Extended Eye Analysis Methods – see Methods, Eye-movement recordings for summary

Eye tracking data analysis

Several analyses of the eye tracking data were performed using ILAB software (Gitelman, 2002), Matlab 7.9 R2009b (The Mathworks Inc., Natick MA), and Microsoft Excel 2004 (Microsoft Corp., Redmond WA) to confirm (1) that the animals maintained fixation for the majority of the time during the scanning runs, and (2) that there were no systematic differences in the eye position, in the amount of eye movement, and in the frequency of saccades, while different portions of the visual field were stimulated.

Eye blinks were removed using the ILAB software which performs the filtering by combining two methods: (1) filtering data by incorrect eye position information and (2) filtering by 0 pupil size (Gitelman, 2002). Eye data samples removed by the blink filter along with 25 samples before and after the interval were replaced via nearest neighbor interpolation. In each monkey, eye positions, amounts of eye movement, and frequency of saccades were compared using repeated-measures ANOVAs to test for main effects of stimulus location on these measures. Individual comparisons between the stimulus locations were performed using matched paired *t*-tests. Significant pairwise comparisons ($p < 0.05$) are reported prior to correction for multiple comparisons, and comparisons that remained significant after Bonferroni correction (alpha level of 0.01) are also reported). Effect sizes for significant pairwise comparisons are reported using Cohen's *d*.

Analysis of eye position

To investigate the possibility that eye position shifted systematically to different locations depending on the location of the visual stimulus, we calculated mean horizontal (X) and vertical (Y) eye positions during stimulation of different portions of the visual field. The eye positions in each monkey were compared using repeated-measures ANOVAs to test for main effects of stimulus location on eye position.

<u>Polar angle experiment</u>

Frequency histograms of horizontal and vertical eye position during stimulation of each visual quadrant (i.e. right lower visual field (Q1), left lower visual field (Q2), left upper visual field (Q3), right upper visual field (Q4)) were derived for each monkey (Supplementary Figure 1 A). For both monkeys, the vast majority of all horizontal and vertical eye position samples (M1: Q1: X = 99.27%, Y = 98.92%; Q2: X = 99.01%, Y = 99.20%; Q3: X = 99.44%, Y = 99.48%; Q4: X = 99.36%, Y = 99.10%; M2: Q1: X = 98.92%, Y = 98.44%; Q2: X = 99.00%, Y = 98.44%; Q3: X = 97.71%, Y = 97.38%; Q4: X = 98.07%, Y = 97.66%) fell within the specified window around the fixation point (+/- 2° from fixation point).

The mean eye position for each visual quadrant was compared. For monkey M1, mean horizontal eye positions (Q1: $M = 0.08°$, $SD = 0.27$; Q2: $M = 0.01°$, $SD = 0.31$; Q3: $M = -0.03°$, $SD = 0.27$; Q4: $M = 0.18°$, $SD = 1.21$) were not significantly different [M1: X: $F(3,95) = 2.17$, $p = 0.09$]. Mean vertical eye positions (Q1: $M = -0.36°$, $SD = 0.31$; Q2: $M = -0.45°$, $SD = 0.30$; Q3: $M = 0.35°$, $SD = 0.26$; Q4: $M = -0.37°$, $SD = 0.33$) showed a main effect of stimulus location [M1: Y: $F(3,95) = 3.53$, $p = 0.02$]. Pairwise comparisons revealed that vertical eye position shifted slightly downward during stimulation of the lower left visual field [Q1 vs. Q2: $t(95) = 2.57$, $p = 0.01$, $d = 0.26$; Q2 vs Q3: $t(95) = 2.92$, $p = 0.004$, $d = 0.30$; Q2 vs Q4: $t(95) = 4.45$, $p < 0.001$, $d = 0.45$]. However, the largest distance between mean vertical eye positions was 0.09°, and none of the pairwise comparisons remained significant after Bonferroni correction.

Similarly, for monkey M2, neither mean horizontal (Q1: $M = 0.08°$, $SD = 0.37$; Q2: $M = 0.11°$, $SD = 0.38$; Q3: $M = 0.17°$, $SD = 0.45$; Q4: $M = 0.15°$, $SD = 0.53$) nor mean vertical (Q1: $M = 0.02°$,

$SD = 0.39$; Q2: $M = 0.00^\circ$, $SD = 0.32$; Q3: $M = -0.01^\circ$, $SD = 0.61$; Q4: $M = -0.02^\circ$, $SD = 0.56$) eye positions were significantly different for each of the four visual quadrants [M2: X: $F(3,91) = 0.95$, $p = 0.42$; Y: $F(3,91) = 0.12$, $p = 0.95$].

These results indicate that both monkeys kept their gaze within the specified fixation window, and there was not a tendency to shift gaze either horizontally or vertically with the stimulus position during the mapping of polar angle.

Eccentricity experiment

Frequency histograms of horizontal and vertical eye position during stimulation of four bands of visual eccentricity (i.e. 0-2° (E1), 2-4° (E2), 4-7.5° (E3), 7.5-15° (E4)) of equal time durations (10 s) were derived for each monkey (Supplementary Figure 1 B). For both monkeys, almost all the horizontal and vertical eye positions samples (M1: E1: X = 97.74%, Y = 98.27%; E2: X = 99.50%, Y = 99.46%; E3: X = 99.22%, Y = 99.10%; E4: X = 98.89%, Y = 98.81%; M2: E1: X = 98.50%, Y = 98.24%; E2: X = 98.61%, Y = 98.55%; E3: X = 99.44%, Y = 99.45%; E4: X = 98.21%, Y = 98.21%) fell within the fixation window.

