Supplemental information
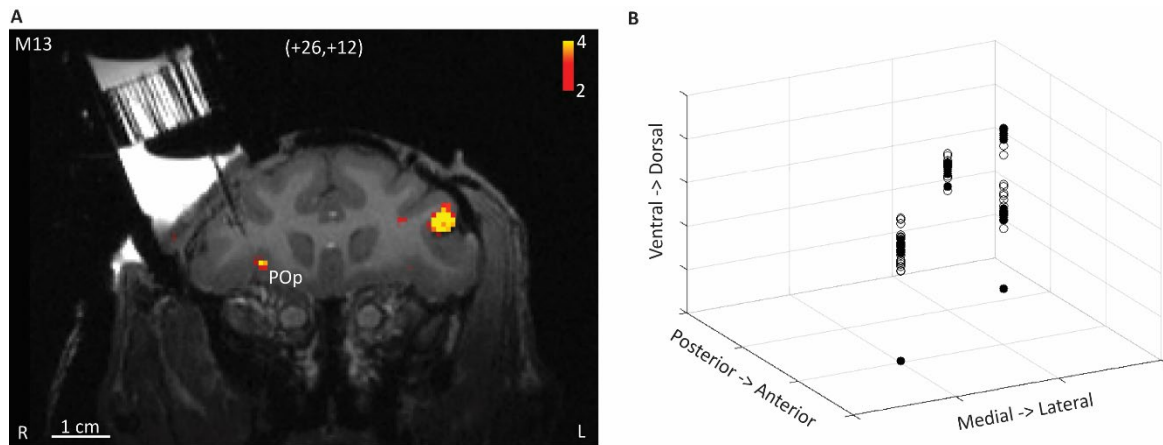
**Fast face-selective responses in prefrontal**

face patches of the macaque

Eline Mergan, Qi Zhu, Xiaolian Li, Rufin Vogels, and Wim Vanduffel
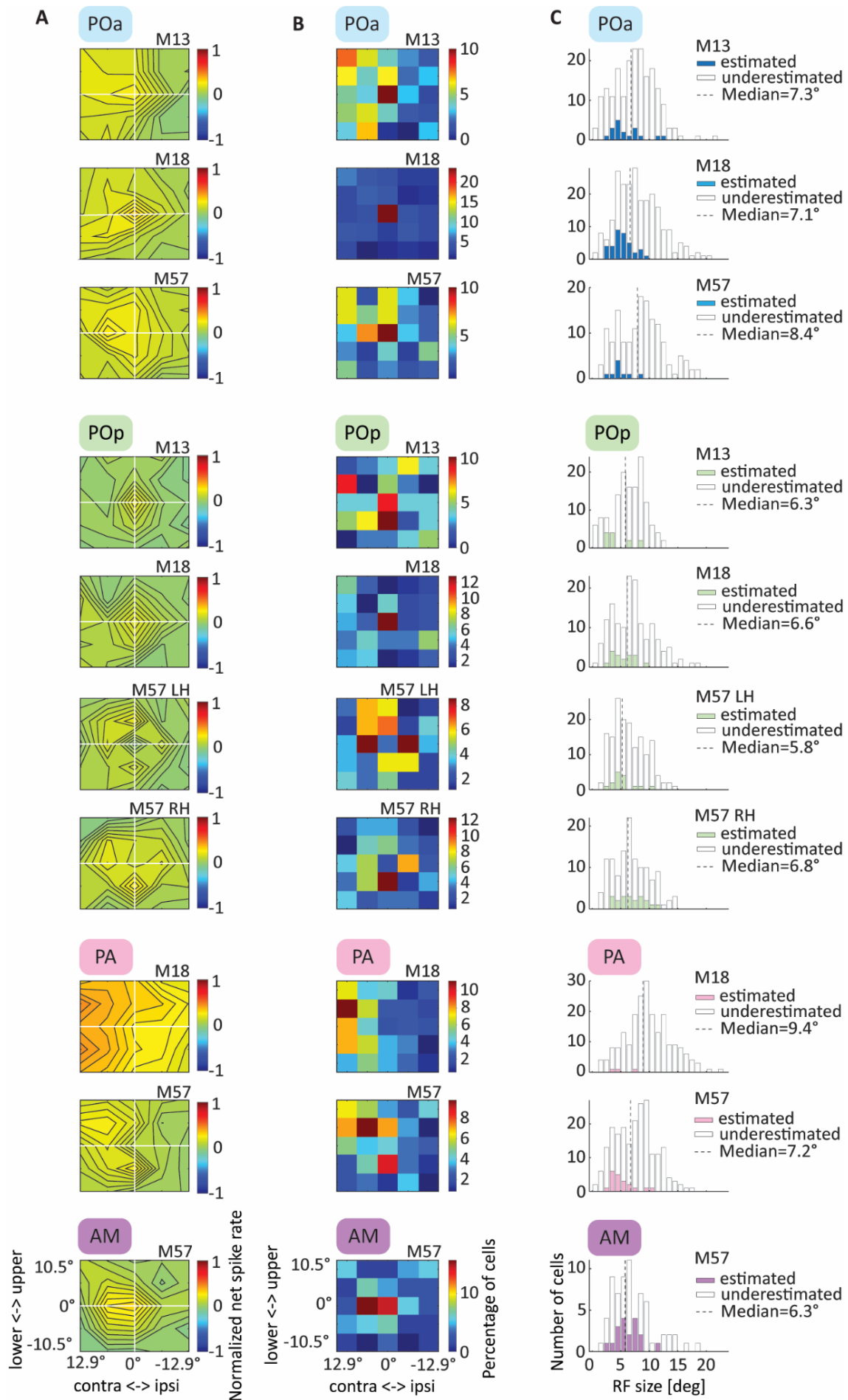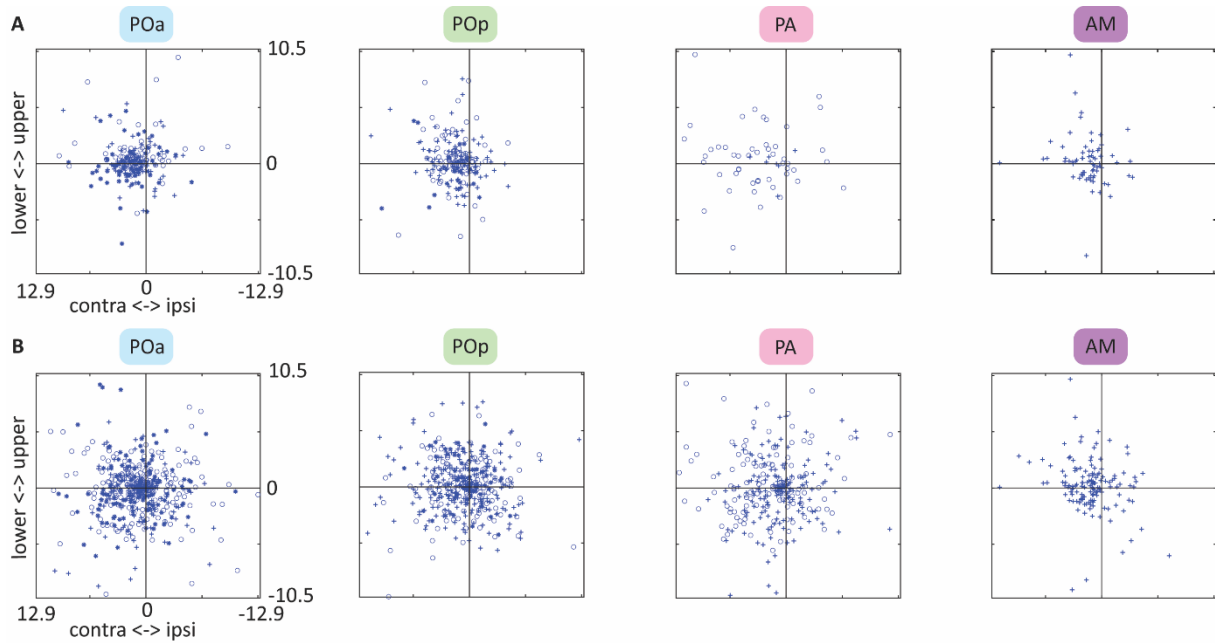
Supplemental Figures

