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Research Project: Identifying individual cone fundamentals using Rayleigh matching

Experiment: Forced-choice Rayleigh matching using a OneLight Spectra digital light synthesis engine

Background/Experimental question:

Individual differences in human L and M cone fundamentals occur because of variation in wavelength of photopigment peak spectral sensitivity (lambda max) and in photopigment optical density. Because differences in cone fundamentals lead to individual variability in color perception, characterizing these individual differences holds many practical applications.

Several methods exist for estimating cone individual difference parameters, including color matching (Asano, Fairchild, Blondé, & Morvan, 2016), Rayleigh matching (Neitz & Jacobs, 1986; Sanocki et al., 1993; He & Shevell, 1994), Moreland matching (Moreland and Kerr, 1979; Moreland, 2004), analysis of the genes that encode photoreceptor photopigments (Neitz & Neitz, 2011), and electroretinogram (ERG) flicker photometry (Jacobs et al., 1996). However, some of these techniques are time consuming or do not uniquely determine the cone fundamentals.

The proposed experiment aims to evaluate the use of Rayleigh matching to estimate individual difference parameters for L and M cones. (Since Rayleigh matching uses longer wavelengths, it does not reveal information about S cones). Thomas and Mollon (2004) found that changes in lambda max and optical density are confounded when Rayleigh matches are conducted for a single reference wavelength. In this project, we will investigate whether a series of Rayleigh matches with multiple reference wavelengths can be used to disambiguate these parameters.

We previously conducted simulations to explore the feasibility of a Rayleigh matching procedure with multiple reference wavelengths. We generated simulated observer cone fundamentals using the Asano et al. (2016) model of population variation in lambda max and optical density, had simulated observers complete a series of Rayleigh matches using a simulated forced-choice staircase procedure, and fit the parameters of the Asano et al. model to best account for observers’ match data. The results from the simulations will be presented at the Vision Sciences Society annual meeting in May 2021. In general, we found that a series of Rayleigh matches allowed accurate recovery of individual difference parameters and of L and M cone fundamentals. This validates our approach in principle, indicating that Rayleigh matching with multiple reference wavelengths can resolve ambiguity about L and M cone fundamentals that occurs when a single reference wavelength is used. However, we found that cone recovery became less accurate as increasing levels of noise were added to simulated observers' matching decisions. Because of this, further investigation is needed to determine whether our approach is feasible in an experimental setting.

The proposed pilot experiment is an initial evaluation of a forced-choice Rayleigh matching procedure with multiple reference wavelengths in human observers. It employs a procedure similar to that of our simulations and uses much of the same experimental code, but it displays lights using an actual digital light synthesis engine under computer control (OneLight Spectra). In this pilot study, we aim to test the within-subject reliability of a forced-choice Rayleigh matching procedure using the OneLight, as well as analyze differences in Rayleigh matching between subjects. We will also test whether subjects' measured Rayleigh matches can be used to generate reasonable estimates of their cone fundamentals that incorporate individual differences. This will provide an initial evaluation of our approach.

Methods/Approach:

Subjects

The two members of the research team will serve as subjects in the initial pilot experiment. Both subjects are over age 18 and have no known color deficiencies. Both are familiar with the purpose of the study and have experience with the experimental procedure. The experimental protocols are approved by the UPenn IRB, and both subjects will provide informed consent.

Sessions

Each subject will complete Rayleigh matches in several experimental sessions. Matches will be made for each of six reference wavelengths (see *Stimuli*). Each subject will complete four matches for each reference wavelength. Two of the matches will be within a single session, and two will be completed in a session on a different day. The exact distribution of matches across sessions will be governed by how many matches each subject can complete within an experimental session. Sessions will generally last one to two hours.

For each subject, the different reference wavelengths will be tested in a pseudorandom order. A vector containing all possible reference wavelengths will be shuffled by using Matlab's randperm() function to generate a new indexing, and Rayleigh matches will be conducted in the order specified by the shuffled vector. Separate shuffled vectors will be generated for the 'first day' sessions and the 'second day' sessions.

For each reference wavelength on each day, two Rayleigh matches will be made in succession—one with the primary mixture displayed first, and one with the reference light displayed first. The order of these two matches for a given reference wavelength will be randomized.