The mean eye positions at the four eccentricity bands were compared. For monkey M1, mean horizontal eye positions showed a main effect of stimulus location, where the mean eye positions during stimulation of the central portions of the visual field were farther to the left (E1: $M = 0.17^\circ$, $SD = 0.24$; E2: $M = 0.16^\circ$, $SD = 0.27$) compared to the mean eye positions during stimulation of more peripheral stimulus locations (E3: $M = 0.26^\circ$, $SD = 0.24$; E4: $M = 0.23^\circ$, $SD = 0.31$) [M1: X: $F(3,55) = 3.18$, $p = 0.03$; Significant pairwise comparisons: E1 vs. E3: $t(55) = 4.59$, $p < 0.001$, $d = 0.61$; E2 vs E3: $t(55) = 3.24$, $p = 0.002$, $d = 0.43$]. However, none of the significant pairwise comparisons remained significant after applying the Bonferroni correction. Mean vertical eye positions at each stimulus eccentricity band (E1: $M = -0.19^\circ$, $SD = 0.27$; E2: $M = -0.12^\circ$, $SD = 0.21$; E3: $M = -0.17^\circ$, $SD = 0.28$; E4: $M = -0.17^\circ$, $SD = 0.25$) did not show a main effect of stimulus location [M1: Y: $F(3,55) = 1.64$, $p = 0.18$].

Similar to monkey M1, the mean horizontal eye positions for monkey M2 showed a main effect of stimulus location, where the mean eye positions during stimulation of more central portions of the visual field were farther to the left (E1: $M = -0.07^\circ$, $SD = 0.37$; E2: $M = -0.06^\circ$, $SD = 0.34$) compared to the mean eye positions during stimulation of more peripheral portions of the visual field (E3: $M = 0.04^\circ$, $SD = 0.27$; E4: $M = 0.04^\circ$, $SD = 0.30$) [M2: X: $F(3,103) = 5.07$, $p = 0.002$; Significant pairwise comparisons: E1 vs. E3: $t(103) = 2.67$, $p = 0.01$, $d = 0.27$; E1 vs. E4: $t(103) = 2.59$, $p = 0.01$, $d = 0.25$; E2 vs. E3: $t(103) = 3.05$, $p = 0.003$, $d = 0.30$; E2 vs. E4: $t(103) = 2.68$, $p = 0.01$, $d = 0.26$]. However, none of the pairwise comparisons remained significant after Bonferroni correction. Mean vertical eye positions at each stimulus eccentricity band (E1: $M = 0.17^\circ$, $SD = 0.48$; E2: $M = 0.16^\circ$, $SD = 0.39$; E3: $M = 0.11^\circ$, $SD = 0.26$; E4: $M = 0.14^\circ$, $SD = 0.40$) did not show a main effect of stimulus location [M2: Y: $F(3,103) = 0.682$, $p = 0.56$].

These results indicate that during eccentricity mapping, neither monkey showed a tendency to shift gaze vertically, but there was a tendency to shift horizontal eye position slightly to the left by approximately a tenth of a visual degree during stimulation of the central visual field compared to stimulation of the periphery. This tendency, however, was not significant after correcting for multiple comparisons, and the calculated effect sizes were small. Furthermore, it is not expected that such a shift would affect topographic eccentricity maps given the small distance of the shift.

Analysis of amount of eye movement

Because the fixation window was large enough to allow for small saccadic eye movements less than or equal to 4°, a measure of eye movements was calculated based on the total amount of horizontal and vertical eye movements during stimulation of different portions of the visual field. The distance the eye traveled between each camera cycle (60 Hz) was summed to obtain this measure, which captured all eye movements, regardless of whether they were within the fixation window or not, that may have contributed to eye movement–related confounds. Amounts of eye movement in each monkey were compared using repeated-measures ANOVAs to test for main effects of stimulus location.

Polar angle experiment

The amount of eye movement during stimulation of each visual quadrant was compared. For monkey M1, the amount of horizontal (Q1: M = 17.58°, SD = 13.58; Q2: M = 21.62°, SD = 23.82; Q3: M = 17.84°, SD = 13.12; Q4: M = 19.97°, SD = 46.62) and vertical (Q1: M = 20.68°, SD = 10.78; Q2: M = 21.10°, SD = 19.53; Q3: M = 19.05°, SD = 8.93; Q4: M = 19.49°, SD = 19.98) eye movement between the four quadrants was not significantly different [M1: X: $F(3,95) = 0.92$, p = 0.43; Y: $F(3,95) = 0.76$, p = 0.52].

Similarly, for monkey M2, the amount of horizontal (Q1: M = 13.25°, SD = 6.38; Q2: M = 12.50°, SD = 5.75; Q3: M = 13.75°, SD = 9.46; Q4: M = 13.71°, SD = 9.96) and vertical (Q1: M = 21.63°, SD = 8.18; Q2: M = 19.69°, SD = 6.83; Q3: M = 21.63°, SD = 10.07; Q4: M = 21.08°, SD = 10.66) eye movement between the four quadrants was not significantly different [M2: X: $F(3,91) = 0.67$, p = 0.57; Y: $F(3,91) = 1.54$, p = 0.20].

These results indicate that there was not a tendency in either monkey to make more eye movements for any particular stimulus position during the mapping of polar angle.

