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

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**ABSTRACT:**

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

**INTRODUCTION**

**2 EXPERIMENTAL METHODS**

**Overview**

We followed the methodology published in our previous work [cite paper]. In previous work, we measured human lightness discrimination thresholds under variability of reflectance spectra of background objects. The work presented here follows the same experimental methods, except that the stimuli used in the experiment were different. In this section, we will mainly focus on the differences from the previous work. We refer the reader to the previous work for details of the experimental methods.

Similar to our previous experiment, 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. 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 spherical target object was lighter. Each trial contained a standard image and a comparison image. 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.

In this work, we measured the effect of variation in two types of object-extrinsic properties on human lightness discrimination thresholds. These two extrinsic properties were: the reflectance spectra of the background objects and the intensity of the light source. We performed three experiments. In the first experiment (referred to as preregistered experiment 6), 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. In the second experiment (referred to as preregistered experiment 7), we measured lightness discrimination thresholds as a function of the amount of variation in the intensity of the light source while the background was fixed. In the third experiment (referred to as preregistered experiment 8), we measured lightness discrimination thresholds for simultaneous variation in both the background object reflectance spectra and the light source intensity.

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 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 the 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 flat, and the objects were gray.

The shape of the spectral power distribution function of the light sources was chosen as CIE D65 reference illuminant. The intensity of the light sources 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 threshold 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. The first experiment (preregistered as Experiment 6) studied the effect of variation in reflection spectra of background objects on human lightness discrimination thresholds. It 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 second experiment (preregistered as Experiment 7) studied the effect of variation in intensity of the light sources in the scene on human lightness discrimination thresholds. The third experiment (preregistered as Experiment 8) studied the variation of simultaneous variation of background object reflection spectra and the light source intensity on human lightness discrimination thresholds. 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. In the case of 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 previously developed by us. 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. 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. We approximated the empirical distribution of the projection weights with a multivariate normal distribution. We generated 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 background object reflectance variation. A covariance scalar of 1 corresponds to the full reflectance variation of the model of natural reflectance.

The power spectrum of the light sources 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 the parameter 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 these two parameters, the covariance scalar and the range parameter, for the three experiments were as follows:

Background object reflectance variation (preregistered Experiment 6): To study lightness discrimination thresholds with variation in reflectance spectra of background objects, we generated images for nine conditions. Six of these conditions were for chromatic variation at six logarithmically spaced values of covariance scalar: [0, 0.01, 0.03, 0.1, 0.3, 1.0]. Three conditions were for achromatic variation at covariance scalars: 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.

When displayed on the experimental monitor, the average luminance of the standard image for covariance scalar 0.00 was 94.0 cd/m2. The average luminance of the target object for the 11 LRF levels were [130.0, 131.5, 133.0, 134.5, 136.0, 137.5, 138.9, 140.3, 141.7, 143.1, 144.5] cd/m2.

Light source intensity variation (preregistered Experiment 7): To study lightness discrimination thresholds with variation in light source intensity, we generated images for seven 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.

When displayed on the experimental monitor, the average luminance of the standard image for covariance scalar 0.00 and range parameter 0.00 was 93.3 cd/m2. The average luminance of the target object for the 11 LRF levels were [128.9, 130.5, 132.0, 133.5, 135.0, 136.4, 137.9, 139.3, 140.7, 142.1, 143.4] cd/m2.

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

When displayed on the experimental monitor, the average luminance of the standard image for covariance scalar 0.0 and range parameter 0.00 was 87.1 cd/m2. The average luminances 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 covariance scalar 1.0 and range parameter 0.30 was 87.8 cd/m2. The average luminances 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.

**Observer Recruitment and Exclusion**

Observers were recruited from the North Carolina Agricultural and Technical State University and the 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. 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.

**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 is 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*) 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 = 20/30; *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 preregistered 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 compares the dot product *of*

The model related the thresholds (*T*) in the experiments to the variance in the intrinsic noise of the observer () and the variance in the object extrinsic factors () through the relation:

*(1)*

where is the covariance scalar (see Methods: Reflectance and Illumination Spectra). The variance in the

We fit a similar function form to the thresholds of preregistered Experiment 7 where we replaced by the range parameter .

**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 in color. 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 and are similar across observers. As the covariance scalar increases, log squared threshold increases. The thresholds are comparable for chromatic and achromatic variation. ~~These features are seen in the mean data (Figure 7) and in the data for all observers (Figure 8).~~

[MAKE LOG THREHSOLD FIGURE FOR INDIVIDUAL OBSERVERS]

**Equivalent noise characterization of background variation**

**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 spectrum of 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 \delta 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 XXX. This compares well with the internal noise obtained using the thresholds obtained from background reflectance spectra variation.

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

Finally, 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 background objects with fixed light source spectrum, variation in intensity of light source with fixed background, and simultaneous variation in the intensity of light source and background object reflectance spectra for chromatic and achromatic. 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. We see that the threshold for simultaneous variation of light intensity and reflectance spectra of background objects is higher than the condition with individual variations. As observed earlier, the threshold for achromatic and chromatic conditions are comparable.

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.

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**

**5 ACKNOWLEDGEMENTS**: NSF BCS 2054900 (VS).

**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.

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1. The preregistration documents relevant to this paper 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)