Rayleigh Matching Procedure

Subjects will conduct a series of forced-choice Rayleigh matches using the OneLight Spectra digital light synthesis engine. They will be shown two fields in alternation: a primary mixture and a reference light. The wavelengths of these lights will be fixed for the duration of a given Rayleigh match. Each Rayleigh match will consist of a series of forced-choice trials, where the mixing ratio and reference intensity are adjusted based on subject responses.

On each trial, the two fields will be shown one after the other for 500 ms each, followed by a neutral field shown for 1 s. This stimulus sequence will repeat until the subject responds. Subjects will be prompted to make forced-choice judgements of the redness and brightness of the second field relative to the first field (i.e. "is the second field redder than the first field"), providing both redness and brightness judgements on each trial. Stimulus presentation will be repeated in the pattern specified above until the subject responds using a button box. Subject responses will then be used to adjust the lights for subsequent trials, following a staircase procedure: the redness judgement will be used to adjust the primary ratio, while the brightness judgement will be used to adjust the reference intensity. Separate staircases will be maintained for the primary ratio and the reference intensity. The program will record a subject match and terminate automatically once both staircases have converged. In practice, the two fields should appear very similar for the subject at the match point.

The experiment will take place in a darkened room, and only the right eye will be tested. Subjects will view the stimuli through the OneLight Psychophysics large-field reticle. Prior to testing, they will remove corrective lenses and adjust the device eyepiece to bring the reticle into as good focus as possible.

Stimuli

All stimuli will be presented using the OneLight Spectra digital light synthesis engine, which generates narrowband spectra with width of approximately ~15-20nm FWHM around a specified center wavelength. The primary mixture will be an additive mixture of spectra of primaries at 670 nm and 560 nm center wavelength. The reference light's center wavelength will vary throughout the different Rayleigh matches in the experimental session. Each subject will complete Rayleigh matches with the reference wavelength centered at 570 nm, 584 nm, 598 nm, 612 nm, 626 nm, and 640 nm.

The relative intensities of the primaries at their maximum settings will be adjusted so that the matches of observers with normal color vision are not set at the limits of available settings. Based on pilot experiments and simulations, we have chosen different scale factors for matches at different reference wavelengths. The 670 nm primary will be used at its maximum intensity. The 560 nm primary in the primary mixture will be scaled to 0.02 * the maximum height that the OneLight can produce for reference wavelengths shorter than 620 nm, and to 0.004* the maximum height for reference wavelengths longer than 620 nm. The reference wavelength will be scaled to 0.01 * the maximum height the OneLight can produce for reference wavelengths shorter than 630 nm, and to 0.25 * its maximum height for reference wavelengths longer than 630 nm.

The neutral field will be generated from a spectral power distribution with a uniform amplitude of 0.001 across all wavelengths tested.

Staircase Parameters

Mixing ratio and reference intensity will be adjusted using separate staircase procedures, and a Rayleigh match will be recorded once both staircases have converged.

201 settings will be available for both reference intensity and mixing ratio, evenly spaced between 0 and 1, once the effective maximum for each primary has been determined as above. The actual number of device steps may not be 201 for some cases. The reference intensity setting will be applied as a multiplicative scale factor to reduce the amplitude of the reference light from its maximal value. The mixing ratio setting will be applied as a multiplicative scale factor to the amplitude of the 670 nm peak, while the 560 nm peak will be scaled by 1 – the mixing ratio setting. Thus, a setting of 0 will represent the greenest possible light, while a setting of 1 will represent the reddest possible light.

At the start of a given Rayleigh match, the mixing ratio and reference intensity will be set to random values. They will then be modified based on subject responses to bring the two fields into agreement. For example, if a subject responds that the (second) reference field is brighter than the primary mixture field, the reference intensity will be reduced. If a subject responds that the reference field is redder than the primary mixture field, the primary ratio will be increased. The exact magnitude of the increase or decrease will depend on the step size at that point in the experiment. Four step sizes will be available, representing changes of 40, 10, 2, and 1 positions in the settings array. At the start of a given Rayleigh match, the largest step size will be used. The step size will be reduced on the first trial where both the redness brightness staircases have reversed once, continuing in this manner until the smallest step size is reached.

The program will record a Rayleigh match once both staircases have undergone two reversals at the smallest step size. The match will be represented as the average of the last two reversals for each staircase.