Supplementary Figure 1: Face-selective activity in face patch POp in M13. (A) Electrode track towards the targeted face patch POp in M13. The track from the guidetube is clearly visible and targets the center of the activation (color bar, t-scores). Horsley-Clarke coordinates of the face patch are indicated on top. R and L indicate right and left hemisphere. (B) Three-dimensional representation of face-selective and non-face-selective visually responsive neurons across the electrode contact points across all recording sessions in POp in M13. Black dots correspond to face-selective and white dots to non-face-selective neurons. – Related to Figure 1.
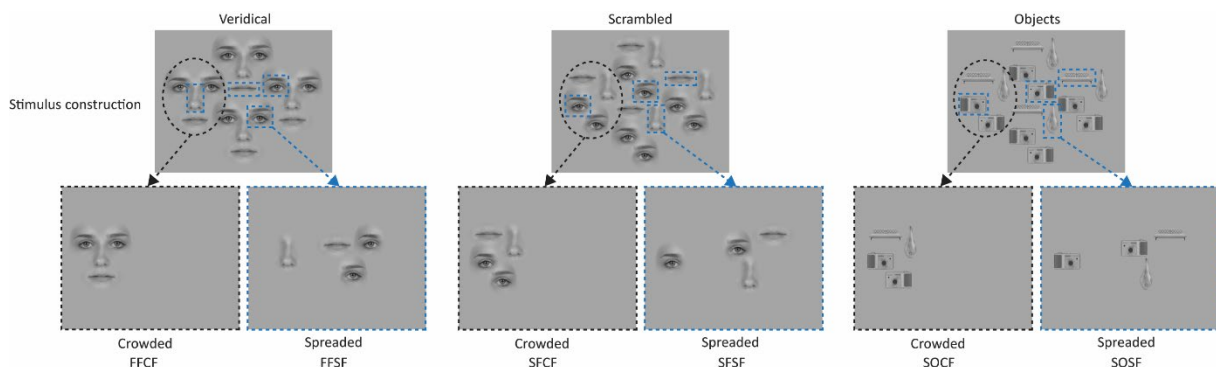

Supplementary Figure 2: Face configuration fMRI stimulus set. Veridical faces were configured from face features in a normal composition (FFCF). Scrambled faces were composed of repositioned face features (SFCF). Objects resembling face features were repositioned as in the scrambled face category (SOCF). These 3 categories were the 'crowded' configurations, and exist for eight different identities and each identity was presented in four parafoveal positions. Besides 'crowded' configurations, 'spreaded' configurations were generated. These stimuli were created by selecting one different face feature from each of the four veridical faces, while keeping their spatial locations (FFSF). Similarly, for the scrambled faces and scrambled objects, different face features and objects were selected (SFSF and SOSF, respectively). – Related to Figure 1.

A

POa

M13

M18

M57

POp

M13

M18

M57 LH

M57 RH

PA

M18

M57

AM

M57

lower <-> upper
10.5°
0°
-10.5°

12.9°   0°   -12.9°
contra <-> ipsi

Normalized net spike rate

B

POa

M13

M18

M57

POp

M13

M18

M57 LH

M57 RH

PA

M18

M57

AM

M57

lower <-> upper
10.5°
0°
-10.5°

12.9°   0°   -12.9°
contra <-> ipsi

Percentage of cells

C

POa

M13
estimated
underestimated
Median=7.3°

M18
estimated
underestimated
Median=7.1°

M57
estimated
underestimated
Median=8.4°

POp

M13
estimated
underestimated
Median=6.3°

M18
estimated
underestimated
Median=6.6°

M57 LH
estimated
underestimated
Median=5.8°

M57 RH
estimated
underestimated
Median=6.8°

PA

M18
estimated
underestimated
Median=9.4°

M57
estimated
underestimated
Median=7.2°

AM

M57
estimated
underestimated
Median=6.3°

Number of cells

0   5   10   15   20
RF size [deg]

Supplementary Figure 3: Receptive fields of non-face-selective neurons. (A) Interpolated average RF maps for each monkey's face patch. Responses of each neuron were normalized by dividing them with the highest net response to one of the 25 tested positions. Normalized response strength is indicated by the color bar. The response was measured at 25 locations, equally spaced from 10.5° above to 10.5° below the horizontal meridian and 12.9° ipsilateral to 12.9° contralateral visual field. (B) Distribution of response peaks of non-face-selective neurons across the tested positions. Percentage of neurons that preferred a specific position in the visual field is indicated by the color bar. (C) Distribution of RF sizes of non-face-selective neurons in each face patch. RF size is measured as the square root area within the 50% contour line. Color bars denote the number of neurons for which the 50% contour lines were closed within the mapped visual field. White bars correspond to the number of neurons for which the RF size was underestimated. – Related to figure 3.

