma^2$  is the covariance scalar (see (Singh, Burge, & Brainard, 2022) for details). The variance of the extrinsic properties ( $\sigma_{e0}^2$ ) resulting from the variation in the image can be computed as  $R^T \Sigma_{e0} R$ , where  $\Sigma_{e0}$  is the covariance matrix of the variation in the images. We calculate the pixel-by-pixel covariance matrix of the image database for each condition and use the receptive field vector  $R$  to estimate the quantity  $R^T \Sigma_{e0} R$ .

**Background reflectance variation:** To estimate the variance of the intrinsic noise of the observer and extrinsic variation in the images, we chose the value of the Gaussian noise variance ( $\sigma_{ri,B}^2$ ) and the surround sensitivity  $v_{s,B}$  to minimize mean squared difference between the model and experimental thresholds measured at the six values of the covariance scalar.  $\sigma_{ri,B}^2$  provided the estimate of the intrinsic noise. The extrinsic noise ( $\sigma_{e0,B}^2$ ) was estimated by using the best fit surround sensitivity ( $v_{s,B}$ ) of the receptive field ( $R$ ) and the sample covariance matrix of the images ( $\Sigma_{e0}$ ) at  $\sigma^2=1$  in the relation  $R^T \Sigma_{e0} R$ .

**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  $\sigma^2$  by the range parameter  $\delta$ . We chose the value of the Gaussian noise variance ( $\sigma_{ri,L}^2$ ) and receptive field surround sensitivity ( $v_{s,L}$ ) to minimize the mean square difference between the observer and model thresholds measured at the seven values of the range parameter.  $\sigma_{ri,L}^2$  provided the estimate of the observer's intrinsic noise.

In natural viewing conditions, the intensity of the light source varies over several orders of magnitude (Singh, Cottaris, Heasly, Brainard, & Burge, 2018). This range of variation cannot be captured in the experiment due to the limitations of the monitor. To estimate the extrinsic noise, we used the best fit

surround sensitivity ( $v_{s,L}$ ) and the sample covariance matrices to calculate the quantity  $R^T \Sigma_{e0} R$  as a function of the range parameter  $\delta$ . We fit the resulting values with an exponential function (see Figure S1). The extrinsic noise ( $\sigma_{e0,L}^2$ ) was chosen as the value of the exponential fit at  $\delta = 1$ . The parameter ( $\sigma_{e0,L}^2$ ) could be used to estimate the extrinsic noise for more naturalistic variations using the exponential fit.

### 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 reflectance spectra were sampled from a multivariate normal distribution which was a statistical model of natural surface reflectance spectra. The amount of variation in the reflectance spectra was controlled by multiplying the covariance matrix by a covariance scalar ( $\sigma^2$ ). 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. For each of the nine conditions and for each observer, discrimination thresholds were measured three times in three separate blocks. The psychometric functions for these nine conditions are shown for one observer in Figure 6. See Figure S2 for the psychometric functions of all six observers. We notice that as the covariance scalar increases, the slope of the psychometric functions decreases, corresponding to an increase in discrimination thresholds. The thresholds for chromatic and achromatic variation are comparable.

Figure 7 shows the change in discrimination thresholds as function of the variance in the reflectance of the background objects. Here we plot the mean log threshold squared (averaged across observers,  $N = 6$ ) as a function of the log of the covariance scalar. The thresholds and standard error of the mean (SEM) from Figure 7 are listed in Table S1. We observe that the thresholds are nearly constant at small values of the covariance scalar. Once the value of the covariance scalar starts increasing, log threshold squared increases. Further, the thresholds are comparable for chromatic and achromatic variation. The p-values 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, indicating that the differences in the mean thresholds are not statistically significant. Figure S3 shows the discrimination thresholds measured in preregistered Experiment 6 and previously reported thresholds in (Singh, Burge, & Brainard, 2022). The measured thresholds are consistent between the two experiments.