Post-session Calibration

At the end of every session, we will display the lights that subjects identified as matches and measure their spectral properties. For each match, we will display the lights corresponding to the last two mixing ratio settings on the OneLight, measure them using a PR670 spectroradiometer, and average the two spectral power distributions. We will repeat this procedure for the lights corresponding to the last two reference intensity settings. We will also measure the neutral light and the dark spd one time for each session.

Data Analysis

Summary Statistics

To assist in data representation, each pair of radiometer-measured spectra identified as a match will be converted to a mixing ratio/reference intensity point representation. The point representations will be computed using a regression procedure to find the scale factors which, when applied to the predicted spectra at their maximal intensity, will come as close as possible to the measured spectra. The point representations of matches will be used for qualitative data analysis and data visualization. For each subject, we will calculate the mean and standard error of mixing ratio and reference intensity at the match, using the point representations of subjects' measured matches.

We will also compare subjects' matches to the nominal match for a standard observer. The nominal match will be found by simulating an observer with standard cone fundamentals and searching among all possible reference and primary mixture spectra (predicted) to find the pair that minimizes L and M cone opponent contrast (see below for details of this procedure). Since both observers are believed to have normal color vision, we expected both subjects' matches to fall reasonably close to the nominal match and to each other's matches.

Cone Fundamental Fitting

We will also fit the Asano et al. model of cone individual differences to each subject's match data to obtain estimated L and M cone fundamentals. The Asano et al. model accounts for how cone fundamentals are affected by eight individual parameters (in addition to age and field size): lens density, macular pigment density, and lambda max and optical density for L, M, and S cones. In our fit, we will restrict lens density and macular pigment density to their average values, as lens pigment and macular pigment are believed to have minimal effect on light reaching the photoreceptor at longer wavelengths. We will also restrict L and M lambda max and optical density estimates to within 3 standard deviations of their means, using Asano et al.'s estimates of population-level variability. When computing cone fundamentals, we will also include the actual subject age and a large (10 degree) field size to match the large field.

For each reference wavelength used, we will average the radiometer-measured primary mixture and reference spectra for all subject matches at that reference wavelength. Thus, we will obtain a single spectral pair for each reference wavelength tested. These averaged spectra will be passed into the fitting program, which will fit cone fundamentals to minimize the opponent contrast of each match pair.

The fitting program will first compute cone excitations for each pair of spectra and convert these to an opponent contrast representation, using the following matrix equation:

$$\begin{bmatrix} LUM\ contrast \\ RG\ contrast \\ BY\ contrast \end{bmatrix} = \begin{bmatrix} LUM\ weight & 0 & 0 \\ 0 & RG\ weight & 0 \\ 0 & 0 & BY\ weight \end{bmatrix} \begin{bmatrix} 2/3 & 1/3 & 0 \\ 1 & -1 & 0 \\ -0.5 & -0.5 & 1 \end{bmatrix} \begin{bmatrix} L\ cone\ contrast \\ M\ cone\ contrast \\ S\ cone\ contrast \end{bmatrix}$$

We will set 'LUM weight,' 'RG weight,' and 'BY weight' to 40.3908, 205.7353, and 62.9590, respectively. In our simulations, these values were found to bring the opponent contrast space in best agreement with the CIELAB uniform color space (CIE, 1977; Brainard, 2003), which was designed so that a unit step in any direction of the space approximates a near-threshold perceptual difference. After converting to opponent contrast, the fitting program will calculate the vector length of luminance and red/green contrast and take the RMSE across all match pairs. The program will then adjust the L and M cone fundamentals parameters to minimize the RMSE, using Matlab's fmincon routine with an 'active-set' algorithm.

*Although we do not plan to independently validate subjects' cone fundamentals in this pilot experiment, we will check whether the fitted cone fundamentals fall within a reasonable range for color-normal observers. We will also check how well the fitted cone fundamentals account for each individual match. To do this, we will compute the L and M cone excitations for the measured primary mixture and reference light at the match, using both the best-fit cone fundamentals and the standard cone fundamentals. We will then take the mean and SEM of cone excitations for matches at each reference wavelength tested. For comparison, we will compute the predicted L and M cone excitations for standard 10 degree L and M cone fundamentals.

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