Supplementary Figure 4: Location of RF centers of individual face-selective and non-face-selective neurons in each face patch. (A) RF centers of face-selective neurons. (B) RF centers of non-face-selective neurons. RF centers of monkeys overlap in each face patch. The symbols indicate different monkeys: * = M13, o = M18, + = M57. Solid black lines denote horizontal and vertical meridians. Visual degrees of the tested visual field are indicated on the x and y-axes. – Related to Figure 3.
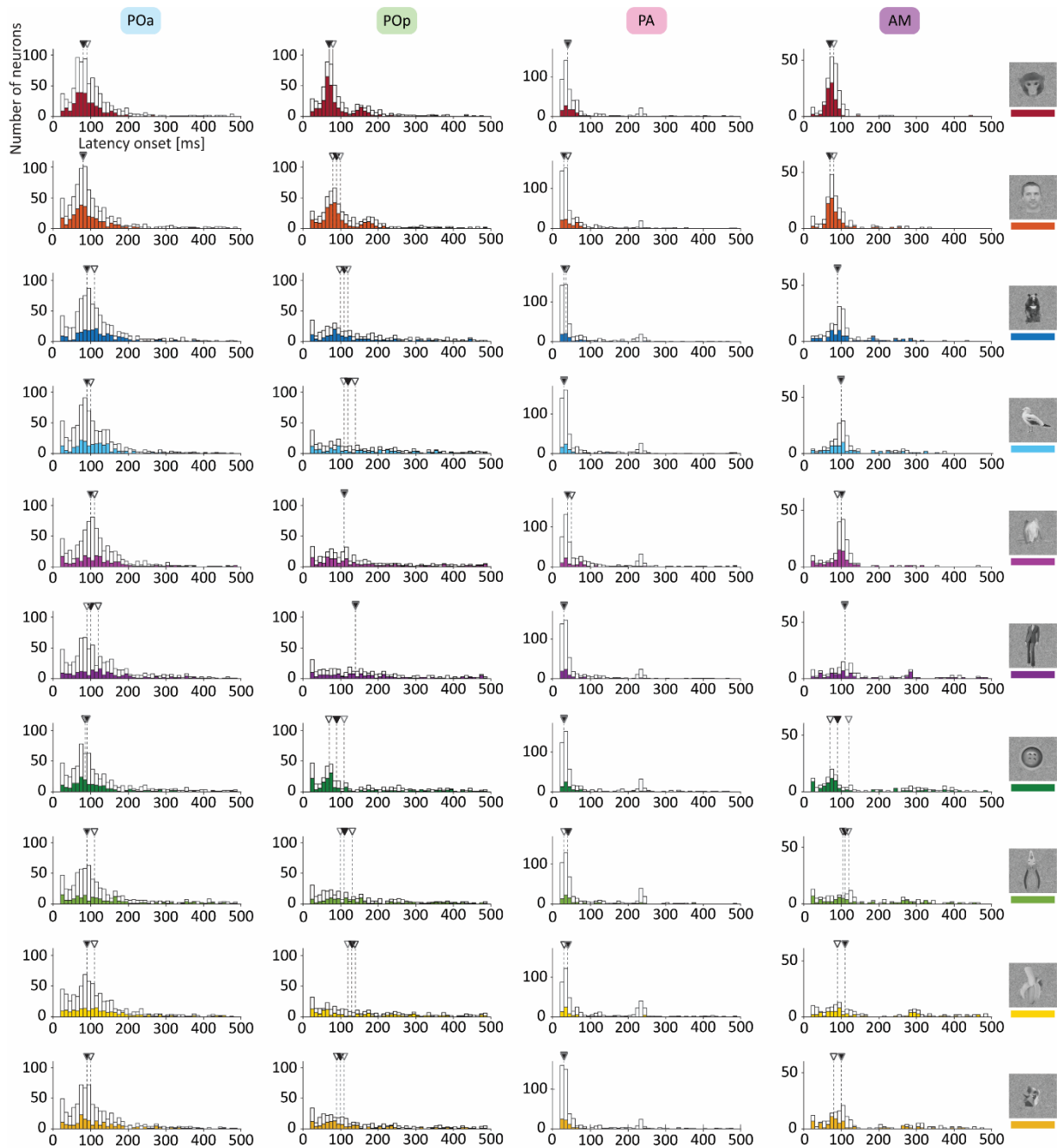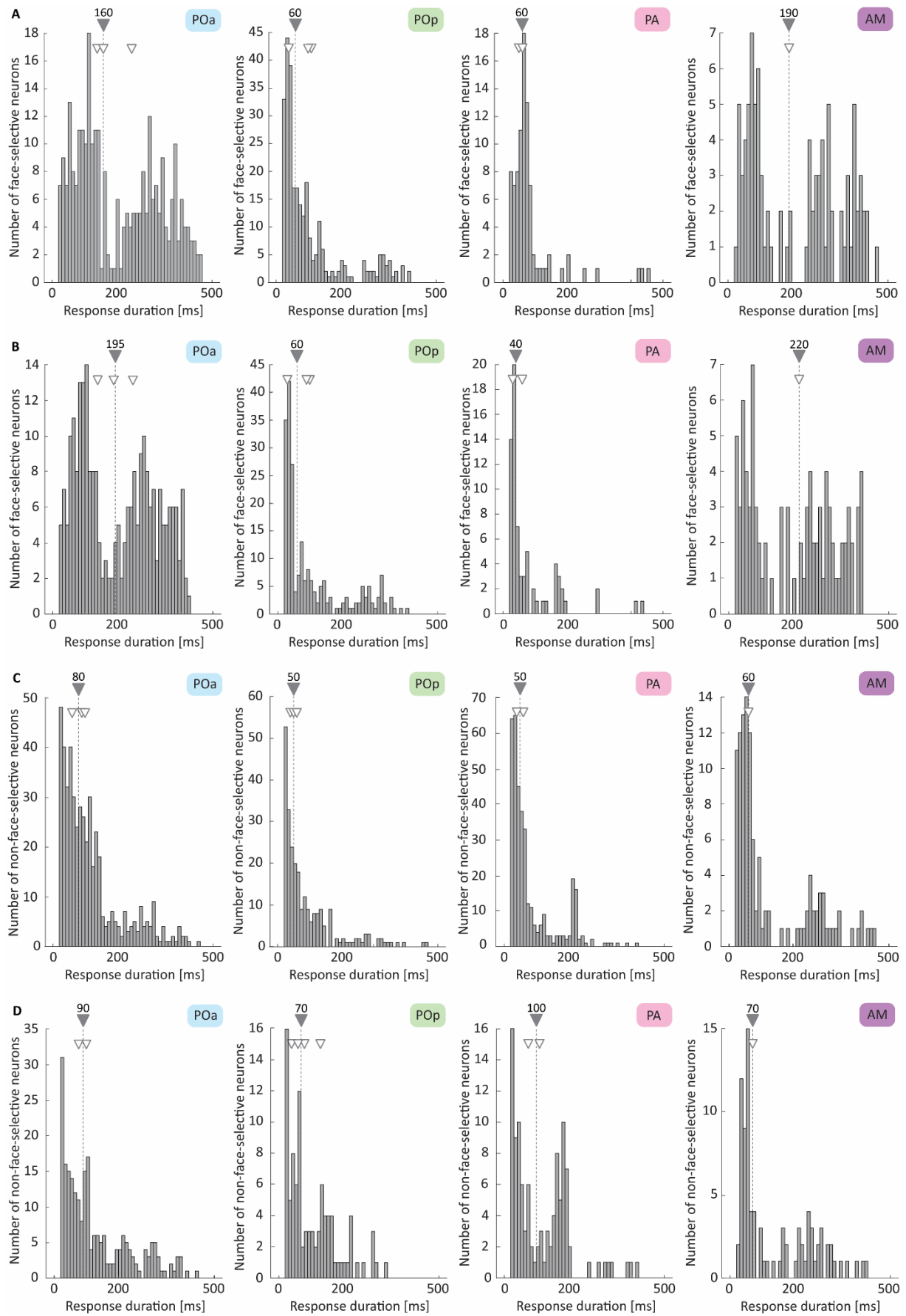
Supplementary Figure 5: Distribution of latency onsets of all neurons for each category. The latency onset is the time when the spike density function exceeds 2.5 SDs above the baseline activity (100 ms until stimulus onset) for 2 consecutive 10 ms bins. For each face patch, data is combined across monkeys. White bars are latencies of all visually responsive neurons. Overlapping colored bars are the latencies of only face-selective neurons. Dotted lines indicate median latencies of the different neural populations. Full black triangles correspond with median latencies of all neurons combined. Dark grey triangle outlines indicate the median latencies of the face-selective population, and the lighter grey triangle outlines indicate the median latencies of the non-face-selective population. – Related to Figure 4.

