nature neuroscience

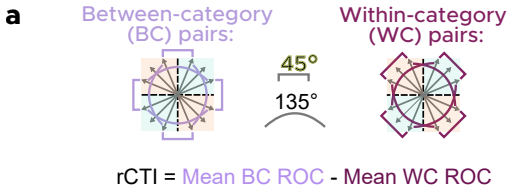
Supplementary information

https://doi.org/10.1038/s41593-024-01744-x

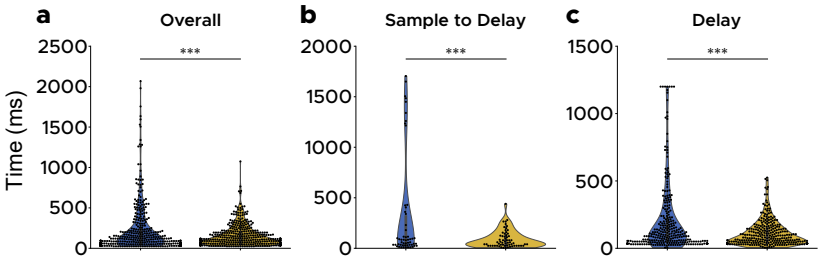
Primate superior colliculus is causally engaged in abstract higher-order cognition

In the format provided by the authors and unedited

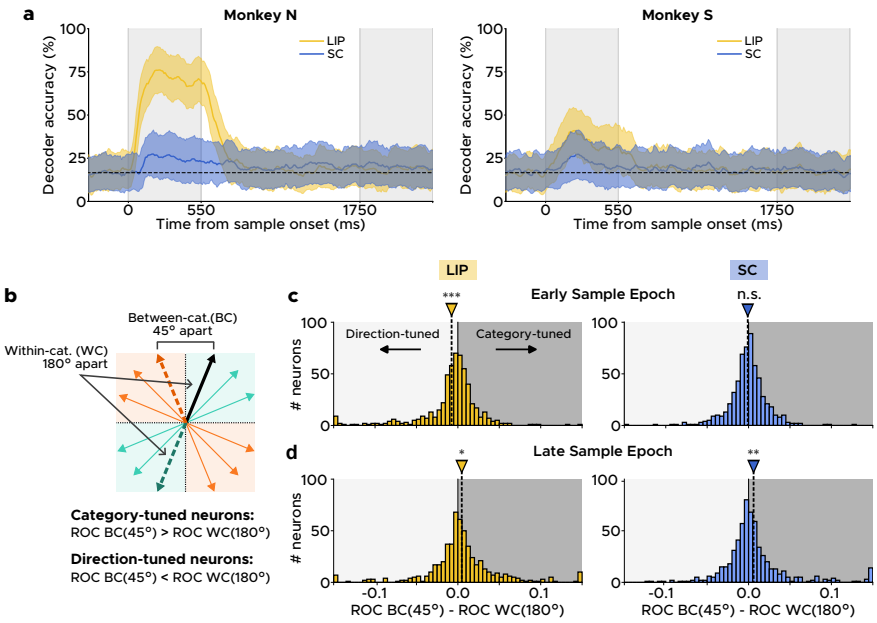
Supplementary figures and tables



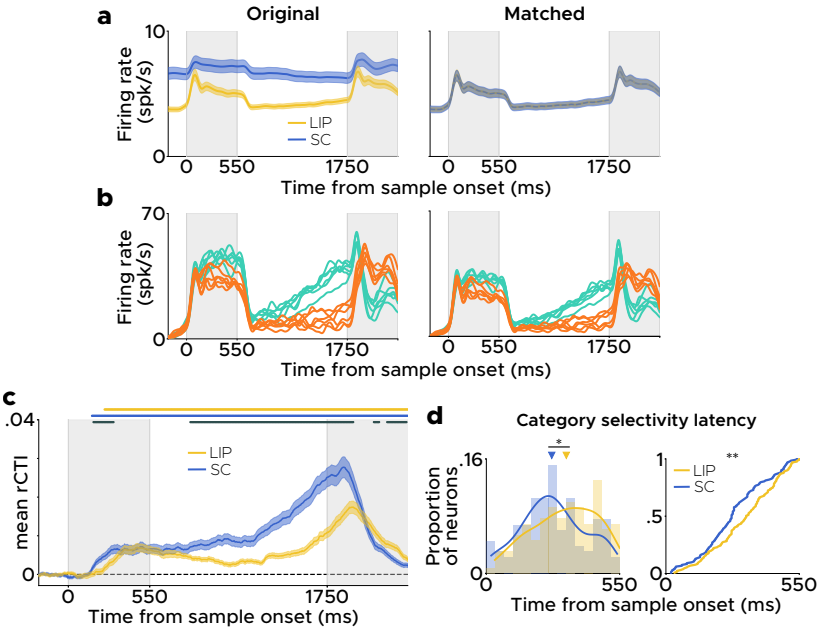
Supplementary Fig. 1: rCTI method and shuffling procedure. a, Schematic of the rCTI analysis used to quantify strength of category tuning in each neuron. rCTI compared ROC values between pairs of sample directions that are in the same category (Within-Category; WC) vs different categories (Between-Category; BC). WC and BC groups each consisted of eight sample directions (four pairs spaced 45 degrees apart and four pairs spaced 135 degrees apart.



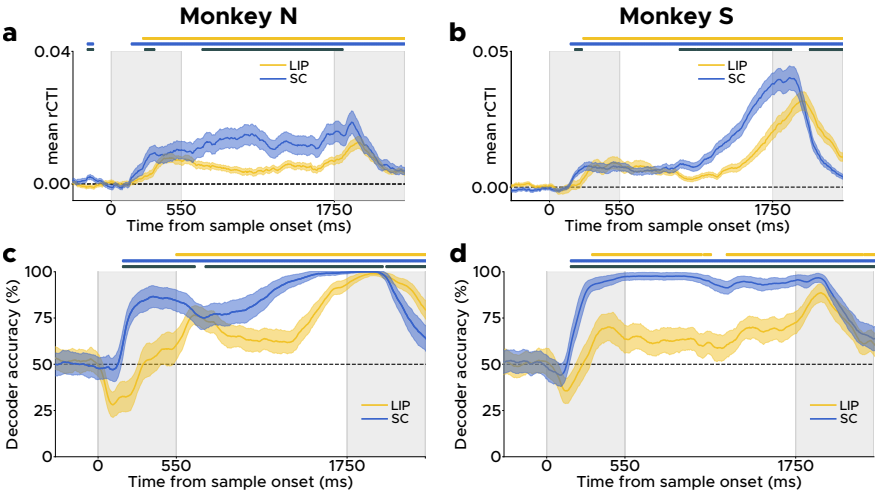
Supplementary Fig. 2: Duration of persistent category encoding. For each neuron in LIP (yellow) and SC (blue), we computed the number of consecutive time points in which rCTI values were significantly greater than zero (indicating category selectivity) during different periods of the DMC task. **a,** "Overall" time period includes the entire sample, delay, and first test epochs. There was a significantly greater mean duration in SC than LIP (SC: mean = 240 ± 321 ms; n = 360 neurons; LIP: mean = 156 ± 138 ms; n = 390 neurons, P < .001, two-tailed permutation test). **b,** "Sample to Delay" period includes neurons that were selective during the late Sample period and assesses how long those neurons continue to remain selective during the Delay. Mean duration of persistent category selectivity was significantly higher in SC than LIP (SC: mean = 335 ± 522 ms; n = 51 neurons; LIP: mean = 90 ± 86 ms; n = 60 neurons, P < .001, two-tailed permutation test). **c,** Mean duration of category selectivity during the delay period was significantly longer in SC compared to LIP neurons (SC: mean = 220 ± 274 ms; n = 261 neurons; LIP: mean = 114 ± 96 ms; n = 278 neurons, P < .001, two-tailed permutation test). (*** P < .001)