Eccentricity experiment

The amount of eye movement during the stimulation of four bands of visual eccentricity was compared. For monkey M1, the amount of horizontal eye movement (E1: M = 22.66°, SD = 23.10; E2: M = 15.64°, SD = 10.77; E3: M = 17.88°, SD = 11.13; E4: M = 23.48°, SD = 27.85) showed a main effect of stimulus location [X: $F(3,55) = 2.89$, p = 0.04]. Pairwise comparisons revealed significantly more horizontal eye movements during stimulation of the most central (i.e. 0-2°) and the most peripheral (i.e. 7.5-15°) portions of the visual field compared to stimulation of the intermediate portion of the visual field (i.e. 2-4°) [Q1 vs. Q2: $t(55) = 3.01$, p = 0.004, d = 0.40; Q4 vs. Q2: $t(55) = 2.20$, p = 0.03, d = 0.29]. Neither of these pairwise comparisons remained significant, however, after Bonferroni correction. The amount of vertical eye movement (E1: M = 24.23°, SD = 17.70; E2: M = 20.22°, SD = 8.03; E3: M = 22.34°, SD = 10.58; E4: M = 26.38°, SD = 17.92) between the four eccentricity bands was not significantly different in M1 [Y: $F(3,55)$ = 2.57, p = 0.06].

For monkey M2, the amount of horizontal eye movement (E1: M = 14.08°, SD = 9.93; E2: M = 14.36°, SD = 8.49; E3: M = 13.43°, SD = 8.16; E4: M = 15.90°, SD = 13.91) did not show a main effect of stimulus location [X: $F(3,103) = 1.93$, p = 0.13]. However, vertical eye movements (E1: M = 15.17°, SD = 9.82; E2: M = 16.76°, SD = 9.45; E3: M = 13.64°, SD = 5.96; E4: M = 15.05°, SD = 10.90) did show a main effect of stimulus location, where eye movements differed between the two intermediate eccentricity bands [Y: $F(3,103) = 2.89$, p = 0.04; E2 vs. E3: $t(103) = 4.32$, $p <$ 0.001, d = 0.42], an effect that remained significant after Bonferroni correction.

Taken together, the small differences in amounts of eye movements at different eccentricity bands between monkeys were not consistent, and generally did not remain significant after correction for multiple comparisons (except for one comparison in M2). These small individual differences are likely to reduce the sensitivity in detecting eccentricity maps, but are not likely to affect the large-scale layout of the topographic organization.

Analysis of eye fixation maintenance

Saccades were defined as eye movements that exceeded the boundaries of the 4° fixation window and were not removed by the blink filter. During the course of a 3-minute scan, the animals made relatively few saccades. For the polar angle mapping experiment, monkey M1 had an average of 6.54 ±5.69 saccades per scan, and monkey M2 had an average of 5.33 ±4.29 saccades per scan. For the eccentricity mapping experiment, M1 and M2 had an average of 8.14 ±7.69 and 4.96 ±4.35 saccades per scan, respectively. The frequency of saccades in each monkey were compared using repeated-measures ANOVAs to test for main effects of stimulus location.

Polar angle experiment

For monkey M1, the frequency of saccades (Q1: $M = 1.04$, $SD = 1.43$; Q2: $M = 1.63$, $SD = 1.93$; Q3: $M = 1.92$, $SD = 2.45$; Q4: $M = 1.96$, $SD = 2.16$) did not show a main effect of stimulus location [M1: $F(3,23) = 1.55$, $p = 0.21$]. Similarly, the frequency of saccades in monkey M2 did not differ by visual quadrant (Q1: $M = 1.24$, $SD = 1.41$; Q2: $M = 1.05$, $SD = 1.77$; Q3: $M = 1.29$, $SD = 1.10$; Q4: $M = 1.76$, $SD = 2.07$)[M2: $F(3,20) = 0.96$, $p = 0.42$].

Eccentricity experiment

For monkey M1, the frequency of saccades (Q1: $M = 3.07$, $SD = 3.27$; Q2: $M = 0.57$, $SD = 1.40$; Q3: $M = 1.36$, $SD = 1.45$; Q4: $M = 3.14$, $SD = 3.04$) showed a main effect of stimulus location [M1: $F(3,13) = 7.51$, $p < 0.001$]. Pairwise comparisons revealed significantly more saccades during stimulation of the most foveal and the most peripheral eccentricity bands compared to the two intermediate bands [E1 vs. E2: $t(13) = 3.49$, $p = 0.004$, $d = 0.93$; E1 vs. E3: $t(13) = 2.22$, $p = 0.05$, $d = 0.59$; E4 vs. E2: $t(13) = 3.71$, $p = 0.003$, $d = 0.99$; E4 vs. E3: $t(13) = 2.96$, $p = 0.01$, $d = 0.79$]. None of the pairwise comparisons remained significant after Bonferroni correction. For monkey M2, the frequency of saccades (Q1: $M = 1.46$, $SD = 1.77$; Q2: $M = 1.46$, $SD = 1.97$; Q3: $M = 0.86$, $SD = 1.08$; Q4: $M = 1.18$, $SD = 1.31$) did not show a main effect of stimulus location [M2: $F(3,27) = 1.36$, $p = 0.26$].

Taken together, the analysis of saccade frequency in both experiments shows that neither monkey made saccades very often, and when they did make saccades, there were no systematic differences in their frequency for any particular stimulus location.