Supplementary Figure 6: Response latency of non-face-selective neurons to face images. (A) Distribution of latency responses to face images in each face patch. Median latencies for each face patch are depicted next to the violin plots. The latency onset is the time when the spike density function exceeds +2.5 SDs above baseline activity (-100 to 0 ms before stimulus onset) for two consecutive 10 ms bins. Dots indicate the latencies of the individual neurons. Outer boundaries of the bright rounded shade are the 99th percentile (top) and 1st percentile (bottom). Outer boundaries of the squared irregular darker shade are the 3rd quartile (top) and 1st quartile (bottom). The boundaries of the rectangular narrow shade indicate the mean + std (top) and mean – std (bottom). The Asterix and horizontal narrow stripe indicate the mean and median respectively. Population response latencies for faces in the orbitofrontal face patches were significantly slower than in PA (LMM combined across monkeys: POa vs PA, p = 2.467e^{-11}, POp vs PA, p = 3.9257e^{-15}). FDR corrected post-hoc comparisons between latencies in the different face patches for the monkeys separately revealed significant differences between POa and POp in M13 (p = 9.2072e^{-4}), but not in M18 and M57. Only in M18 both orbitofrontal face patches were significantly different from PA (POa vs PA, p = 1.2556e^{-24} and POp vs PA, p = 3.2052e^{-22}). (B) Distribution of face-selective latency responses in each face patch. For each non-face-selective neuron, a right-tailed Wilcoxon rank sum test between the face category response and the least preferred category, determined whether median spike rate was significantly larger for faces in each 10 ms bin from stimulus onset until 500 ms after. The time bin where the response for faces was significantly larger than the least preferred category for 2 consecutive 10 ms bins, is the face-selective latency onset of that neuron. Population face-selective response latencies in the orbitofrontal face patches were significantly slower than in PA (LMM combined across monkeys: POa vs PA, p = 8.3969e^{-4}, POp vs PA, p = 8.3969e^{-4}). FDR corrected post-hoc comparisons between latencies in the different face patches for the monkeys separately revealed significant differences only in M18 between the orbitofrontal face patches and PA (POa vs PA, p = 1.8205e^{-5} and POp vs PA, p = 1.0510e^{-6}). (C) Population PSTH (10 ms bins) of non-face-selective neurons in each monkey's face patch. The SEMs (calculated over neurons) above and below the PSTH lines are depicted as a shade. Only neurons with a significant selective latency response to faces are included. Responses are baseline subtracted. Population responses to faces are

indicated by full lines, and responses to the least preferred categories across neurons are indicated by dotted lines. Median visually driven and median selective latencies are indicated by empty and full circles on top of each plot, respectively. Different colors mark the different face patches. Stimulus presentation lasted from 0 to 200 ms. For the face category, 20 stimuli were included, and the least preferred non-face categories included 10 stimuli. The total number of trials included in the PSTH, is the sum of trials across these stimuli for all non-face-selective neurons (with a selective latency). M18: 24137 and 12055 trials for faces and non-face stimuli in POa, 10265 and 5144 trials for faces and non-face stimuli in POp, and 17840 and 8944 trials for faces and non-face stimuli in PA. M57: 20632 and 10310 trials for faces and non-face stimuli in POa, 7651 and 3830 trials for faces and non-face stimuli in POp LH, 5634 and 2820 trials for faces and non-face stimuli in POp RH, 13465 and 6737 trials for faces and non-face stimuli in PA, and 20540 and 10284 trials for faces and non-face stimuli in AM. M13: 15941 and 7965 trials for faces and non-face stimuli in POa, and 3616 and 1815 trials for faces and non-face stimuli in POp. – Related to Figure 4.

Supplementary Figure 7: Distribution of face and face-selective-response durations of face-selective and non-face-selective neurons. For each face patch, data was combined across monkeys.