We fit the thresholds to the linear receptive field (LINRF) model (Eq. 1) developed in (Singh, Burge, & Brainard, 2022). The LINRF model provides the estimate of the variance of the internal noise of the observer as  $\sigma_{ri,B}^2 = 0.026$  and the variance of the extrinsic variability due to the reflectance of background objects as  $\sigma_{e0,B}^2 = 0.039$ . The equivalent noise level, the ratio of the external variance to intrinsic noise, is  $\sim 1.5$ , 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, this indicates 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 by multiplying the normalized spectrum by a scalar sampled from a log-uniform distribution in the range  $[1 - \delta, 1 + \delta]$ . The reflectance spectra of the background objects were fixed. We measured lightness discrimination thresholds for seven values of the range parameter  $\delta$  for five human observers. The psychometric function of one of the observers for these seven conditions are shown in Figure 8. Figure S4 shows the psychometric functions of all observers. Figure 9 shows how the thresholds change as the amount of variation in the light source intensity increases. The data is averaged over five observers (also see Figure S5). Table S2 lists the mean thresholds and the SEM measured in this experiment. 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 the range parameter. A fit of the mean squared threshold with the linear receptive field model gives the value of internal noise as  $\sigma_{ri,L}^2 = 0.028$ . This compares well with the internal noise obtained from the background reflectance spectra variation experiment ( $\sigma_{ri,B}^2 = 0.026$ ). The variance of the extrinsic variability estimated at range parameter  $\delta = 1$  is  $\sigma_{e0,L}^2 = 0.052$ . The equivalent noise level, the ratio of external variation to intrinsic noise is  $\sim 1.8$ . This indicates that the variation in the lightness representation induced by the variation in light source intensity is close to the internal variation of that representation at these levels. In natural conditions, where light source intensity varies over several order of magnitudes, the extrinsic noise can be estimated by generating images at the level of variation and using the LINRF model.

## 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, variation in the reflectance spectra of background objects with fixed spectrum of the light sources for achromatic and chromatic backgrounds, 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 backgrounds. 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 S6 shows the psychometric functions of all observers. Figure 11 shows the mean log squared threshold of all six observers for these six conditions. Table S3 lists the mean thresholds and SEM from Figure 11. 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, indicating that the differences in the mean thresholds are not statistically significant.

Figure 11 also shows the squared thresholds of the LINRF model for the six conditions. We used the intrinsic noise and the surround sensitivity ( $v_s$ ) parameters of the background reflectance variation experiment to estimate the threshold of the LINRF model for the no-variation condition, background spectra variation conditions, and the simultaneous variation conditions (Experiment 6, Figure 7). For the light intensity variation condition, we used the parameters of the light source intensity variation experiment (Experiment 7, Figure 9). See Figure S7 for the predictions of the LINRF model with same set of parameters for all six conditions.

We can use the linear receptive field model to compare the extrinsic variance of the simultaneous variation condition to the variance of the individual variations. According to the linear receptive model,

the square of the threshold is proportional to the sum of the variance of observers' intrinsic noise and the extrinsic variation in the stimuli (Eq. 1). The squared threshold at the no variation condition is equal to the variance of the observers' intrinsic noise. In case of extrinsic variation, the increase in threshold square compared to the no variation condition equals the variance of the extrinsic variation. When there are more than one independent sources of extrinsic variation, the total variance of the simultaneous variation should be the sum of the variance of the individual variations. This predicts that the increase in threshold square for simultaneous variation condition should be equal to the sum of the corresponding increase for the individual variation conditions.

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 squared threshold of the simultaneous variation condition is comparable to the sum of the increase in squared threshold for the individual variations. The p-value of the hypothesis that the mean increase in squared thresholds for simultaneous variation is equal to sum of the mean increase in the squared thresholds of light intensity variation and background object reflectance variation are 0.86 and 0.80 for chromatic and achromatic conditions respectively. The variance of the extrinsic noise calculated for the background variation condition ( $\sigma^2 = 1$ ,  $\delta = 0$ ) is 0.0015 and the light intensity variation condition ( $\sigma^2 = 0$ ,  $\delta = 0.3$ ) is 0.0017. As expected, the variance of the simultaneous variation condition ( $\sigma^2 = 1$ ,  $\delta = 0.3$ ), which is 0.0033, is comparable to the sum of individual variances (0.0032).

## 4 DISCUSSION

The visual system is known to maintain a stable representation of object lightness despite variations in the proximal signal due to the scene. In this work we characterize the extent of such stability for variability in the spectra of background objects and light sources in a scene. We measured human observers' threshold of discriminating two objects based on their lightness as a function of amount of variation in these spectral properties. We observe that for low levels 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 variation 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 the amount of variability in the extrinsic property, thus providing a comparison of the variance in the 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. Further, for simultaneous variation of these properties the effects added linearly, resulting in the variance of the simultaneous variation to be equal to the sum of the variance of the individual 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, indicating that lightness and chromaticity are encoded independently. This hypothesis could be tested by measuring chromaticity discrimination thresholds under chromatic and achromatic variation of background objects.