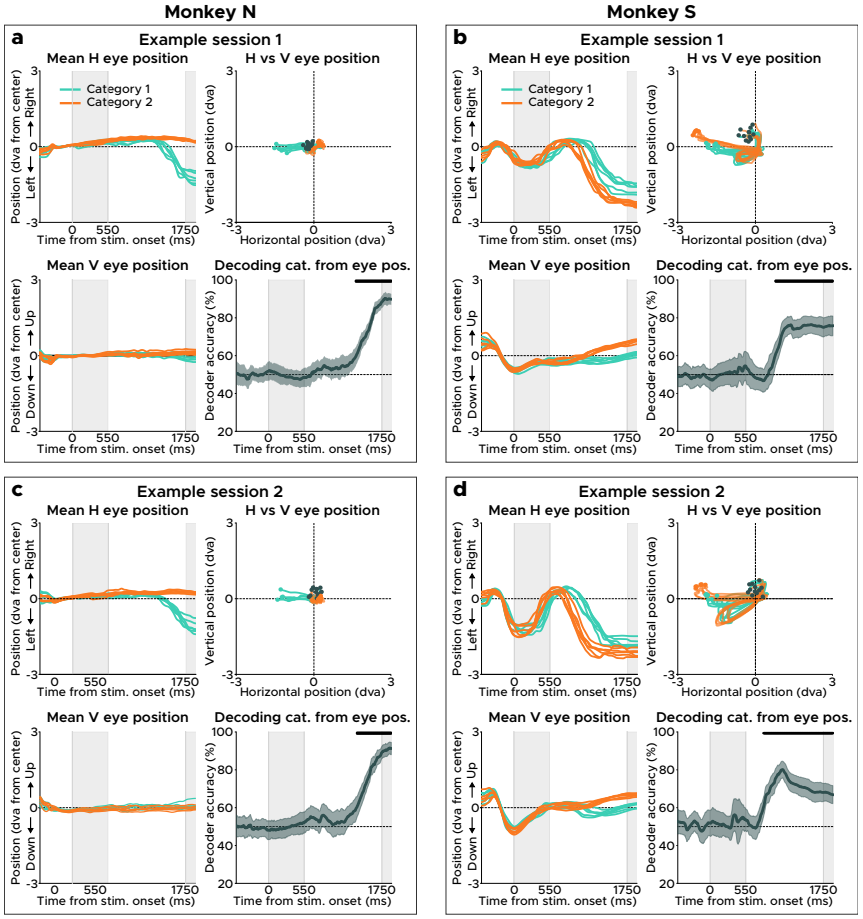
Supplementary Fig. 3: Direction encoding in LIP and SC. a, Time course of direction classifier accuracy across LIP and SC neuronal populations. Lines and shading indicate mean ± s.d. **b,** Schematic of the procedure for quantifying the strength of category and direction tuning in individual neurons. We used ROC analysis to compare firing rates of each of the eight near-boundary sample directions and two comparison directions: one that is 45° away and in the opposite category (BC(45°)) and another that is 180° away and in the same category (WC(180°)). Category-tuned neurons will have distinct firing rates (and therefore higher ROC values) for the BC(45°) directions and similar firing rates for the WC(180°) directions, while direction-tuned neurons will have low ROC values for the BC(45°) directions and high ROC values for the WC(180°) directions. We computed the mean ROC BC(45°) - ROC WC(180°) across the eight sample directions for each neuron and characterized the distributions of values across the neural populations. Negative ROC BC(45°) - ROC WC(180°) values are indicative of direction tuning, while positive ROC BC(45°) - ROC WC(180°) values are indicative of category tuning. **c,** Distribution of BC-WC values across neurons during the early sample period (0-250 ms from sample stimulus onset). Left: In LIP, the mean BC-WC was significantly < 0 (mean = -.008, s.d. = .039, one-sample t-test, $t(554) = -4.809$, two-tailed $P < .001$), indicating predominance of direction tuning in the LIP population. Right: In SC, the mean BC-WC was not significantly different from 0 (mean = -.001, s.d. = .025, one-sample t-test, $t(603) = -1.139$, two-tailed $P = .255$). **d,** Distribution of BC-WC values across neurons during a later task epoch (400-750 ms from sample stimulus onset). In both LIP and SC, the mean BC-WC was significantly > 0 (LIP: mean = .005, s.d. = .048, one-sample t-test, $t(554) = 2.440$, two-tailed $P = .015$; SC: mean = .008, s.d. = .047, one-sample t-test, $t(603) = 4.072$, two-tailed $P < .001$), indicating predominance of category tuning. (* $P < .05$), ** $P < .01$, *** $P < .001$).