Filled triangles and corresponding dotted vertical lines indicate the median population response duration. Triangle outlines mark the median response duration of the monkeys separately. (A) The response duration of a face-selective neuron is the time between the latency onset and offset of the first response peak for the face category. The onset is the time where the spike rate exceeds the baseline response with +2.5 SDs for 2 consecutive 10 ms bins. The offset is the time where the spike rate goes below the threshold of +2.5 SDs above baseline for 2 consecutive 10 ms bins. (B) The face-selective latency onset of a face-selective neuron is the time where the response for faces was significantly larger than for the least preferred category for 2 consecutive 10 ms bins. The offset is the time where the spike rate drops below +2.5 SDs from baseline for 2 consecutive 10 ms bins. The duration of the face-selective response, is the time between the latency onset and offset. (C) Response durations of the non-face-selective neurons. (D) Face-selective response durations of the non-face-selective neurons. – Related to Figure 4.
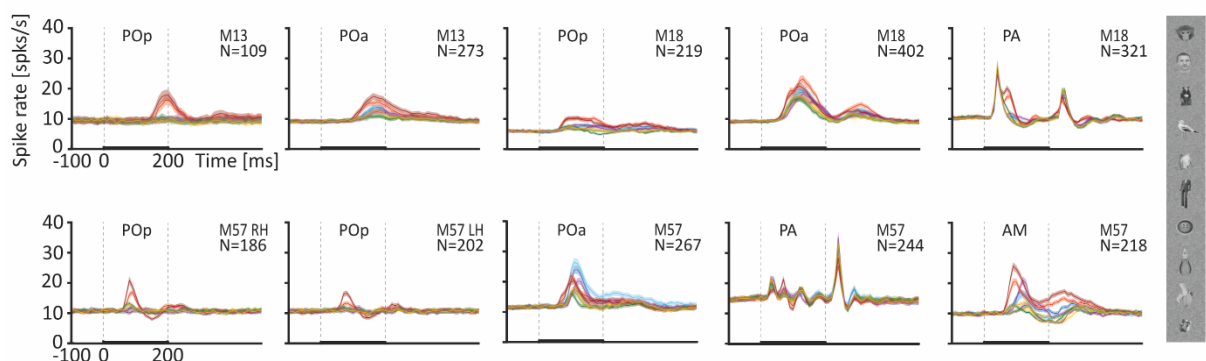
Supplementary Figure 8: Population PSTH of all visually responsive neurons combined in each face patch. Category responses are color-coded and indicated by the exemplar images of each category. The SEMs (calculated over neurons) above and below the PSTH lines are depicted as a shade. Stimulus presentation is indicated by vertical dotted lines. The numbers of included neurons in each monkey's face patch are indicated in the right upper corner of each plot. For each category, ten stimuli were included. The total number of trials across neurons for each category on average is: 31457 in POp and 11122 in POa of M13; 22043 in POp, 403184 in POa and 32265 in PA of M18; and 18732 in POp RH, 20329 in POp LH, 27092 in POa, 26392 in PA and 22060 in AM of M57. – Related to Figure 1.
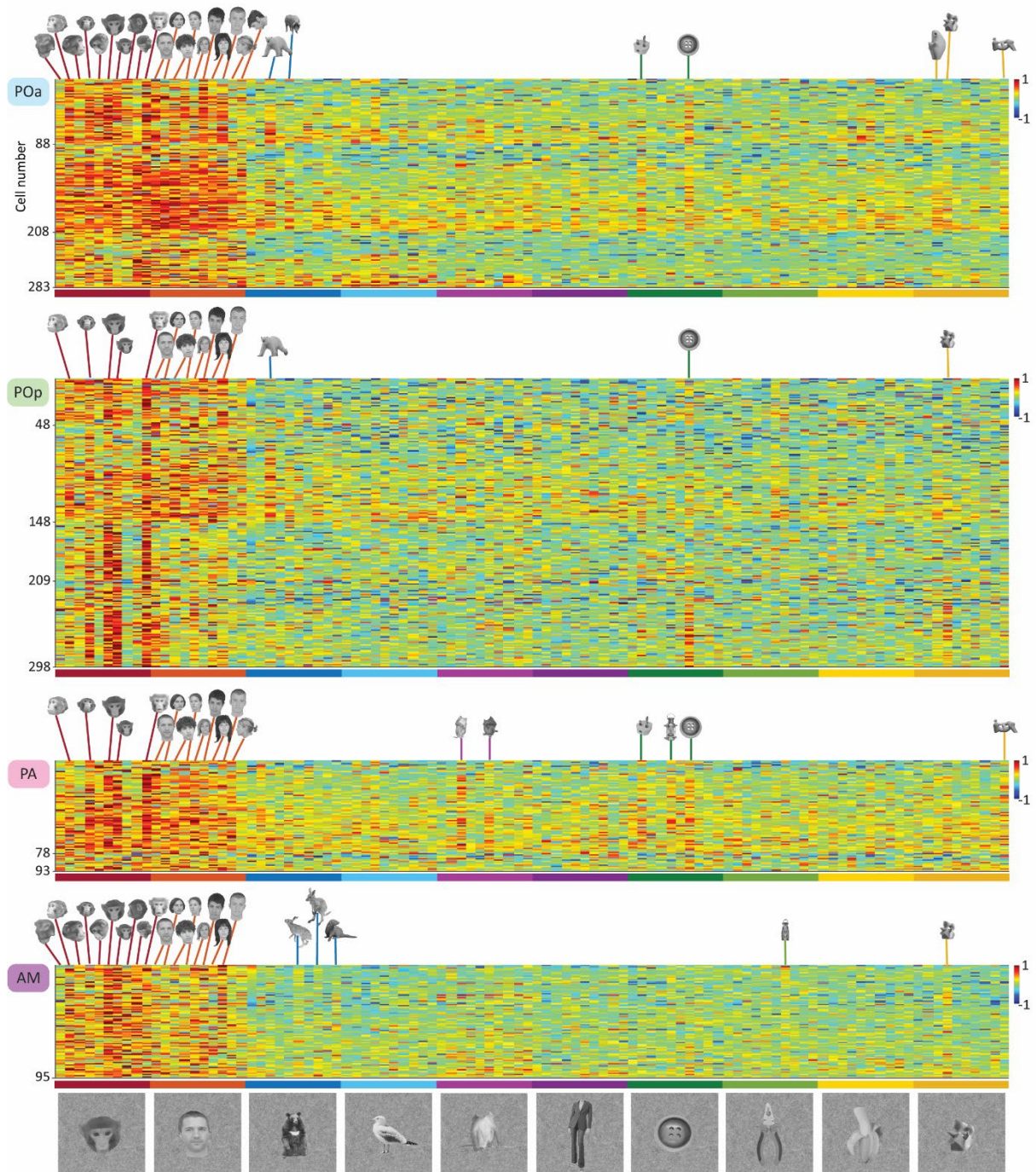
