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Supplementary Information for

Neural representations of perceptual color experience in the ventral visual pathway

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SI Materials and Methods.

Stimuli. All stimuli were generated using Matlab and Psychtoolbox (1) and were presented using a PROPixx projector (1920 x 1080 resolution, 120 Hz refresh rate, 60 Hz per eye) with a circular polarizer directed onto a rear-projection screen for dichoptic projection. In all experiments, observers viewed stimuli while wearing circularly polarized 3D glasses inside the scanner. The gamma correction of luminance level from the projector was measured using a Minolta LS110 luminance meter. The chromaticity at maximum luminance for R, G, and B was determined using a USB4000 spectroradiometer (Ocean Optics). Each observer's perceptual equiluminance for R, G, and B was obtained using heterochromatic flicker photometry.

In chromaticity model building, a rotating spiral grating (radius, 3°; speed of rotation, 0.134°/sec) was presented with one of 8 chromaticities chosen from DKL color space (2) as shown in Fig. 1A. The DKL space is a spherical space in which the elevation angle corresponds to luminance and the azimuth angle corresponds to hue (L-M opponency represented by 0° and 180°, S-(L+M) opponency represented by 90° and 270°). Finally, the radius value in an equiluminant plane represents a change in saturation. To transform XYZ chromaticity values (3, 4) to display-specific DKL coordinates, we set the current display's achromatic value according to the MacLeod & Boynton equiluminant cone excitation space for equal-energy spectrum (EES) white (5) (l=0.667, s=1.0). This cone-excitation space is defined using Smith and Pokorny cone fundamentals (6), and by normalizing the s-values to the s-value of EES white. The 8 chromaticities were obtained from the equiluminant plane of the DKL color space (elevation = 0) and were equally spaced (45-deg steps along the azimuth with equal radius of 0.8) at the hue angles (Fig. 1B). Each chromaticity was repeated 3 times per run and data from 8 to 10 model building runs were collected per observer. For each switch rivalry condition, a pair of two chromaticities diametrically opposite along the intercardinal axis was used. Two different pairs were tested: magenta (45°) with green (225°), and blue (135°) with orange (315°). Intercardinal hues were used to drive signals in the visual cortex excited by either (or both) cardinal axis (L/(L+M) and S/(L+M)). Luminance of the background and the spiral grating was set to 30cd/m2 (equiluminance was set for each individual participans). Chromaticity values in terms of CIE chromaticity coordinates (7) were magenta (x=0.334, y=0.28), green: (x=0.338, y=0.407, blue (x=0.294, y=0.29) and orange (x=0.388, y=0.376).

Identifying ROIs: Retinotopic Mapping and color localizer. A standard retinotopic procedure was employed to define borders of visually responsive cortical areas (V1, V2, V3, V4v, and VO1). On a different day, observers also completed 4 runs of a color localizer. On each block, a red-green flickering stimulus was presented for 12 sec followed by a 12 sec blank fixation period while the observer was performing a fixation change detection task. Each stimulus block was repeated 6 times within a run. The red-green flickering stimulus was used to maximally modulate both the L− M and S − (L + M) axes simultaneously. Voxels that responded significantly more to the red-green flickering stimulus than a fixation period were selected in each region-of-interest (ROI) for subsequent analyses ($q < .001$).

Reconstruction of subjectively experienced colors. Neural representations of colors during rivalry were reconstructed in each visual region using an inverted encoding model(IEM). The IEM provides a link between population-level neural activity and color representations, as it allows reconstruction of a specific color represented within a given visual area from the pattern of the area's voxel-wise responses. Eight sinusoids raised to the sixth power (FWHM = 0.94 rad) basis functions were used to evenly cover the entire DKL color space. Each basis function was centered at each of 0, 45, 90, 135, 180, 225, 270, and 315°. All voxel signals were normalized to discard potential amplitude differences across different chromatic stimuli. Specifically, within each run, voxel signals were z-scored and baseline (normalized mean responses across all stimulus colors) was removed by linear projection for each chromatic stimulus. The baseline normalization was performed to ensure that the IEM results reflect the patterns of voxel signals that pertain to the color experiences rather than to global signal differences across conditions (due to head

motion, gradient inhomogeneity, physiological noise, and attentive state of observers) by scaling responses of all conditions to approximately the same range.

First, data from 8 chromaticity presentations with a fixation task served as a training dataset (B1) to build a chromaticity model. The training data comprised an *m* x *n* matrix, *m* as a number of voxels within each visual areas and *n* as a number of chromaticities times number of trials within a session. Building a chromaticity model involved estimating chromaticity selective weights for individual voxels (W, *m* x *k* channels) by mapping voxel signals to channel outputs (C1, *k channels* x *n*):

$$B_1 = WC_1 \quad \text{(equation 1)}.$$

Ordinary least-squares estimation was used to solve W:

$$W = B_1 C_1{}^T (C_1 C_1{}^T)^{-1} \quad \text{(equation 2)}.$$

Finally, switch rivalry data were used as a test dataset (B2) to compute chromaticity channel outputs (C2) that correspond to each subjective color experience:

$$C_2 = (W^T W)^{-1} W^T B_2 \quad \text{(equation 3)}.$$

In order to isolate the moments of specific color experiences, only BOLD signals when observers exclusively experienced one color or the other (e.g., magenta or green) during the switch rivalry (B2) were used for the analysis. Specifically, the first 10 sec of each stimulus presentation period were excluded from analysis to account for initial unstable percepts. Then, time points were found during which one stable percept (e.g., green or magenta) was maintained throughout a full TR of 1 sec. This procedure removed the time points that lasted for less than the duration of 1 sec or more than 1 sec but not synced with a TR. Lastly, a 5 sec temporal shift was added to account for hemodynamic delay of 4 to 6 sec. The average proportion of each dominant color experience to the total duration of the switch rivalry condition was 20.27% (magenta), 10.07% (green), and 32.17% (mixed) across observers.

Each color response profile from the IEM analysis consisted of eight values, each of which represents a channel output with a peak at 0, 45, 90, 135, 180, 225, 270, or 315° within the DKL color space. To further quantify and visualize the color represented in each visual region, 360 basis functions were created, which were evenly spaced over the entire range of the DKL hue plane in steps of 1° (8). Each basis function also had eight values at the same hue angles from 0° to 315°, with varying amplitudes but with the same area under the curve. Then, correlations were computed between the estimated color response profile and each of the 360 basis functions. Out of the 360 correlation values, the hue angle of the basis function that resulted in the highest correlation was selected as the color represented by a given color response profile and that resulting color was plotted on the DKL hue plane. All rivalry and replay conditions were analyzed using the identical analysis procedures based on the same chromaticity encoding model.

The accuracy of the reconstructed color was computed by taking the difference between the reconstructed color and the perceived color for each target chromaticity (e.g., 45° for magenta and 225° for green). The difference measures were averaged across magenta and green (or blue and orange) and tested against chance (90°) to evaluate the accuracy of color representations in each region.

Statistical procedures. All statistical tests were performed using the nonparametric randomization test. The color labels of the training data (8 chromaticities) were randomly shuffled 1,000 times, yielding 1,000 sets of model weights for each visual region. Then, the channel outputs and resulting difference measures were computed for each experimental condition (switch rivalry and replay) using each set of weights. To test the statistical significance of the reconstructed color representation for each condition and each visual area, a null distribution of one-sample t-tests between each difference measure against chance (90°) was created. The

probability of obtaining a t-value greater than the original t-value given the null distribution was reported as the one-tailed *p* value.

To compare the difference between the rivalry and replay conditions, task labels were additionally shuffled 1,000 times. The difference measure from the resulting shuffled dataset was computed and a null distribution of paired t-tests between the two task conditions was obtained for each visual region. Moreover, the significance of the interaction effect between the task conditions and visual regions was assessed using a null distribution of two-way repeated ANOVAs based on the same shuffled dataset. All repeated tests were controlled for the false discovery rate.

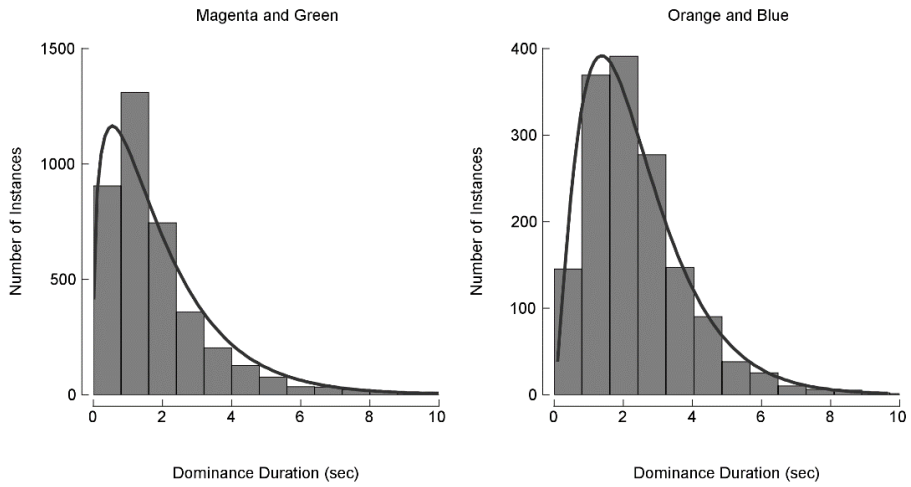

Fig. S1. *Duration of color experiences during switch rivalry.* The distribution of dominant color experiences followed a typical gamma distribution (magenta – green, k: 1.38, θ: 1.41; blue – orange, k: 2.38, θ: 0.99). Results are collapsed across observers (9 observers for magenta – green and 4 observers for blue – orange) and color pairs. The mean dominance durations for the different color pairs were similar (magenta – green, 2.23 sec; blue – orange, 2.32 sec).

