# Preregistration document for measuring color discrimination thresholds in deuteranopes

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## Purpose

This study examines the color discrimination thresholds of deuteranopes in the LS-cone isolating plane. The methods are similar to those used in our measurements of the chromatic discrimination field in the isoluminant plane (Hong et. al, 2025).

## Methods

### Apparatus

The experiment will be conducted using an Alienware computer (Aurora 11) running Windows 11, equipped with Intel® Core™ i7-10700K processor and NVIDIA GeForce RTX 3080 GPU. The display is a DELL U2723QE monitor (59.8 cm width, 33.6 cm height, 3480 x 2160 resolution, 60 Hz refresh rate, achieving 12-bit effective color depth. This bit depth is achieved via the spatial dithering implicit in the rendering of the stimuli, rather than because of the intrinsic bit depth of the video pipeline at individual pixels. The monitor will be positioned 130 centimeters from the chinrest, subtending a visual angle of 25.9 x 14.7 degrees of visual angle. Monitor color and luminance measurements were obtained using a Klein K-10A colorimeter and a CR-250 spectroradiometer. The pixel resolution of the display is approximately 140 pixels/deg, above the typical human foveal resolution limit.

The Alienware computer will be used solely for stimulus presentation, whereas adaptive sampling of the stimuli is performed on a separate custom-built PC with a high-performance Gigabyte motherboard (X299X aorus master), an NVIDIA GeForce RTX 5070 GPU and a 12-core Intel i9-10920X processor. This computer also runs Windows 11. The two computers communicate via a shared network disk, using a custom protocol based on text files that both computers could read and write. It is possible that we will change the system that performs adaptive sampling, with the goal of reducing the compute time required for adaptive trial selection. We will post an addendum if this is done.

A USB speaker (3 Watts output power, 20k Hz frequency response) is used for playing auditory feedback, and a gamepad controller (Logitech Gamepad F310) is used for registering trial-by-trial response.

### Stimulus

The visual scene was constructed in Unity (v2022.3.24f1) and rendered using its standard shader. The scene consisted of three identical blobby 3D objects, each created in Blender (v4.0) with a matte, non-reflective surface. On each trial, the surface color of the blobby objects is varied by adjusting their RGB values in Unity. The three blobby objects (2.5 x 2.5 dva; 203,900 pixels each) are arranged in a triangular configuration. Each blobby object is centered and floating inside its own cubic room (3.3 x 3.3 dva; cubic room background x = 0.3125, y = 0.3294, Y = 84.3396). The centers of the blobby objects are 3.7 dva apart. Each room, along with the

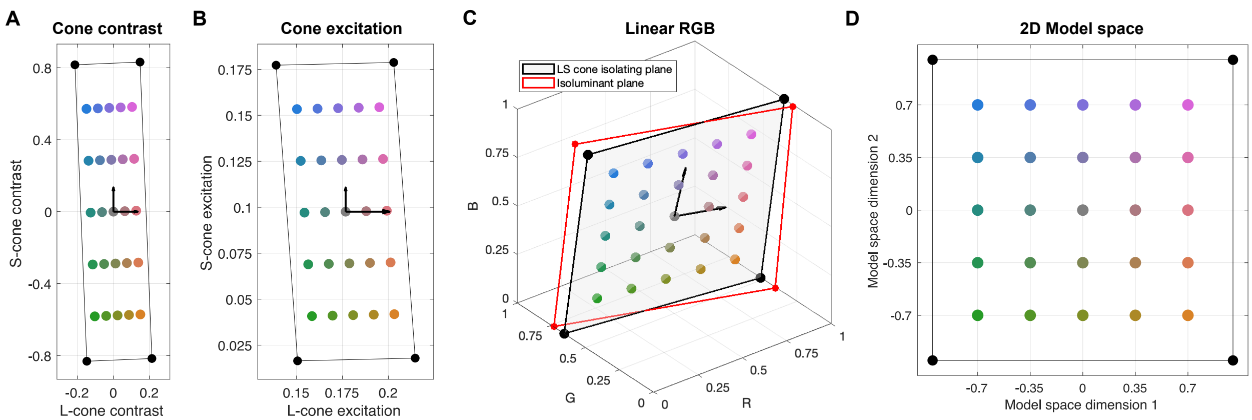


**Figure 1. Transformation between cone-contrast space and the model space.** (A) Cone-contrast space. M-cone contrast is fixed at 0 and therefore not shown. Arrows indicate two linearly independent vectors that span the L–S cone-contrast plane. Black curves show the boundary RGB values on the L–S cone-isolating plane that remain within the monitor's gamut, and black dots mark the corner points. (B) Cone-excitation space. Cone excitations are computed with respect to the CIE 2-degree cone fundamentals, each normalized to a maximum of 1 and with spectral radiance in units of Watts/[cd-m2-sr]. M-cone excitation is held constant at 0.151 based on our calculations, so that dimension is not shown. (C) Linear RGB space. Red curves show the boundary RGB values on the isoluminant plane used in Hong et al. (2025) for comparison. (D) Two-dimensional model space bounded between -1 and 1, as the Chebyshev basis functions. Color dots are shown to illustrate the transformation.