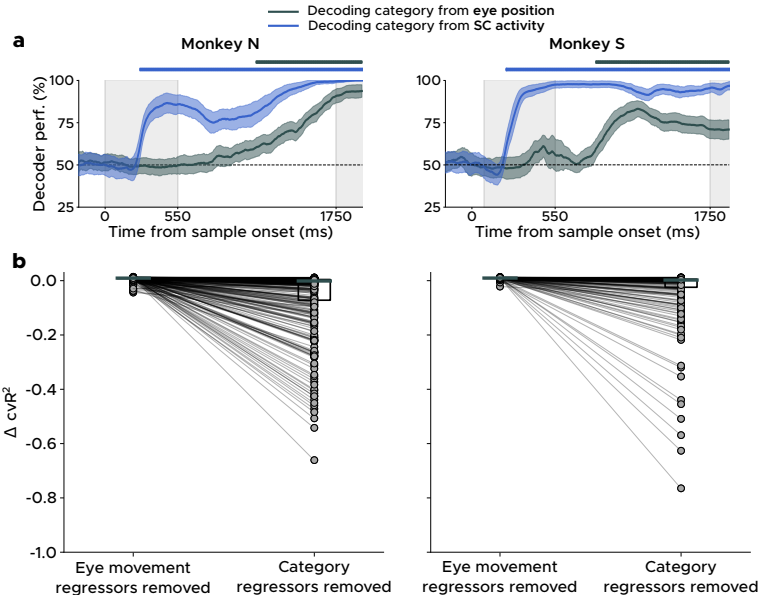
Supplementary Fig. 4: Category tuning in firing rate-matched LIP and SC neurons a, Mean firing rates across neurons in LIP and SC before (left) and after (right) firing rate-matching. Error shading indicates s.e.m. across neurons. **b,** PSTH of an example SC neuron before (left) and after (right) firing rate-matching. **c,** Time course of mean rCTI across firing rate-matched LIP and SC neurons. Shading indicates s.e.m. colored bars above the panel indicate time points at which values significantly exceed chance in each brain area, and black bars above the panel indicate time points at which there is a significant difference between brain areas ($P < .050$, two-tailed permutation tests). **d,** Latency of category selectivity in rate-matched neurons that are category-tuned during the Sample epoch (0-550 ms from Sample onset) (LIP: $n = 131$ neurons, SC: $n = 133$ neurons). Left: Distribution of category selectivity latency. Triangular markers indicate median latency (LIP: 330 ± 105 ms, SC: 270 ± 90; $P = .016$, two-tailed permutation test). Right: Empirical cumulative distribution functions of latency values in LIP and SC neurons (two-sample Kolmogorov-Smirnov test, $D = .200$, $P = .010$).



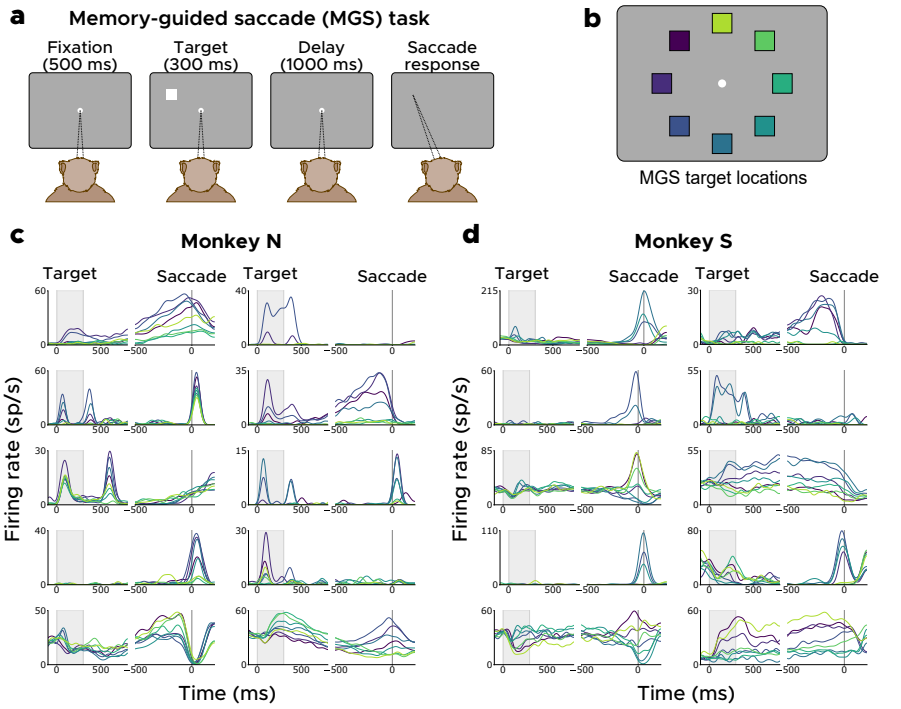
Supplementary Fig. 5: rCTI and category classifier accuracy in LIP and SC by monkey. a, Mean time course of rCTI across LIP and SC neurons in Monkey N. Lines and shading indicate mean ± s.d. rCTI. **b,** same as *a* but for Monkey S. **c,** Time course of cross-quadrant category decoding accuracy in LIP and SC for Monkey N. Lines and shading indicate mean ± s.d. decoding accuracy. **d,** same as *c* but for Monkey S. In all panels, yellow (blue) bars above plot indicate time points at which LIP (SC) values are significantly above chance, and black bars indicate time points at which there is a significant difference between LIP and SC values when either area or both areas are significantly above chance (two-tailed permutation test, all $P < .050$).