References

Gitelman, D. R. (2002) Behav. Res. Methods Instrum. Comput. 34, 605–612

Supplementary Figure Legends

Supplementary Figure 1: *Frequency histograms of horizontal (X) and vertical (Y) eye position for the polar angle and eccentricity mapping scanning sessions.* Monkey subjects (M1 and M2) maintained their gaze on a small fixation spot (0.5° diameter) within a 4° square window. (A) Frequency histograms of eye position for the polar angle experiment where colored lines indicate periods of stimulation for each visual quadrant (right LVF, left LVF, left UVF, right UVF). (B) Frequency histograms of eye position for the eccentricity mapping experiment where colored lines indicate periods of stimulation for four eccentricity bands (0-2°, 2-4°, 4-7.5°, 7.5-15°). Both horizontal and vertical eye position were centered on the fixation spot at zero degrees. Positive values indicate rightward or upward deviations from fixation. The inner red vertical dashed lines indicate the +/- 2° fixation window boundary. Methods for further details.

Supplementary Figure 2: *Volume boundaries of V3a, DP, CIP-1, CIP-2, LIP_{vt} of M1 in coronal, axial, and sagittal sections.* Coronal (top), axial (middle), and sagittal (bottom) plane sections for monkey M1 in .5mm slice segments. All conventions and abbreviations as in Figure 3.

Supplementary Figure 3: *Volume boundaries of V3a, DP, CIP-1, CIP-2, LIP_{vt} of M2 in coronal, axial, and sagittal sections.* Coronal (top), axial (middle), and sagittal (bottom) plane sections for monkey M2 in .5mm slice segments. All conventions and abbreviations as in Figure 3.

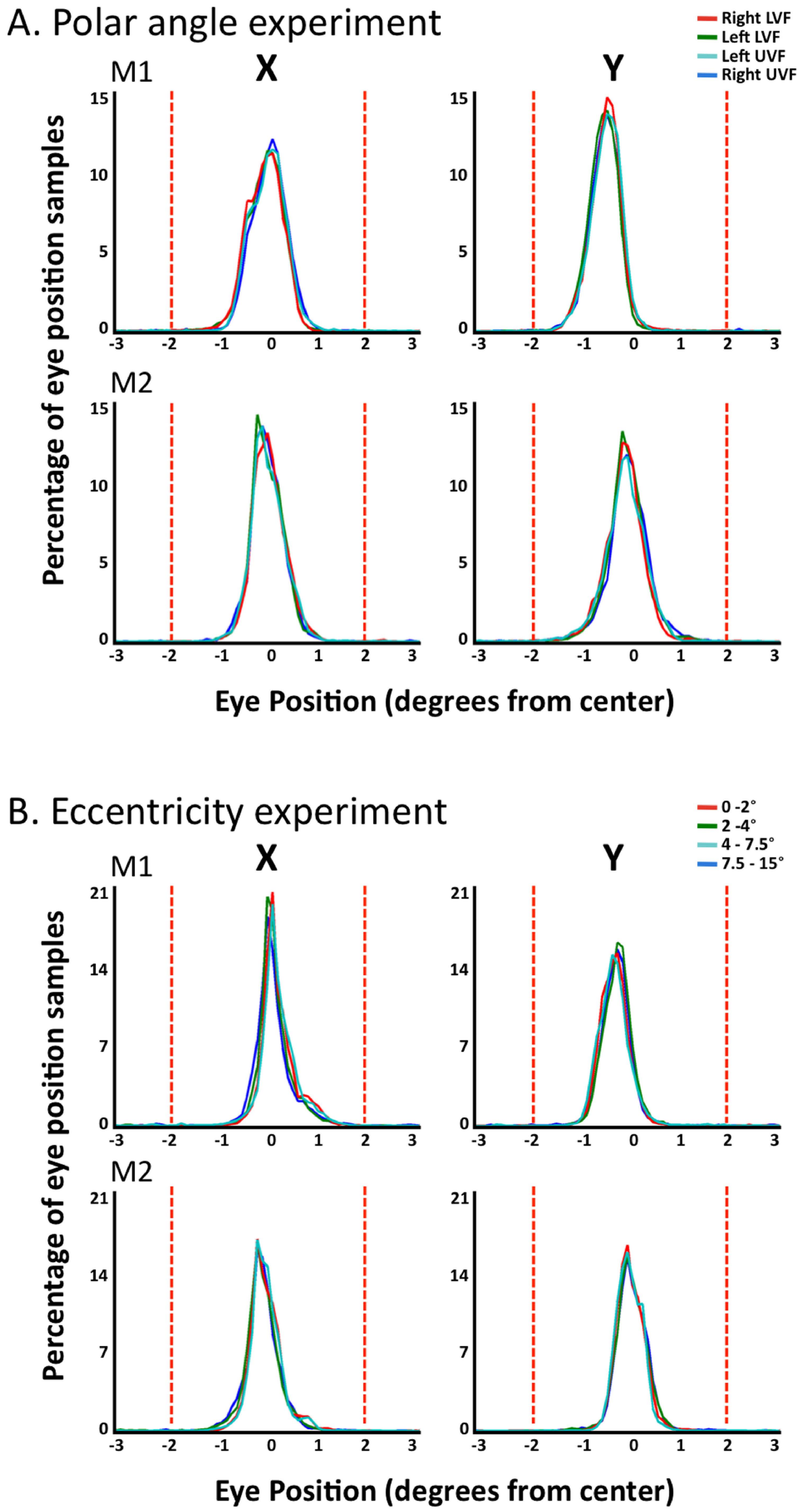
Supplementary Figure 4: *Time series of fMRI signals at borders between V3a, DP, CIP-1, CIP-2, and LIP_{vt}.* (a) Time series of fMRI signals at the UVF (red line) and LVF (blue line) polar angle phase reversals that were defined from the phase progression analysis in monkey M1. (b) Time series of fMRI signals of individual cycles averaged between monkeys M1 and M2 for the borders between V3a and CIP-1 (dark red), CIP-1 and CIP-2 (light blue), CIP-2 and LIP_{vt} (light red), and the anterior border of LIP_{vt} (dark blue).