| Corner | ΔL | ΔM | ΔS | L | M | S | R | G | B | $W_{dim1}$ | $W_{dim2}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Bottom left | -0.148 | 0 | -0.831 | 0.151 | 0.151 | 0.017 | 0 | 0.656 | 0 | -1 | -1 |
| Upper left | -0.214 | 0 | 0.816 | 0.139 | 0.151 | 0.177 | 0 | 0.483 | 1 | -1 | 1 |
| Upper right | 0.148 | 0 | 0.831 | 0.203 | 0.151 | 0.179 | 1 | 0.344 | 1 | 1 | 1 |
| Lower right | 0.214 | 0 | -0.816 | 0.215 | 0.151 | 0.018 | 1 | 0.517 | 0 | 1 | -1 |

**Table 1. Corner vertices of the LS-isolating plane in the cone contrast, cone excitation, RGB and model spaces.**

| $M_{LMS\text{->}RGB}$ | | | $M_{RGB\text{->}2DW}$ | | |
|---|---|---|---|---|---|
| 15.593 | -15.561 | 1.333 | 1.788 | -1.524 | -0.264 |
| -2.147 | 6.732 | -1.231 | -0.212 | -1.524 | 1.737 |
| -0.144 | -0.404 | 6.209 | 0.212 | 1.524 | 0.264 |

**Table 2. Transformation matrices between LMS, RGB and the model spaces.**

blobby stimulus inside it, is illuminated exclusively by an achromatic spotlight positioned in front of the object and set to maximum intensity (R = G = B = 1). The three rooms were presented against a spatially uniform background (x = 0.3118, y = 0.3313, Y = 149.2435). A figure showing the basic stimulus spatial configuration is available in Hong et al. (2025).

## Design

One difference between the current design and Hong et al. (2025) is that we will no longer interleave validation trials, as our earlier work has already validated the use of the Wishart Process Psychophysical Model (WPPM) to characterize discrimination thresholds in a plane in color space. Since we will not have validation trials to slot in while AEPsych computes the next trial before timeout, our fallback strategy will rely solely on pre-generated Sobol trials. These Sobol trials will be generated with subject- and session-specific seeds (**Table 3**) to keep the experiment moving. They will be scaled by one of three factors (2/8, 3/8, 4/8), with an equal number of trials at each scale. We will then replace 5% of these trials with easy catch trials using the largest absolute Δ values, i.e., [-0.25, -0.25], [-0.25, 0.25], [0.25, -0.25], or [0.25, 0.25]. These catch trials allow us to detect observer lapses in attention.

Additionally, we restrict both the reference and comparison stimuli to lie on the L–S–isolating plane in cone-contrast space. Stimuli are rendered in RGB space, whereas trial placement and model fitting are carried out in the model space for mathematical convenience, as this space is aligned with the Chebyshev basis functions used in the model (see Hong et al., 2025). As a result, we need to compute transformation matrices to convert between cone-contrast, cone-excitation, RGB, and model spaces.

We begin with the L–S–isolating plane in cone-contrast space and identify two linearly independent vectors that emanate from the origin (zero cone contrast) and span the ΔL–ΔS plane (**Fig. 1A**). Together with the origin, these define three points, which we transform from cone-contrast space to LMS cone-excitation space by scaling the contrasts by the background cone excitations and adding them to the background (**Fig. 1B**). We then map these three points into linear RGB space using transformation matrices computed from the cone fundamentals and the monitor primaries (**Fig. 1C**). In RGB space, we use these three points to derive two linearly independent basis vectors via Gram–Schmidt orthogonalization, densely sample linear combinations of these basis vectors, and, along each direction, identify the last in-gamut point before the trajectory exits the monitor gamut. From this set of boundary points we determine four corner points of the 2D model space, which define the transformation matrix into the model coordinates (**Fig. 1D**). For illustration, we then map the boundary points from RGB back into LMS and cone-contrast space (both affine linear transformations) to represent the slice of the L–S–isolating plane sampled in the experiment.