**Visual system at threshold level:** For the spectral variabilities studied in this work, the variances in observers' representation of lightness due to extrinsic variations are within a factor of two compared to the variances in observers' intrinsic representation of lightness. If these 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

543 system provides a large degree of stability in the perceptual representation of lightness and seems to work  
544 at near threshold levels.

545 **Rules of Combination:** The increase in squared threshold of simultaneous variation of reflectance  
546 spectra of background object and intensity of light sources from no variation condition were equal to the  
547 sum of the increase in squared threshold of the individual variations. This could be accounted assuming  
548 that the sources of noise are independent, and their effects add linearly.

549 **5 ACKNOWLEDGEMENTS:** We thank Dr. David Brainard for his comments on the manuscript. This  
550 work was supported by National Science Foundation award BCS 2054900.

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

Condition	Observer					
	0003	Bagel	Committee	Content	Observer	Revival
$\sigma^2 = 0.00$	0.0221 $\pm$ 0.0010	0.0185 $\pm$ 0.0018	0.0344 $\pm$ 0.0027	0.0223 $\pm$ 0.0012	0.0311 $\pm$ 0.0053	0.0251 $\pm$ 0.0023
$\sigma^2 = 0.01$	0.0215 $\pm$ 0.0009	0.0194 $\pm$ 0.0020	0.0386 $\pm$ 0.0103	0.0193 $\pm$ 0.0012	0.0263 $\pm$ 0.0059	0.0262 $\pm$ 0.0048
$\sigma^2 = 0.03$	0.0242 $\pm$ 0.0019	0.0261 $\pm$ 0.0020	0.0285 $\pm$ 0.0029	0.0246 $\pm$ 0.0046	0.0292 $\pm$ 0.0007	0.0282 $\pm$ 0.0016
$\sigma^2 = 0.03$ Achromatic	0.0255 $\pm$ 0.0019	0.0213 $\pm$ 0.0024	0.0343 $\pm$ 0.0055	0.0227 $\pm$ 0.0023	0.0267 $\pm$ 0.0040	0.0263 $\pm$ 0.0016
$\sigma^2 = 0.10$	0.0278 $\pm$ 0.0015	0.0238 $\pm$ 0.0010	0.0284 $\pm$ 0.0017	0.0278 $\pm$ 0.0035	0.0335 $\pm$ 0.0024	0.0281 $\pm$ 0.0013
$\sigma^2 = 0.30$	0.0348 $\pm$ 0.0025	0.0277 $\pm$ 0.0024	0.0344 $\pm$ 0.0020	0.0286 $\pm$ 0.0002	0.0277 $\pm$ 0.0019	0.0301 $\pm$ 0.0038
$\sigma^2 = 0.30$ Achromatic	0.0333 $\pm$ 0.0032	0.0284 $\pm$ 0.0028	0.0319 $\pm$ 0.0047	0.0308 $\pm$ 0.0015	0.0358 $\pm$ 0.0030	0.0287 $\pm$ 0.0022
$\sigma^2 = 1.00$	0.0416 $\pm$ 0.0072	0.0316 $\pm$ 0.0008	0.0379 $\pm$ 0.0024	0.0323 $\pm$ 0.0022	0.0405 $\pm$ 0.0042	0.0360 $\pm$ 0.0055
$\sigma^2 = 1.00$ Achromatic	0.0289 $\pm$ 0.0017	0.0310 $\pm$ 0.0015	0.0391 $\pm$ 0.0029	0.0384 $\pm$ 0.0058	0.0312 $\pm$ 0.0015	0.0322 $\pm$ 0.0009