Supplementary Figure 5: *Reproducibility of polar angle maps in dorsal visual cortex.* Data were split into clockwise (a) and counterclockwise (b) runs for right and left hemispheres of M1& M2. Inflated surface reconstructions of dorsal and parietal cortex. Maps were thresholded at 3 s per cycle S.E.M. variance (see Methods). All other conventions and abbreviations as in Figure 1A.

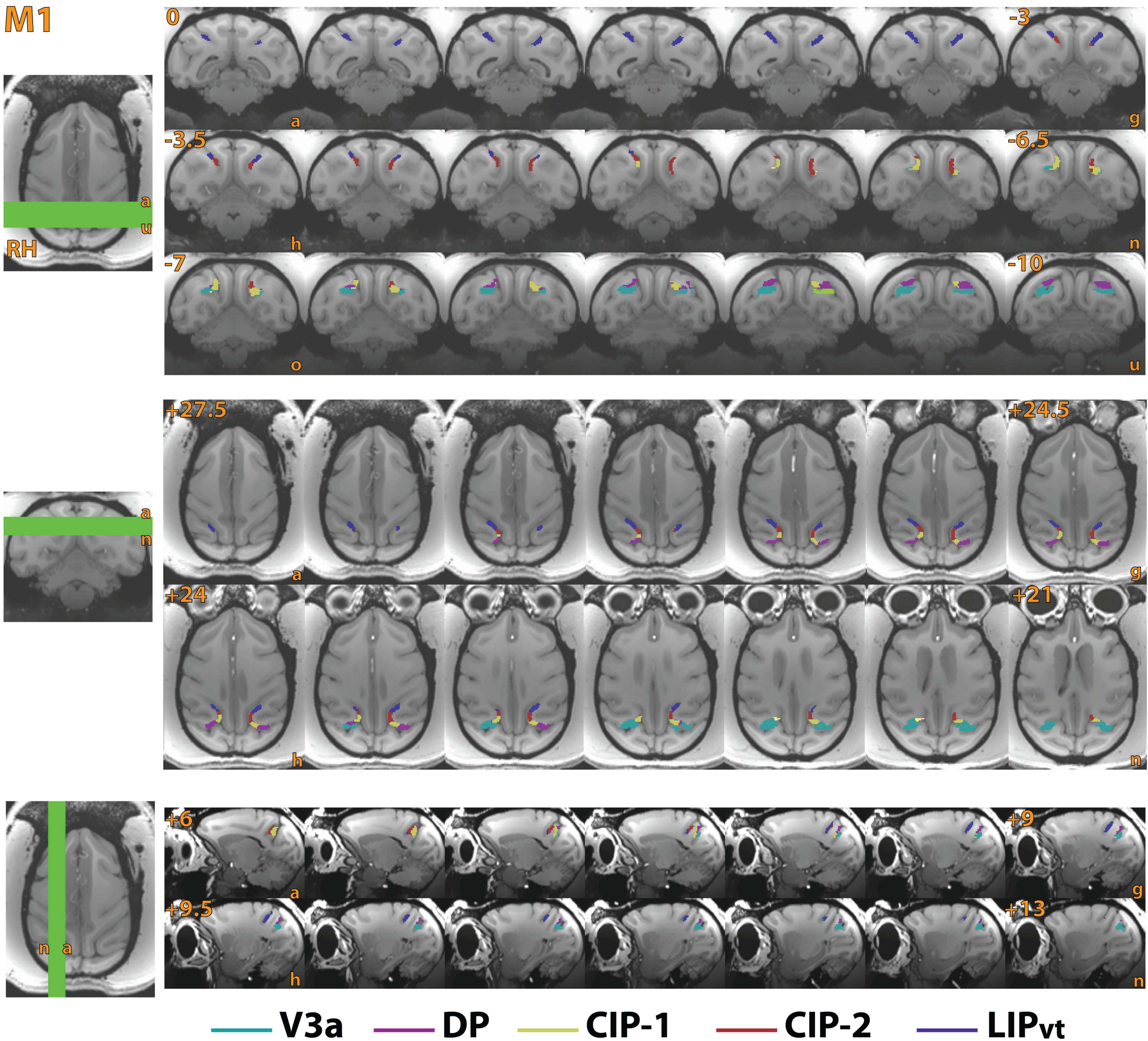
Supplementary Figure 6: *Average alignment indices between clockwise and counterclockwise runs for V1, V3a, CIP-1, CIP-2, LIP_{vt}, and DP.* Histograms of alignment indices ($AI = 1 - |\Delta\varphi| / \pi$). The index values peak around an index value close to 1, which indicates good alignment between clockwise and counterclockwise polar phase estimates. The red line illustrates a distribution for uncorrelated data.