The gamut of the L–S–isolating plane depends on the monitor's spectral properties, which we measured on 10/06/2025 for this preregistered study using the procedures described in Hong et al. (2025). The same calibration data are being used for a second preregistered experiment that we are running concurrently, and additional details are provided in the preregistration for that study. Using the calibration measurements, we computed the transformation matrices to ensure accurate color-space conversions (**Tables 1–2**).

## Procedure

Subjects will perform a three-alternative forced-choice (3AFC) oddity task. Each trial begins with a fixation cross displayed in the center of the three cubic rooms for 0.5 seconds, followed by a blank screen for 0.2 seconds. Then, three blobby stimuli will appear in the middle of the cubic rooms for 1 second. After the stimulus, a response probe ("< ^ >" indicating the three possible responses) will appear, prompting subjects to determine which one is the odd stimulus, with no time constraint. Once subjects make a response using a gamepad controller, a blank screen will appear for 0.2 seconds, followed by visual and auditory feedback on accuracy—“correct” or “incorrect,” accompanied by a beep or buzz tone. The inter-trial interval will be 1.5 seconds. Subjects will be instructed to move their eyes during stimulus presentation and try to fixate on each object.

We will run a 40-trial practice block at the start of each session and then start the experimental trials. In total, subjects will complete 12 sessions, with 500 AEPsych-based trials per session. Note that the actual number of trials per session will exceed 500 because pre-generated Sobol trials will also be slotted in. Subjects will take a break after every 100 AEPsych trials, resulting in 4 breaks per session.

**Subject Recruitment**

We contacted six deuteranopes whose color vision phenotype was previously characterized by us by the Ishihara plates, the Cambridge Colour Test (CRS), and Rayleigh matches (Oculus), and whose genotype was consistent with their phenotype. We will study as many of these deuteranopes who volunteer to participate in this study. As of the date of this preregistration, 3 have expressed interest, 1 has declined, and 2 have not responded. We were unable to obtain current contact information for a seventh deuteranope studied previously. Participants will be compensated at a rate of $20 per hour. We will test the visual acuity of each participant, and confirm their dichromacy (missing M cones) using Ishihara color plates and the CRS while they wear any customary non-tinted eyeware. All participants will be 18 years of age or older.

All participants will consent to participate in the study by reviewing and then signing an IRB approved consent form at the time they are initially enrolled. Consent will be obtained by lab personnel. The experimental procedures and general purpose of the experiments will be explained to the subject before participation begins, as well as the expected duration of their participation. The experimental procedures do not involve any known risks, and participants will be free to withdraw from the experiment at any time.

To identify participants who are not attentive to the stimuli, we will monitor their performance on catch trials. Participants who score below 90% correct on these trials will be gently encourage to be mora attentive, and if a low percentage correct score on these trials continues may be withdrawn prior to completion of the study. We will discard data from subjects who are withdrawn for this reason.

**Data Analysis**

We will fit the WPPM jointly to all trials (AEPsych plus slotted in Sobol). Fitting of this model is described in Hong et al. (2025) and we will use the same WPPM parameters as described in that paper. We will then bootstrap to obtain confidence intervals for the model predictions. This will provide us with a comprehensive characterization of color discrimination thresholds for these participants in their L-S plane, which in the case of deuteranopes is their entire color space.

We will be collecting data from normal trichromatic participants that characterizes their color discrimination throughout the full 3D color space. One analysis we plan to conduct is to identify the slice through the trichromats' discrimination ellipsoids in which the resulting ellipses are most similar to those of the deuteranopes.

| | Source | Practice | Experiment |
|---|---|---|---|
| Pre-generated Sobol trials | Python | N/A | sub# x 100 + session# |
| Sobol scalers | Python | sub# x 10,000 | sub# x 100 |
| Location of the odd stimulus | C# | sub# x 10,000 + session# | sub# x 100 + session# |

**Table 3. Scheme for selecting seeds for different participants from random-number generators.** Three aspects of the experiment require shuffling: (1) the sequence of pre-generated Sobol trials, which are inserted when AEPsych computations take too long, (2) the order of Sobol scalers (1/4, 2/4, 3/4) applied to Sobol-generated trials to balance task difficulty; and (3) the location of the odd stimulus, which can appear at the top, bottom left, or bottom right. (2) is determined only once during the first session, after which subsequent sessions reference the pre-determined indices. In contrast, the rest are generated separately for each session.