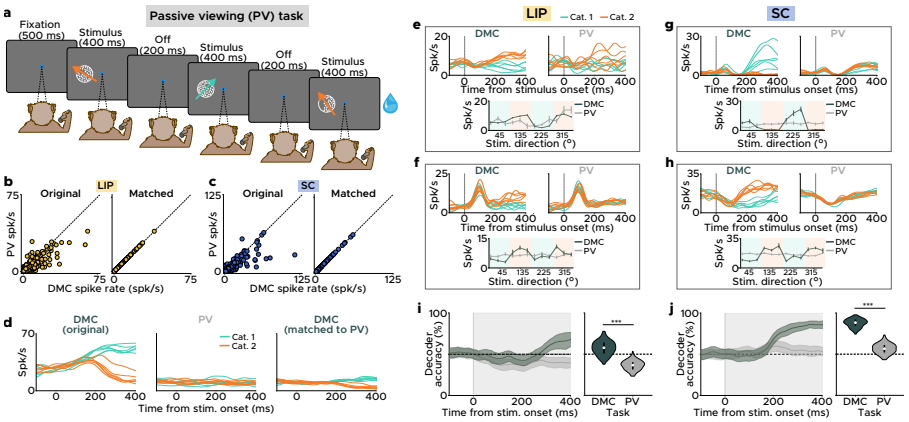
Supplementary Fig. 6: Monkeys' eye movements reflect working memory contents during delay period of DMC task. a, Top left: Mean horizontal eye position across trial time for each sample motion direction during an example session. Bottom left: Mean vertical eye position across trial time. Top right: Mean horizontal vs vertical eye position. Black circles indicate mean eye position at the beginning of the trial, and colored circles indicate the mean eye position at the end of the delay period. Bottom right: Accuracy of cross-quadrant category classifier trained on eye position. Black symbols above panel indicate time points at which the category classifier performs significantly above chance (P <0.05, two-tailed permutation test). Shading indicates s.d. **b,** Same as *a* but for Monkey S. **c, d** Same as *a* and *b* but for another example session.