Supplementary Figure 7: *Average alignment indices between M1 and M2 for polar angle and eccentricity phase estimates for V1, V3a, CIP-1, CIP-2, LIP_{vt}, and DP.*

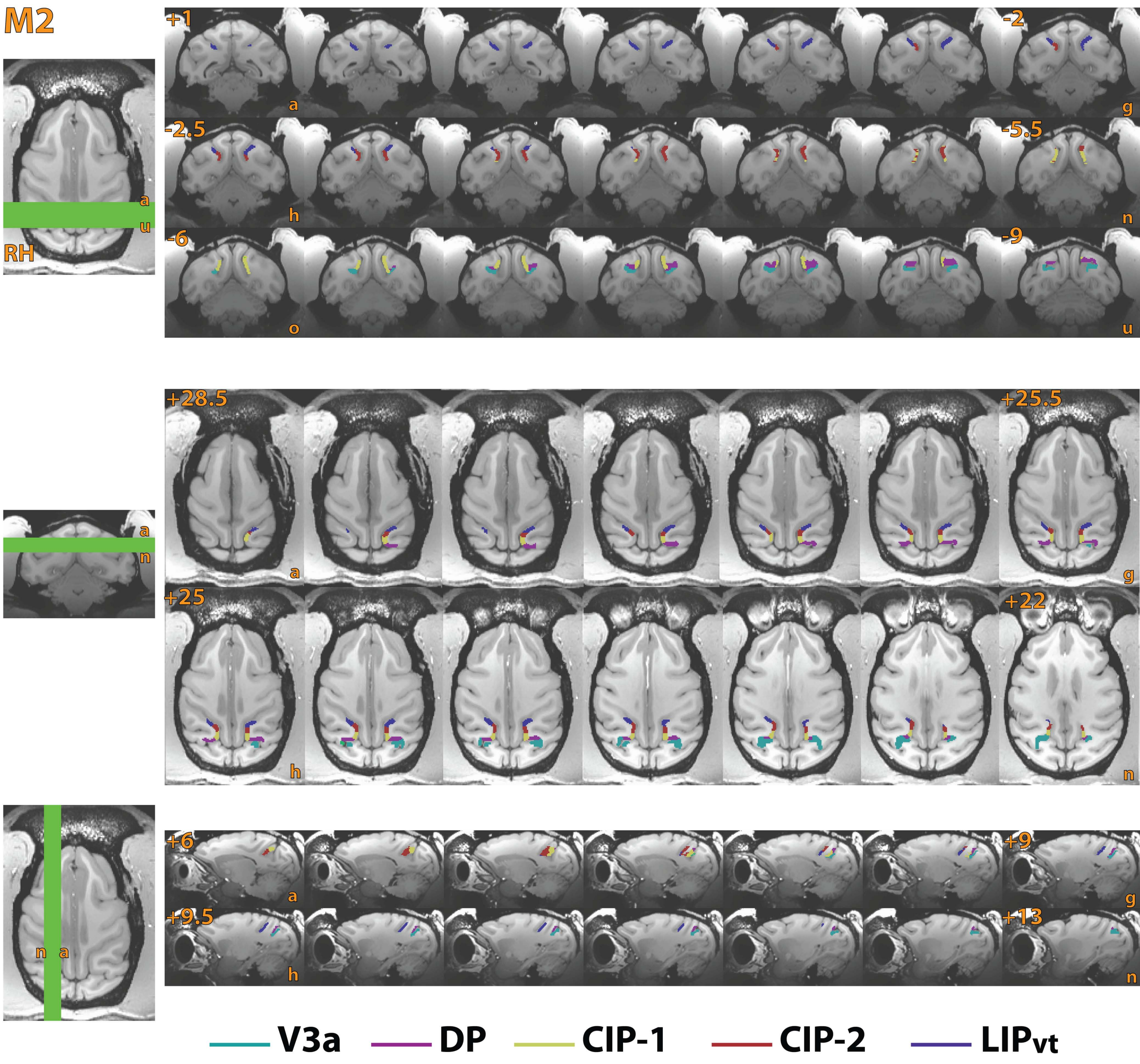
Histograms of alignment indices ($AI = 1 - |\Delta\varphi| / \pi$) for phase estimates from standard mesh surfaces between M1 and M2. (a) Histograms for polar angle phase estimates between monkeys M1 and M2. All conventions as in Supplementary Figure 6. (b) Histograms for eccentricity phase estimates between M1 and M2. All conventions as in Supplementary Figure 6.