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

Condition	Observer					
	0003	Bagel	Content	Oven	Primary	Revival
$\delta = 0.00$	0.0217 $\pm$ 0.0012	0.0181 $\pm$ 0.0001	0.0208 $\pm$ 0.0014	0.0520 $\pm$ 0.0114	0.0329 $\pm$ 0.0061	0.0372 $\pm$ 0.0008
$\delta = 0.05$	0.0228 $\pm$ 0.0018	0.0229 $\pm$ 0.0018	0.0207 $\pm$ 0.0007	0.0580 $\pm$ 0.0064	0.0346 $\pm$ 0.0042	0.0364 $\pm$ 0.0013
$\delta = 0.10$	0.0275 $\pm$ 0.0024	0.0217 $\pm$ 0.0009	0.0242 $\pm$ 0.0040	0.0325 $\pm$ 0.0022	0.0343 $\pm$ 0.0013	0.0376 $\pm$ 0.0072
$\delta = 0.15$	0.0316 $\pm$ 0.0009	0.0238 $\pm$ 0.0011	0.0323 $\pm$ 0.0032	0.0333 $\pm$ 0.0019	0.0345 $\pm$ 0.0042	0.0326 $\pm$ 0.0002
$\delta = 0.20$	0.0447 $\pm$ 0.0100	0.0381 $\pm$ 0.0046	0.0276 $\pm$ 0.0016	0.0493 $\pm$ 0.0120	0.0423 $\pm$ 0.0050	0.0392 $\pm$ 0.0034
$\delta = 0.25$	0.0433 $\pm$ 0.0052	0.0393 $\pm$ 0.0062	0.0308 $\pm$ 0.0023	0.0461 $\pm$ 0.0060	0.0532 $\pm$ 0.0083	0.0387 $\pm$ 0.0025
$\delta = 0.30$	0.0404 $\pm$ 0.0018	0.0429 $\pm$ 0.0033	0.0347 $\pm$ 0.0014	0.0580 $\pm$ 0.0061	0.0465 $\pm$ 0.0047	0.0421 $\pm$ 0.0042

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

Condition	Observer					
	0003	Bagel	Content	Oven	Manos	Revival
No Variation	0.0261 $\pm$ 0.0022	0.0227 $\pm$ 0.0019	0.0246 $\pm$ 0.0004	0.0383 $\pm$ 0.0066	0.0258 $\pm$ 0.0036	0.0366 $\pm$ 0.0085
Background Variation Chromatic	0.0414 $\pm$ 0.0036	0.0340 $\pm$ 0.0058	0.0392 $\pm$ 0.0083	0.0498 $\pm$ 0.0050	0.0306 $\pm$ 0.0013	0.0383 $\pm$ 0.0033
Background Variation Achromatic	0.0394 $\pm$ 0.0027	0.0319 $\pm$ 0.0015	0.0427 $\pm$ 0.0074	0.0683 $\pm$ 0.0048	0.0435 $\pm$ 0.0071	0.0389 $\pm$ 0.0010
Light Intensity Variation	0.0464 $\pm$ 0.0027	0.0656 $\pm$ 0.0208	0.0412 $\pm$ 0.0021	0.0592 $\pm$ 0.0091	0.0464 $\pm$ 0.0046	0.0474 $\pm$ 0.0069
Simultaneous Variation Chromatic	0.0635 $\pm$ 0.0092	0.0536 $\pm$ 0.0014	0.0437 $\pm$ 0.0011	0.0639 $\pm$ 0.0106	0.0768 $\pm$ 0.0085	0.0528 $\pm$ 0.0037
Simultaneous Variation Achromatic	0.0648 $\pm$ 0.0103	0.0540 $\pm$ 0.0017	0.0478 $\pm$ 0.0049	0.0826 $\pm$ 0.0166	0.0749 $\pm$ 0.0082	0.0561 $\pm$ 0.0028



## Figure Captions

**Figure 1: (a) Psychophysical task.** (Adapted from Figure 1 in Singh, Burge, & Brainard, 2022) The psychophysical task involved comparing two images, a standard image and a comparison image, on each trial and selecting the image with the lighter target object. The target object was an achromatic sphere at the center of the image. 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:**  $R_{N-1}$  indicates the recording of the observer's response for the  $(N-1)^{\text{th}}$  trial. The  $N^{\text{th}}$  trial begins 250ms after the completion of the  $(N-1)^{\text{th}}$  trial (Inter Trial Interval, ITI = 250ms). In the  $N^{\text{th}}$  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  $R_N$  in the panel. The next trial begins 250ms after the choice has been recorded.