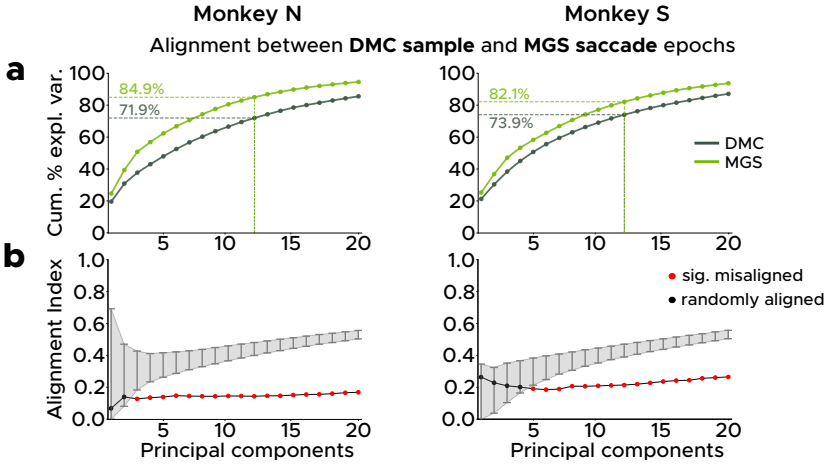
Supplementary Fig. 7: Comparison of the contribution of stimulus category and eye movements to single-neuron activity. a, Time course performance of category classifiers trained on SC neural data (blue) or on horizontal and vertical eye gaze trajectories across all SC recording sessions (grey) (Monkey N: n = 26 sessions, Monkey S: n = 12 sessions. Bars above panels indicate time points at which classifier accuracy performed significantly above chance (P $<$0.05, two-tailed permutation test). **b,** Change in cross-validated R^2 values from full linear encoding models (which include both eye movements and category regressors) to reduced linear models with either eye movement-related or category regressors removed.



Supplementary Fig. 8: Responses of SC neurons during the memory-guided saccade (MGS) task. a, Schematic of the MGS task. **b,** Color-coding scheme used for plotting PSTHs of MGS-task neural activity in panel *c*. **c,** Example PSTHs of SC neurons during the MGS task in Monkey N. Each trace corresponds to one of the eight stimulus positions illustrated in *b*. **d,** same as *c* but for Monkey S.



Supplementary Fig. 9: Passive viewing task. a, Trial structure of the passive viewing (PV) paradigm. Monkeys view a series of 3-5 motion stimuli presented for 400 ms each and separated by a 200-ms delay. Monkeys received a visual cue (a blue fixation circle instead of a white fixation circle as for the DMC task) to indicate the start of a PV trial. **b,** Comparison of mean firing rates of LIP neurons during the DMC and PV tasks (from 50:400 ms after stimulus onset) before (left) and after (right) matching firing rates between the two tasks. **c,** Same as *b* but for SC neurons. **d,** PSTH of an example SC neuron during the DMC task (left), PV task (middle), and PV-matched DMC task (right). **e,** Example LIP neuron recorded in Monkey N. Top panels show the peri-stimulus time histograms during the DMC task (left) and PV task (right). Dotted grey lines indicate stimulus onset time. Bottom panel shows mean firing rate (from 200-400 ms after stimulus onset) for each stimulus direction during the DMC (dark grey) and PV (light grey) tasks. Background color indicates stimulus category. Error bars indicate s.e.m. across trials. **f,** Same as *e* but for Monkey S. **g,** Same as *e* but for SC. **h,** Same as *g* but for Monkey S. **i,** Left: Time course of mean accuracy of cross-quadrant stimulus category classifiers trained on DMC (dark grey) or PV (light grey) data for all neurons in LIP. Shading indicates s.d. across bootstraps. Right: Accuracy of category classifiers trained on whole-epoch data (from 200 to 400 ms after stimulus onset). The mean performance of the DMC classifier is significantly higher than the performance of the PV classifier (DMC: mean = 58.25%, s.d. = 7.65%; PV: mean = 36.62%, s.d. = 6.05%, $P < .001$, two-tailed permutation test. **j,** Same as *i* but for SC. The mean performance of the DMC classifier is significantly higher than the performance of the PV classifier (DMC: mean = 87.78%, s.d. = 5.13%; PV: mean = 57.51%, s.d. = 6.32%, $P < .001$, two-tailed permutation test.



Supplementary Fig. 10: Additional details for for subspace alignment analysis. a, Cumulative % explained variance (EV) for the top 25 principal components for the DMC sample epoch data (dark gray) and MGS saccade epoch data (green) for Monkey N (left) and Monkey S (right). Text indicates the % EV for the 10 principal components included in the alignment analysis shown in Fig. 3. **b,** Alignment indices (black trace) between DMC sample and MGS saccade data as a function of the number of PCs included in the analysis for Monkey N (left) and Monkey S (right). Grey shaded region indicates the distribution of null alignment indices (95% CI). Red markers indicate alignment indices that are significantly lower than chance, and black markers indicate alignment indices that not significantly different from the null distribution.