Supplementary Figure 1



Supplementary Figure 2



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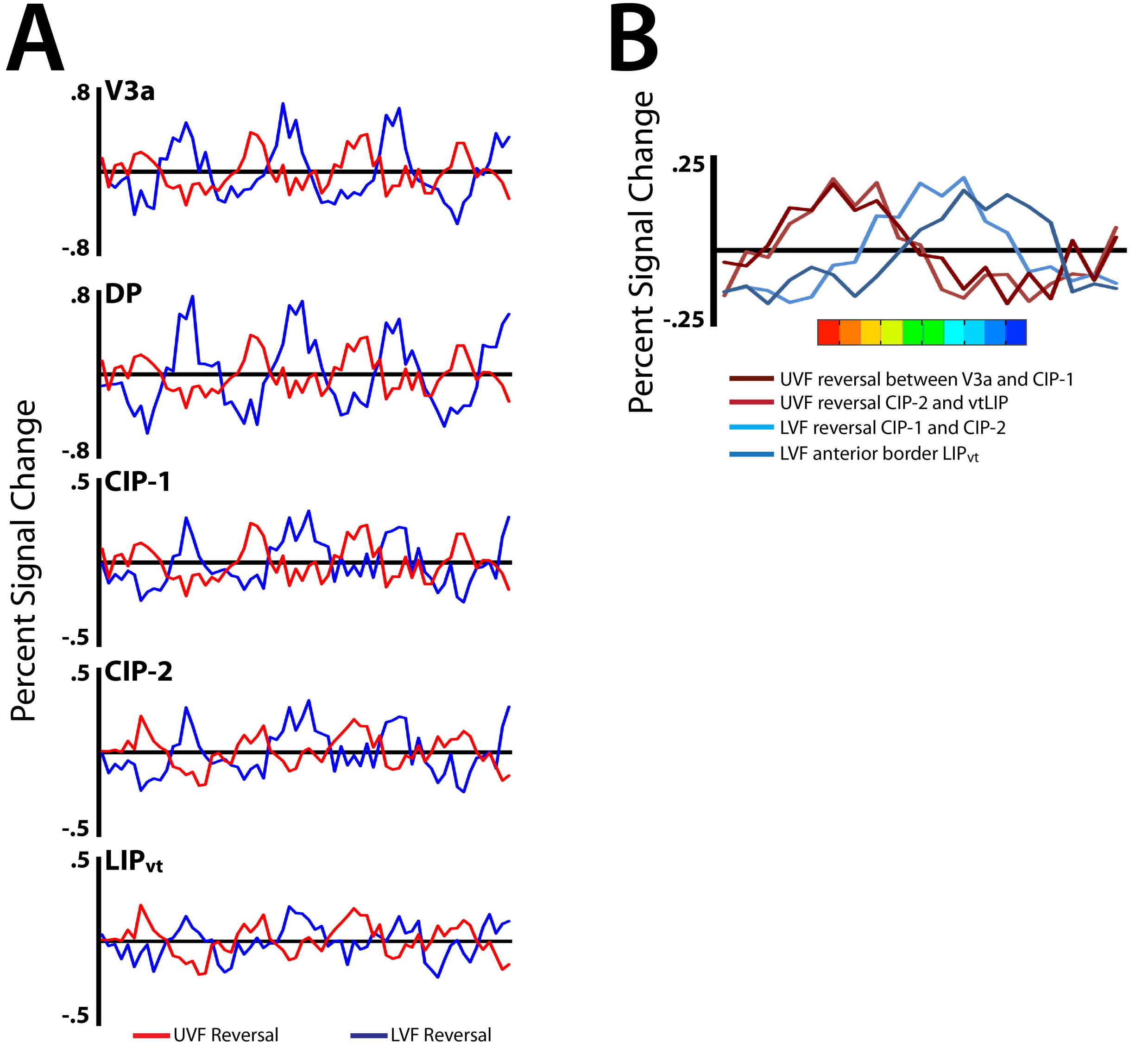