Supplementary Figure 9: Close up of stimulus selectivity of face-selective neurons. For each face patch, responses of face-selective neurons are represented by the rows of the spiking matrix. Normalized response strength is indicated by the color bar. The columns correspond to stimuli, which are grouped per category, as indicated by the example images and color codes on the bottom of the figure. For each face patch, neurons are ranked per monkey (M13, M18 and M57) and ordered by their face-selectivity (FSI), with on top the most face-selective neurons. For each face patch, some preferred images are depicted on top of the spiking matrix. – Related to Figure 5.
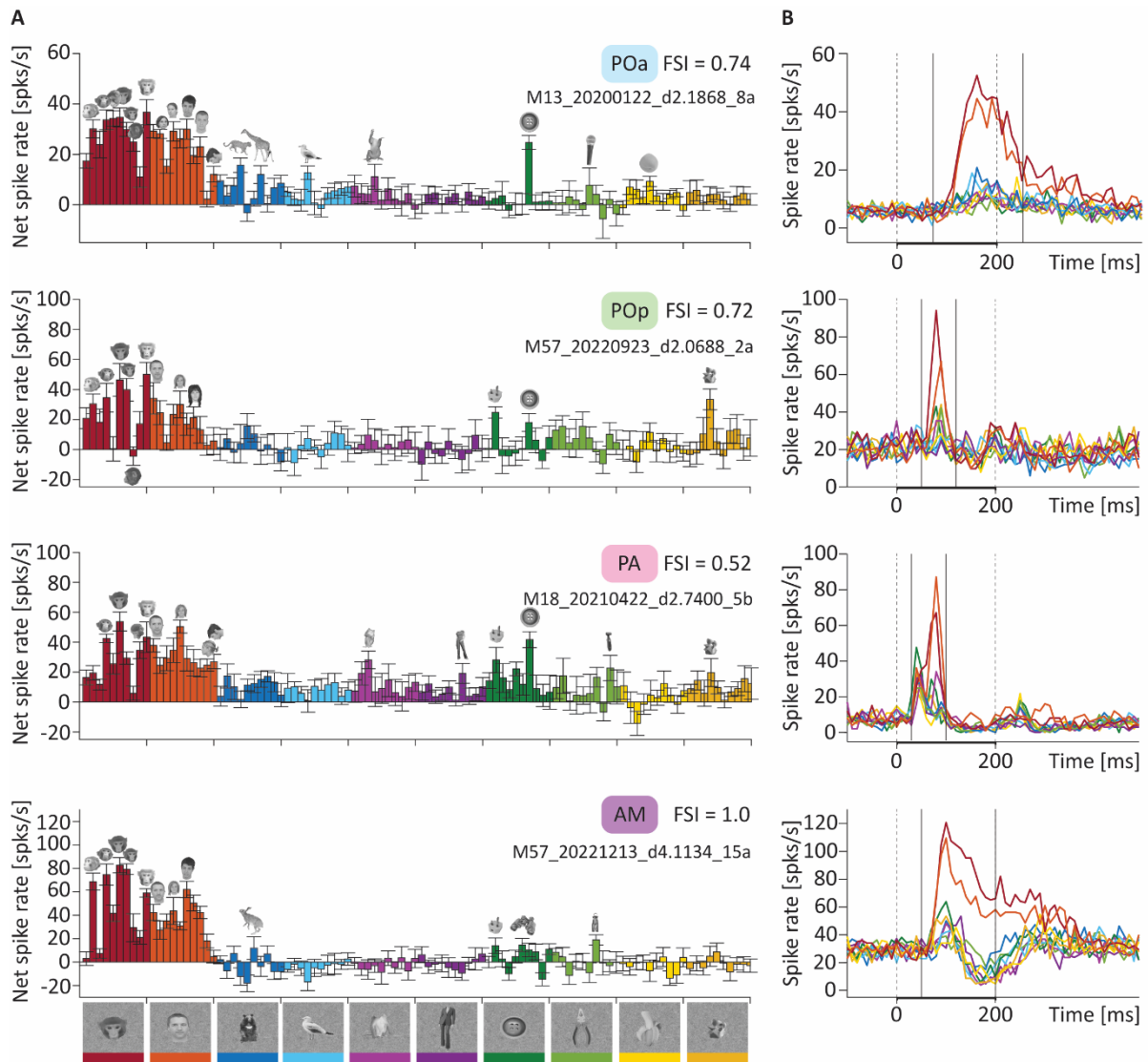
Supplementary Figure 10: Example activity patterns of face-selective neurons in each face patch.
(A) Color-coded selectivity pattern. Each bar represents the net response for a stimulus, grouped per category, as indicated by the different colors. Error bars denote the SEM across trials. The name of the neuron is indicated on the right side of the subplot. (B) PSTH of each category of an individual neuron. Dotted vertical lines indicate stimulus presentation time. Full vertical lines indicate analysis windows to calculate net spike rates in (A). – Related to Figure 5.
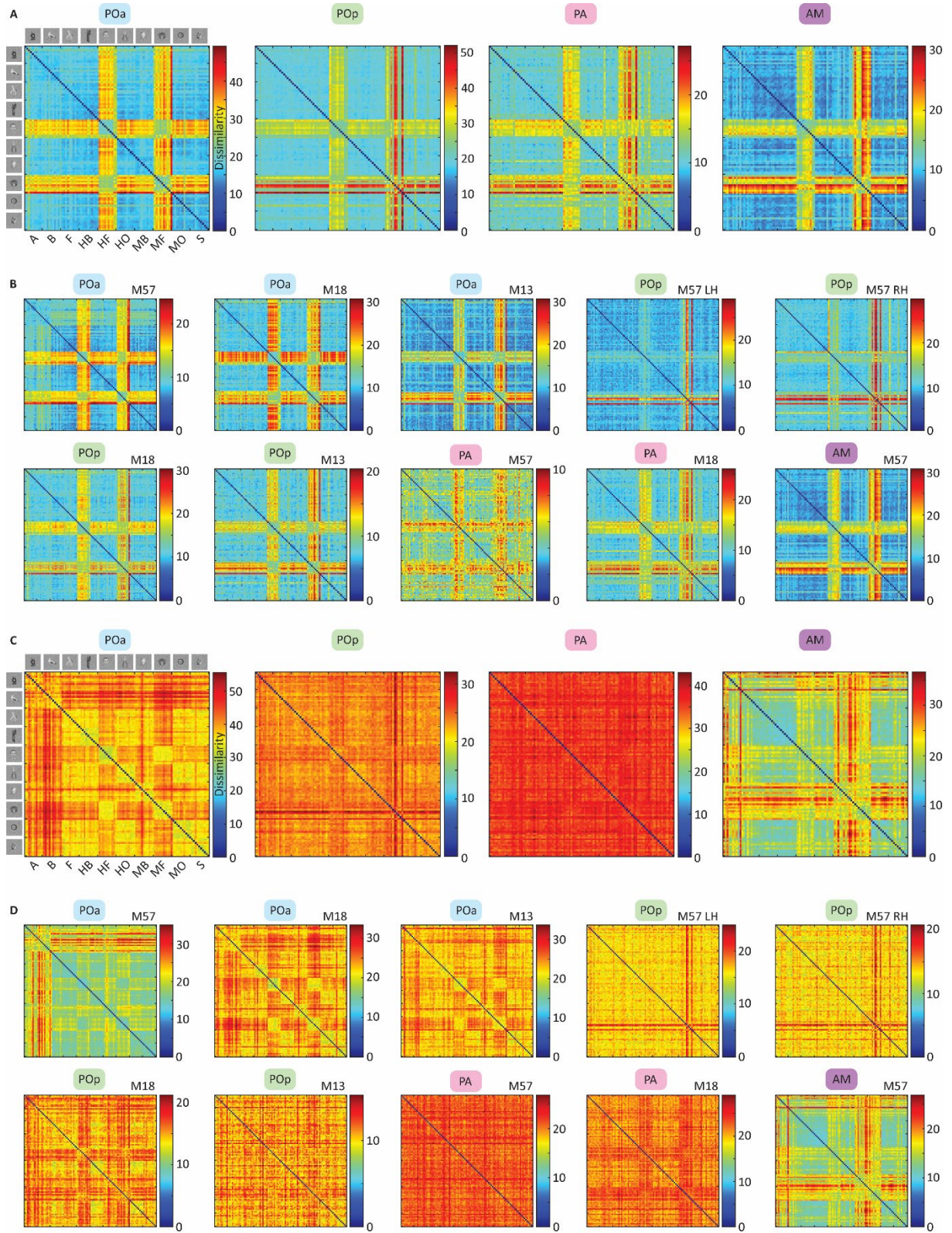
Supplementary Figure 11: Representational dissimilarity matrices of the face-selective and non-face-selective neural population. (A) Dissimilarity matrices for each face patch were computed based on the face-selective neurons across monkeys combined. A 100*100 dissimilarity matrix was constructed by calculating Euclidean distances between the 100 stimuli of the image set. The stimuli are grouped per category. A = animals, B = birds, F = fruits, HB = human bodies, HF = human faces, HO = human-like objects, MB = monkey bodies, MF = monkey faces, MO = monkey-like objects, S = sculptures. (B) Dissimilarity matrices were computed based on the face-selective neurons for each face patch for monkeys separately. (C) Dissimilarities matrices for each face patch were computed based on