**Figure 2: Psychometric function:** We measured the proportion of times the observers selected the target in the comparison image to be lighter as function of the LRF (lightness reflectance factor) of the target object. We collected 30 responses for each of the 11 equally spaced values of the comparison image target object LRF, ranging from 0.35 to 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 randomly selected in a pseudorandom order. To analyze the data, we used maximum likelihood methods to fit a cumulative normal distribution to the proportion comparison chosen data. We imposed constraints on the guess rate and lapse rate, requiring them to be equal and within the range of 0 to 0.05. The threshold was determined as the difference between the LRF values corresponding to a proportion comparison chosen of 0.76 and 0.50, obtained from the cumulative normal fit. The figure presented here illustrates the data for observer 0003 in the second block of the background reflectance variation experiment (previously registered as Experiment 6) for the no variation ( $\sigma^2 = 0.00, \delta = 0$ ) condition. The discrimination threshold was measured to be 0.0208. The point of subjective equality (PSE), which corresponds to a proportion of 0.5 in the comparison task, was found to be 0.409. The lapse rate for this particular fit was determined to be 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 of the covariance scalar 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  $[1 - \delta, 1 + \delta]$ . The amount of variation was controlled by changing the value of the range parameter  $\delta$ . 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 figure shows the psychometric function for observer 0003. The psychometric functions for all six observers are shown in Figure S2. A cumulative normal function was fit to the data from each block to determine the discrimination threshold (see Figure 2). The legend provides the estimated 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 thresholds 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 thresholds.** 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  $\pm 1$  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  $\pm 1$  standard deviation estimated over 10 independent simulations. The legend shows the parameters of the LINRF fit are provided in. 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 psychometric functions for all observers are shown in Figure S4.

**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  $\pm 1$  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  $\pm 1$  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 S6.

**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  $\pm 1$  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) for the None, Background and Simultaneous conditions and using the parameters of the light intensity variation condition (Figure 9) for the Light condition. The blue error bars show  $\pm 1$  standard deviation estimated over 10 independent simulations.

**Figure 12: Extrinsic noise of independent variations add linearly for simultaneous variation:** Mean squared thresholds ( $N=6$ ) for the six conditions in simultaneous variation experiment (black circles). The black error bars represent  $\pm 1$  SEM taken between observers. The bars (red, gray, blue) represent the increase in squared thresholds 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 increase in measured squared threshold for the simultaneous variation conditions and the bars on the left (stacked bars of two different colors) represent the increase in the sum of the squared threshold of the light intensity variation (blue bar) and the corresponding background variation conditions (red or gray).

**Figure S1: Estimation of extrinsic noise for light intensity variation:** Plot of the variance ( $R^T \Sigma R$ ) as a function of the range parameter  $\delta$  on a linear (left panel) and logarithmic (right panel) scale. We fit the function with an exponential of the form  $A * \exp(B \cdot \delta)$ . The variance in the extrinsic noise is estimated as the value of the fit at  $\delta = 1$ .

**Figure S2: Psychometric functions for all observers for background variation experiment.** Same as Figure 6, for all observers retained in background variation experiment.

**Figure S3: Comparison with Singh, Burge, Brainard 2022.** Lightness discrimination thresholds for background variation condition measured in preregistered Experiment 6 and previously reported data from Singh, Burge, Brainard 2022. Preregistered Experiment 6 had both chromatic and achromatic conditions, while the previous experiment (Singh, Burge, Brainard 2022) only had chromatic condition. Singh, Burge, Brainard 2022 made three threshold measurements for each condition for 4 naïve observers.

**Figure S4: Psychometric functions for all observers for light intensity variation experiment.** Same as Figure 8, for all observers retained in light intensity variation experiment.

**Figure S5:** Same as Figure 9, for all six observers in retained in light intensity variation experiment. The parameters for the LINRF model are the same as in Figure 9.

**Figure S6: Psychometric functions for all observers for simultaneous variation experiment.** Same as Figure 10, for all observers retained in simultaneous variation experiment.

**Figure S7:** Same as Figure 11, but the thresholds of the linear receptive field (LINRF) model were estimated using the same set of parameters for all six conditions studied in Experiment 8. Blue square markers show log squared thresholds estimated using the parameters of the background variation condition (Experiment 6, Figure 7). Black triangular markers show log squared thresholds estimated using the parameters of the light intensity variation condition (Experiment 7, Figure 9). The black and blue error bars show  $\pm 1$  standard deviation estimated over 10 independent simulations. The parameters of the background variation condition (Experiment 6, blue squares) predict the thresholds of the no variation condition, the background variation condition, and the simultaneous variation condition quite well, but

697 fail to predict the threshold of the light source intensity variation condition. Similarly, the parameters of  
698 the light source intensity variation condition (Experiment 7, black triangles) predict the thresholds of the  
699 no variation condition, the light source intensity variation condition, and the simultaneous variation  
700 condition quite well, but fail to predict the threshold of the background variation condition. This could  
701 possibly be because observers in the three experiments were different. Future work would aim at studying  
702 these conditions using the same set of observers.

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