Table 1: SC inactivation session information

Monkey	Exp	Treatment	Concentr. (µg/µL)	Injection vol. (µL)	# DMC trials (control)	# DMC trials (treatment)
N	1	Saline	8	0.5	288	292
N	2	Muscimol	5	0.33	308	222
N	3	Muscimol	5	0.33	275	353
N	4	Muscimol	5	0.33	251	510
N	5	Muscimol	5	0.25	331	456
N	6	Muscimol	5	0.25	294	385
N	7	Muscimol	5	0.25	359	218
N	8	Saline	8	0.25	273	369
S	1	Saline	8	0.25	285	427
S	2	Muscimol	5	0.25	302	278
S	3	Muscimol	5	0.25	403	104
S	4	Muscimol	5	0.25	217	138
S	5	Saline	8	0.25	258	285
S	6	Saline	8	0.25	281	547
S	7	Muscimol	5	0.25	258	164
S	8	Muscimol	5	0.25	282	182
S	9	Saline	8	0.25	305	312
S	10	Muscimol	5	0.25	290	240

Details of injection experiments in two monkeys. Each row contains an individual experimental session, and each column contains the details of that session. The column descriptions are as follows: "Monkey:" indicates which monkey the experiment was performed with; "Exp:" session number by animal; "Treatment:" indicates whether the injection was saline or muscimol; "Concentr.:" concentration of muscimol or saline (in µg/µL); "Injection vol.:" total injection volume (in µL); "N DMC trials (control):" total number of completed trials (correct and incorrect) for the DMC task during the control (pre-treatment) block; "N DMC trials (treatment):" total number of completed trials (correct and incorrect) for the DMC task during the treatment block.

Table 2: MGS peak saccade velocity (PSV) during SC inactivation experiments

		Contralateral PSV (°/s)			Ipsilateral PSV (°/s)		
Monkey	Exp	Ctrl ($\mu \pm \sigma$)	Inject ($\mu \pm \sigma$)	P-value	Ctrl ($\mu \pm \sigma$)	Inject ($\mu \pm \sigma$)	P-value
N	1†	455 ± 111	475 ± 103	.441	328 ± 78	319 ± 69	.591
N	2	407 ± 98	253 ± 48	$<.001^{*}$	300 ± 48	353 ± 48	$<.001^{\circledast}$
N	3	396 ± 68	252 ± 39	$<.001^{*}$	287 ± 50	343 ± 45	$<.001^{\circledast}$
N	4	464 ± 112	260 ± 53	$<.001^{*}$	274 ± 51	318 ± 50	$<.001^{\circledast}$
N	5	452 ± 95	279 ± 53	$<.001^{*}$	286 ± 56	325 ± 67	$<.001^{\circledast}$
N	6	458 ± 88	279 ± 53	$<.001^{*}$	280 ± 50	313 ± 61	$.001^{\circledast}$
N	7	430 ± 65	293 ± 60	$<.001^{*}$	255 ± 59	328 ± 60	$<.001^{\circledast}$
N	8†	446 ± 86	436 ± 98	.609	266 ± 63	276 ± 59	.415
S	1†	294 ± 49	311 ± 69	.207	307 ± 62	317 ± 86	.524
S	2	284 ± 118	208 ± 42	$<.001^{*}$	469 ± 61	634 ± 126	$<.001^{\circledast}$
S	3	440 ± 72	206 ± 114	$<.001^{*}$	457 ± 72	517 ± 67	$<.001^{\circledast}$
S	4	473 ± 67	244 ± 134	$<.001^{*}$	482 ± 70	565 ± 93	$<.001^{\circledast}$
S	5†	457 ± 54	480 ± 37	$.013^{\circledast}$	440 ± 81	430 ± 52	.440
S	6†	452 ± 48	441 ± 53	.260	489 ± 64	476 ± 60	.321
S	7	455 ± 70	242 ± 129	$<.001^{*}$	521 ± 99	736 ± 198	$<.001^{\circledast}$
S	8	487 ± 73	188 ± 72	$<.001^{*}$	502 ± 82	591 ± 107	$<.001^{\circledast}$
S	9†	480 ± 54	476 ± 67	.705	442 ± 81	467 ± 74	.115
S	10	476 ± 68	201 ± 55	$<.001^{*}$	460 ± 78	589 ± 117	$<.001^{\circledast}$