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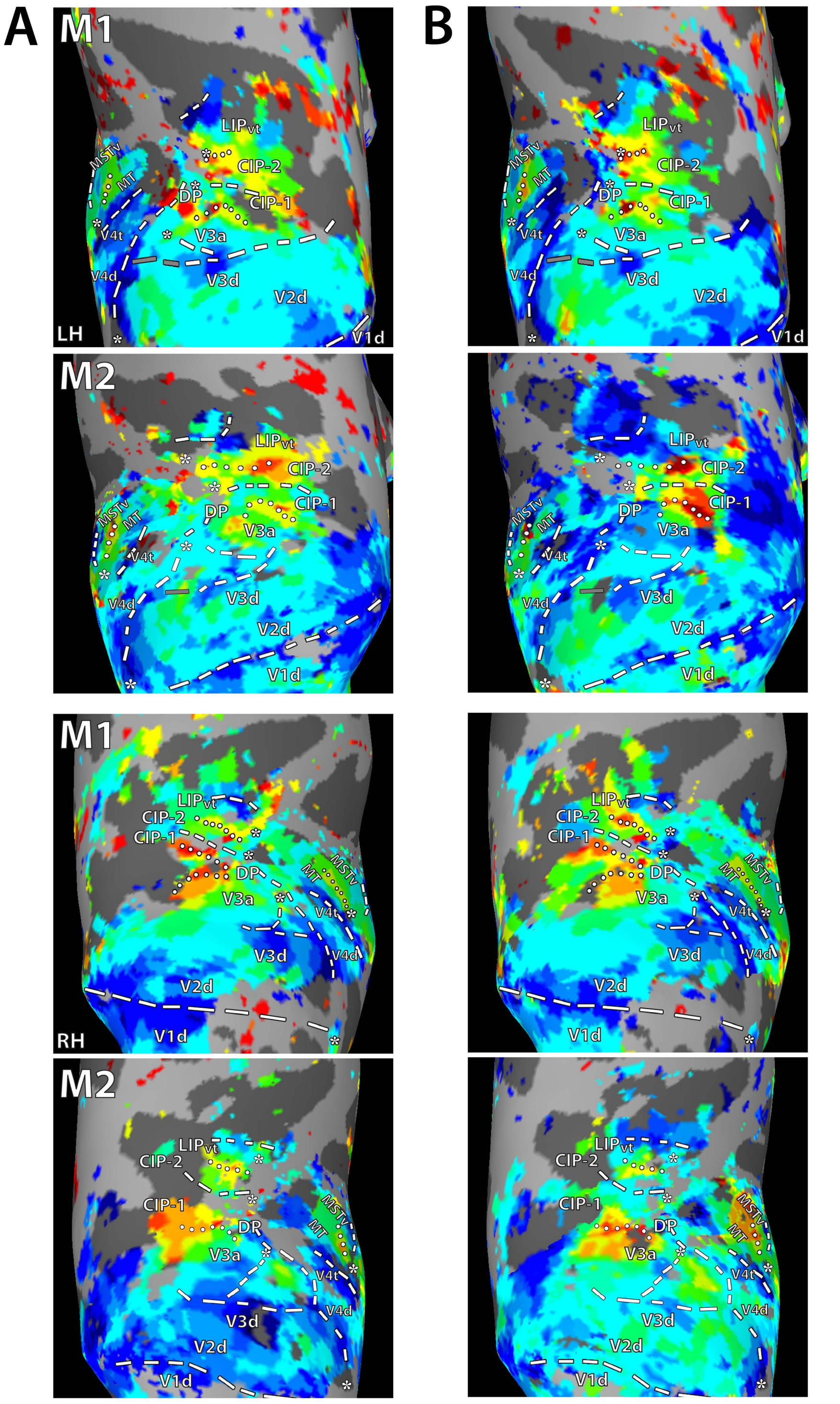
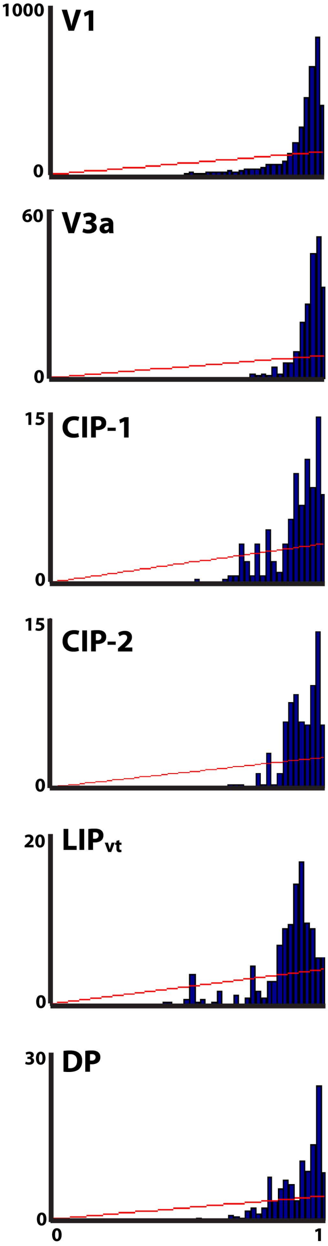
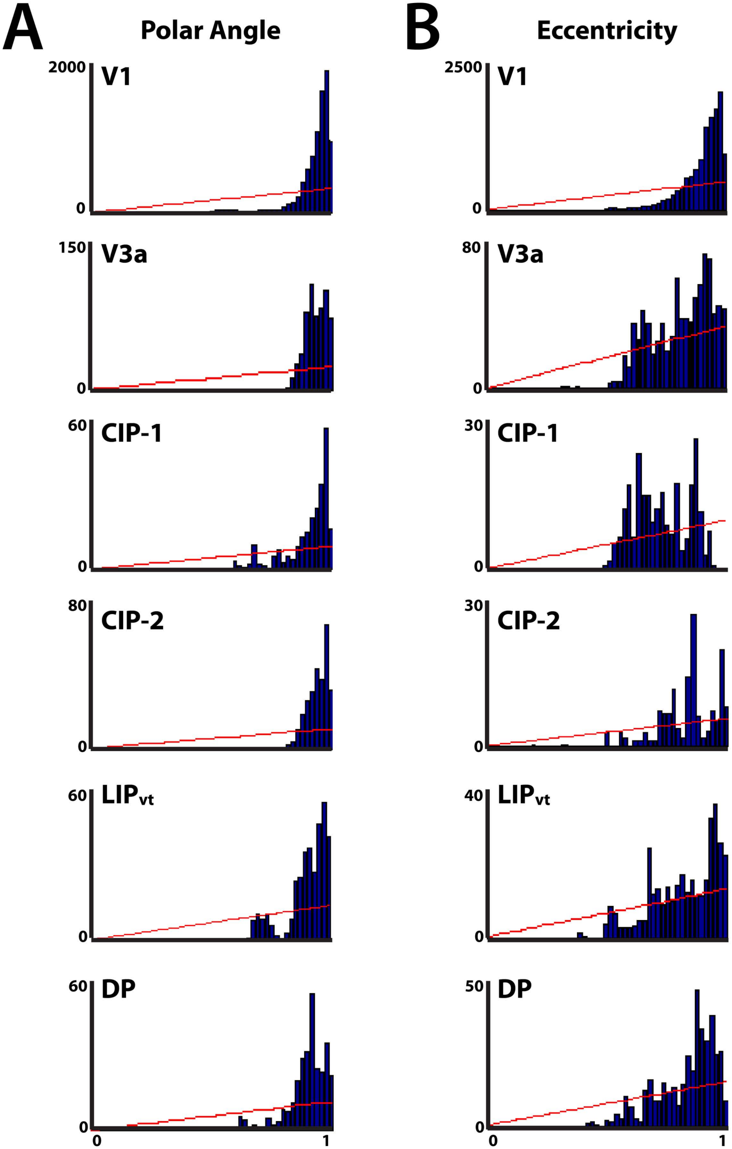


Supplementary Figure 5



Supplementary Figure 6



Supplementary Figure 7