the non-face-selective neurons across monkeys combined as in (A). (D) Dissimilarity matrices computed based on the non-face-selective neurons for each face patch for monkeys separately. Dissimilarity is indicated by the color bar. – Related to Figure 6.

A

POa
N = 658

POp
N = 418

PA
N = 472

AM
N = 123

Linkage distance

B
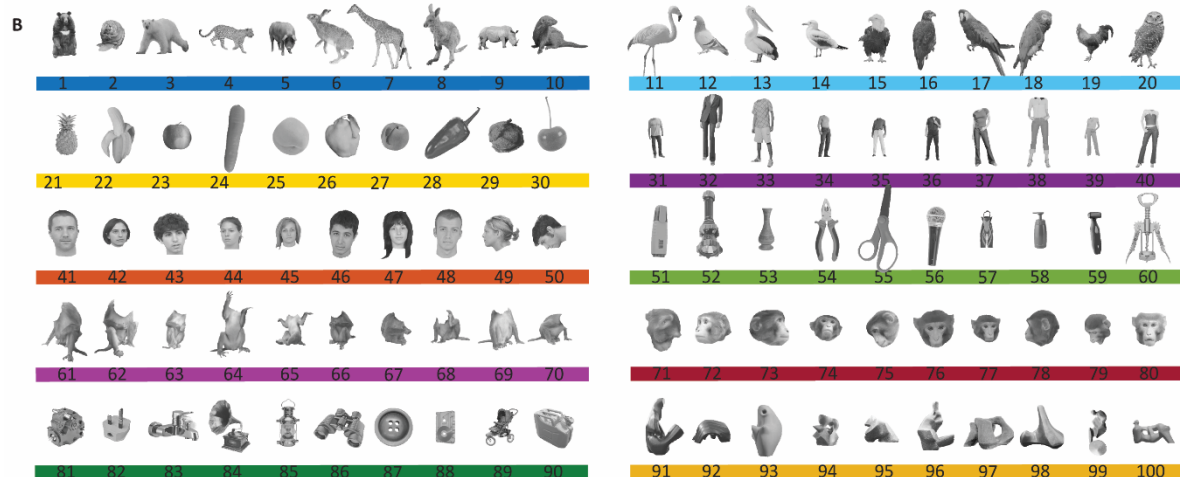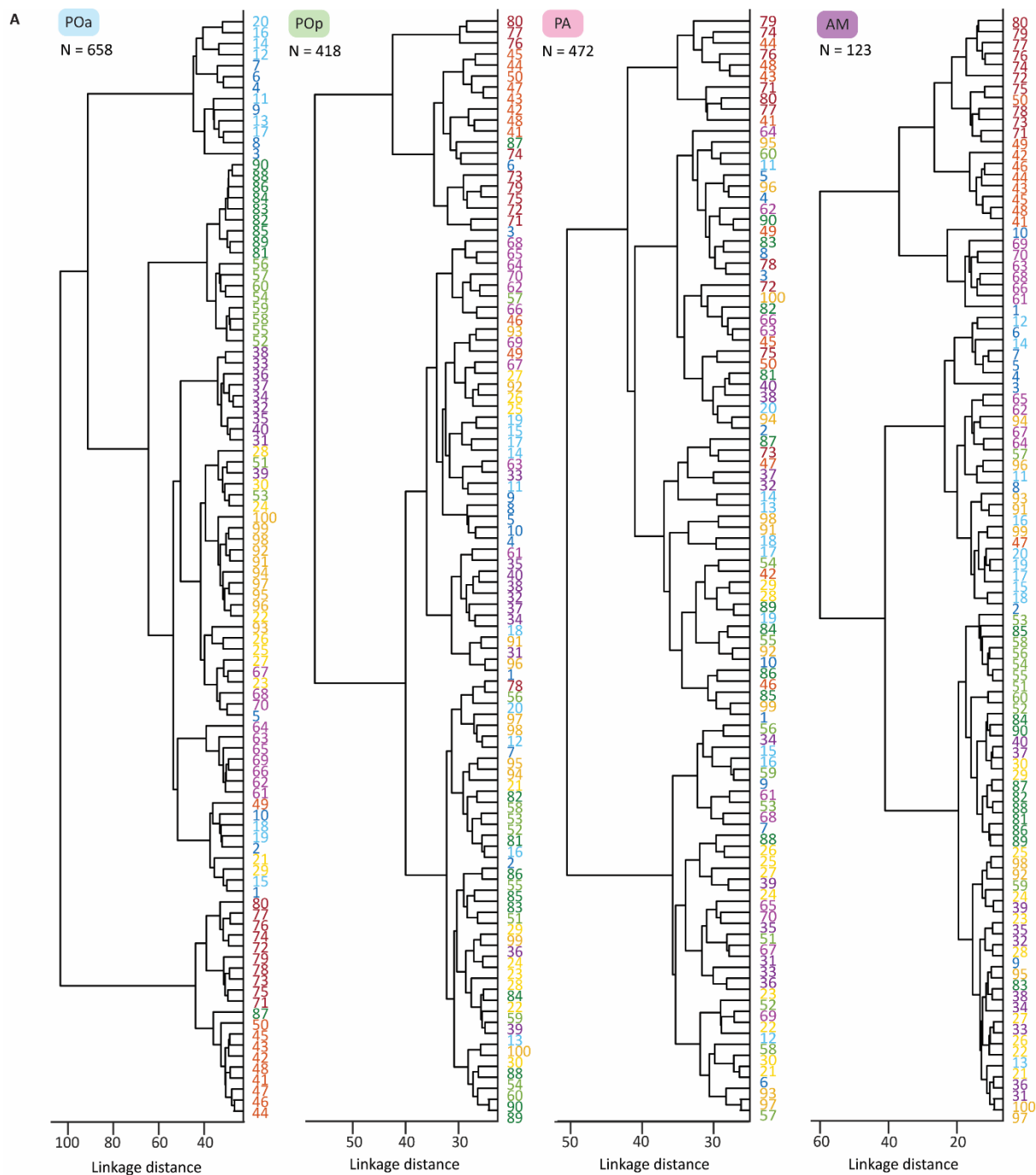
Supplementary Figure 12: Representation of images in non-face-selective neurons. (A) All stimuli were clustered based on Z-score normalized spiking responses averaged across monkeys. Dissimilarity matrices were created with pairwise Euclidean distances between responses for the stimuli. Using Ward's method, hierarchical clustering was performed on these matrices. The numbers of non-face-selective neurons per face patch are indicated in the top left corners. Numbers of the stimuli are color-coded according to their categories (B) Stimuli and their corresponding numbers from the clusters. – Related to Figure 6.