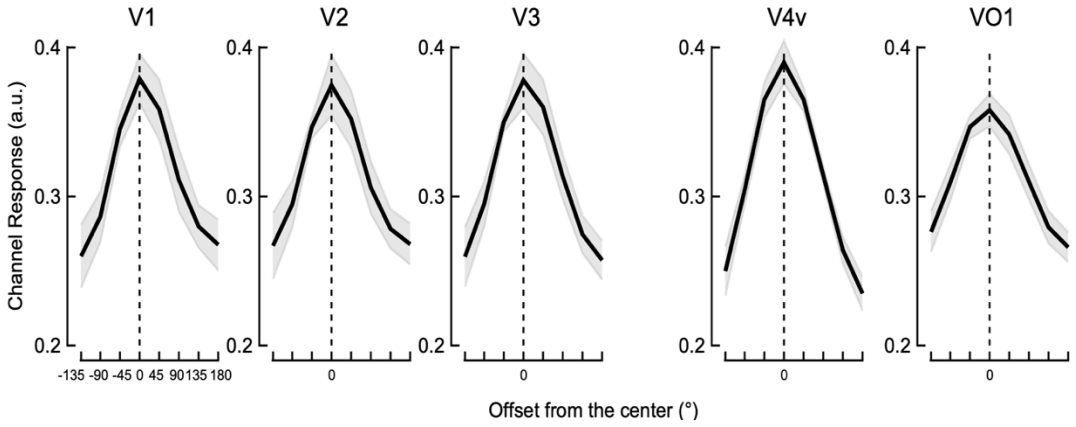

Fig. S2. *Chromaticity encoding model.* For each observer, the timeseries of each voxel during the stimuli presentation in each visual region was extracted and was averaged across the duration of each trial. Next, using a leave-one-run-out procedure, the weight matrix for each of the eight chromaticity channels was computed. The weight matrix of the encoding model was computed based on all trials in the training dataset and was used to estimate chromatically selective responses for each of the eight different chromaticity conditions in the left-out test dataset. The estimated chromaticity responses from each chromaticity condition were shifted to a common center of 0°, which indicates the hypothesized location. For the purpose of visualization, response profiles were averaged across chromaticity conditions and across observers, showing one chromaticity response profile for each region. The quality of the chromaticity response profile was quantified by averaging the difference between each peak of color response profile and the hypothesized locations for each presented chromaticity. Then the difference measure for each region was tested against the chance level of 90°. The chromatic encoding model for early, extrastriate (V1, $p = .026$; V2, $p = .003$; V3, $p < .001$) and ventral visual regions (V4v, $p < .001$; VO1, $p = .028$) showed strong chromatic selectivity. Shaded areas of each response profile represent ± 1 s.e.m..

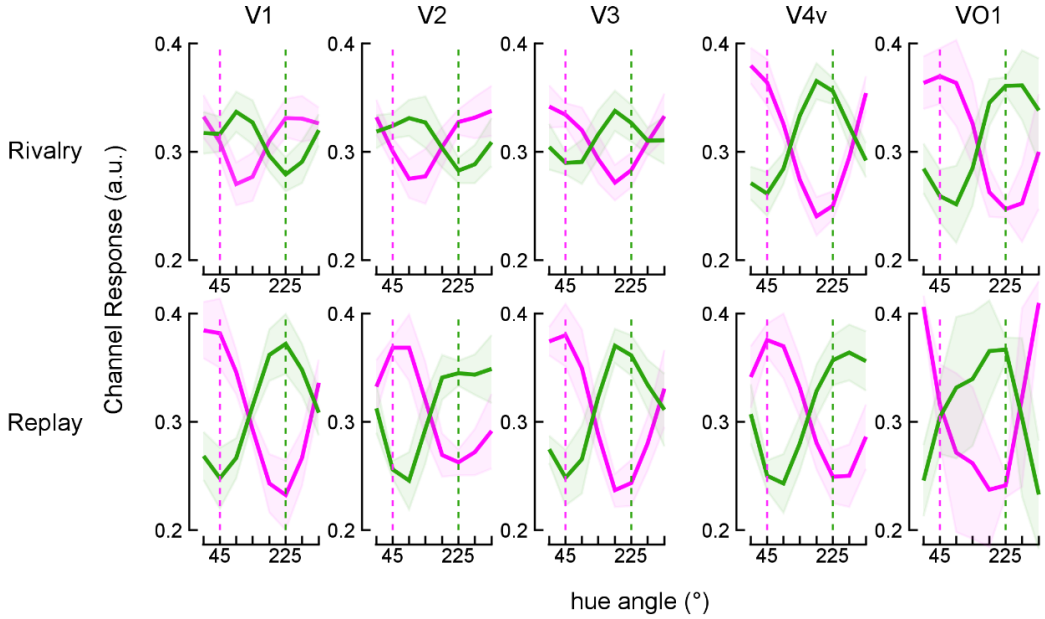

Fig. S2. *Color selective responses in all ROIs*. Color-selective responses during the switch rivalry and replay conditions were averaged across observers for all ROIs (V1, V2, V3, V4v, and VO1). In each ROI, the moments of dominant magenta and green color perception was estimated. Colored dashed vertical lines indicate the hypothesized hue angles of magenta (45°) and green (225°) within DKL color space.

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