† Saline session

* Treatment PSV < Control PSV (all $P < .050$)

⊛ Treatment PSV > Control PSV (all $P < .050$)

Details of the peak saccade parameters during the MGS task for the SC inactivation experiments. Each row contains an individual experimental session, and each column contains the details of that session. The column descriptions are as follows: "Monkey:" indicates which monkey the experiment was performed with; "Exp:" session number (saline injection sessions are indicated with a dagger superscript); "Contralateral PSV Ctrl:" PSV (°/s) for correct trials in control blocks in which the monkey made a saccade towards one of the three targets that are in the hemifield contralateral to the studied hemisphere; "Contralateral PSV Inject:" same as "Contralateral PSV Ctrl" but for the treatment block; "P-value:" two-tailed p-value from a non-parametric permutation test (5000 permutations) to assess whether there was a significant difference in mean PSV between control and treatment blocks for the contralateral saccade trials; "Ipsilateral PSV Ctrl:" PSV (°/s) for correct trials in control blocks in which the monkey made a saccade towards one of the three targets that are in the hemifield ipsilateral to the studied hemisphere; "Ipsilateral PSV Inject': same as "Ipsilateral PSV Ctrl" but for the treatment block; "P-value:" two-tailed p-value from a non-parametric permutation test (5000 permutations) to assess whether there was a significant difference in mean PSV between control and treatment blocks for the ipsilateral saccade trials.

Table 3: DMC performance during SC inactivation experiments

Monkey	Exp	Control % correct [95% CI]	Treatment % correct [95% CI]	Fisher-exact odds ratio	Fisher-exact *P*-value
N	1†	86.8 [82.4–90.2]	85.3 [80.8–88.9]	1.136	.633
N	2	81.8 [77.1–85.7]	53.2 [46.6–59.6]	3.966	<.001*
N	3	83.6 [78.8–87.5]	51.0 [45.8–56.2]	4.912	<.001*
N	4	89.6 [85.3–92.8]	56.1 [51.7–60.3]	6.778	<.001*
N	5	80.1 [75.4–84.0]	67.8 [63.3–71.9]	1.910	<.001*
N	6	88.1 [83.9–91.3]	73.2 [68.6–77.4]	2.703	<.001*
N	7	90.0 [86.4–92.7]	45.4 [38.9–52.0]	10.785	<.001*
N	8†	92.7 [89.0–95.2]	89.4 [85.9–92.2]	1.495	.170
S	1†	78.9 [73.8–83.3]	82.4 [78.5–85.8]	0.799	.283
S	2	88.4 [84.3–91.5]	64.0 [58.2–69.4]	4.286	<.001*
S	3	87.8 [84.3–90.7]	70.2 [60.8–78.1]	3.068	<.001*
S	4	92.6 [88.4–95.4]	56.5 [48.2–64.5]	9.663	<.001*
S	5†	86.0 [81.3–89.7]	84.6 [79.9–88.3]	1.126	.716
S	6†	94.0 [90.5–96.2]	93.1 [90.6–94.9]	1.159	.662
S	7	95.7 [92.5–97.6]	75.0 [67.9–81.0]	7.485	<.001*
S	8	98.6 [96.4–99.4]	75.8 [69.1–81.5]	22.159	<.001*
S	9†	92.5 [88.9–94.9]	94.9 [91.8–96.8]	0.663	.248
S	10	97.2 [94.7–98.6]	73.3 [67.4–78.5]	12.818	<.001*

† Saline session

* Treatment perf. < Control perf. (all $P < .050$)

Details of performance on the DMC task for the SC inactivation experiments. Each row contains an individual experimental session, and each column contains the details of that session. The column descriptions are as follows: "Monkey:" indicates which monkey the experiment was performed with; "Exp:" session number by animal (saline injection sessions are indicated with a dagger superscript); "Control perf.:" Mean ± SD accuracy (in %) for DMC trials during the control block; "Inact. perf.:" Mean ± SD accuracy (in %) for DMC trials during the treatment block; "Fisher-exact odds ratio:" odds ratio for Fisher-exact test to compare performance on control vs. treatment blocks.; "Fisher-exact P-value:" p-value for Fisher-exact test to compare performance on control vs. treatment blocks. (* P < .001)