Supplemental Tables

Supplementary Table 1: Neural populations and their properties in face patches POa, POp, PA and AM

Proportion of neurons with significant one-way anova between categories

	POa FS	POa VD	POp RH FS	POp RH VD	POp LH FS	POp LH VD	PA FS	PA VD	AM FS	AM VD
M13	88%	54%	75%	43%						
M18	94%	73%	84%	64%			82%	34%		
M57	93%	83%	73%	52%	67%	39%	60%	22%	100%	88%

Total number of visually responsive neurons

	POa	POp RH	POp LH	PA	AM
M13	273	109			
M18	402	219		321	
M57	267	186	202	244	218

Number of face-selective neurons

	POa	POp RH	POp LH	PA	AM
M13	88 (32%)	48 (44%)			
M18	120 (30%)	100 (46%)		78 (24%)	
M57	75 (28%)	89 (48%)	61 (30%)	15 (6%)	95 (44%)

Number of neurons with FSI > 0.33

	POa	POp RH	POp LH	PA	AM
M13	140 (51%)	76 (70%)			
M18	163 (41%)	148 (68%)		120 (37%)	
M57	113 (42%)	146 (78%)	153 (76%)	49 (20%)	164 (75%)

Number of neurons with FSI < -0.33

	POa	POp RH	POp LH	PA	AM
M13	56 (21%)	19 (17%)			
M18	109 (27%)	24 (11%)		12 (4%)	
M57	94 (34%)	27 (15%)	29 (14%)	81 (33%)	18 (8%)

Number of neurons with BSI > 0.33

	POa	POp RH	POp LH	PA	AM
M13	55 (20%)	29 (27%)			
M18	82 (20%)	53 (24%)		9 (3%)	
M57	114 (43%)	30 (16%)	37 (18%)	16 (7%)	64 (29%)

FS denotes the face-selective neural population, and VD denotes the whole population of visually responsive neurons, including the face-selective neurons. Percentages next to the number of face-selective neurons, and next to the number of neurons with FSI > 0.33, FSI < -0.33 and BSI > 0.33, are the percentages of neurons relative to the whole visually responsive neural population of that patch in that monkey. LH and RH indicate the left and right hemisphere.

Supplementary Table 2: Receptive field properties in face patches POa, POp, PA and AM

	POa M13	POa M18	POa M57	POp M13	POp M18	POp M57 LH	POp M57 RH	PA M18	PA M57	AM M57
Number of FS neurons	82	97	63	32	85	44	71	68	9	81
Number of non-FS neurons	218	275	158	78	172	174	146	215	235	89
Median max. net spike rate of FS neurons (spks/s)	13	20	12	8	12	18	21	27	21	15
1st and 3rd quartile of max. net spike rate of FS neurons (spks/s)	8-19	8-30	8-17	6-12	6-16	13-22	15-28	10-33	14-32	10-21
Median max. net spike rate of non-FS neurons (spks/s)	8	9	11	5	7	12	13	21	16	9
1st and 3rd quartile of max. net spike rate of non-FS neurons (spks/s)	5-11	6-15	7-15	3-9	5-9	9-17	9-18	14-29	11-21	6-12
% FS neurons preferring the fovea	33	61	27	22	38	0	10	9	11	20
% non-FS neurons preferring the fovea	10	24	10	9	13	3	2	2	4	15
Median RF size of all FS neurons	9.3°	7.3°	8.9°	6.4°	9.0°	8.7°	9.9°	9.9°	9.5°	9.1°
Median RF size of SU FS neurons	8.7°	7.8°	8.5°	8.2°	9.0°	8.5°	9.1°	11.8°	/	8.6°
Median RF size of MU FS neurons	9.8°	7.1°	9.0°	6.1°	9.1°	8.6°	10.2°	9.7°	9.5°	9.1°
Median RF size of all non-FS neurons	7.3°	7.1°	8.4°	6.3°	6.6°	5.8°	6.8°	9.4°	7.2°	6.3°
Median RF size of SU non-FS neurons	7.0°	6.8°	8.2°	6.3°	6.3°	5.7°	7.2°	9.2°	5.7°	5.3°
Median RF size of MU non-FS neurons	7.6°	7.5°	8.7°	6.4°	6.9°	5.9°	6.6°	9.6°	7.3°	6.4°
% underestimated FS neurons	82	60	78	84	82	68	65	99	89	85
% underestimated non-FS neurons	92	87	94	92	90	91	74	99	91	80

FS denotes face-selective neurons, and non-FS are the non-face-selective visually responsive neurons. LH and RH indicate the left and right hemisphere. SU and MU indicate single- and multi-units.