Nucleus Basalis Stimulation Enhances Working Memory and Stabilizes Attractor Networks in Prefrontal Cortex

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ABSTRACT

The action of acetylcholine in the neocortex is critical for executive function. Cholinergic drugs can improve cognitive function in patient populations and normal adults. How endogenous cholinergic action affects neuronal activity in higher cortical areas is unknown. Here we tested the effects of electrical stimulation of the cortical source of acetylcholine in primates, the Nucleus Basalis of Meynert, on neural activity while monkeys performed working memory tasks. Stimulation delivered in an intermittent fashion improved behavioral performance and increased prefrontal activity during the delay period of the task, but did not strengthen the phasic responses of visual stimuli. Tuning of neuronal responses broadened, which rendered the bump of activity in an attractor network more stable, and filtered distracting stimuli more effectively. These results show that effects of acetylcholine on neural activity and selectivity in the prefrontal cortex contrast those of dopamine and stabilize aggregate neural ensembles based on neuromodulatory tone.

INTRODUCTION

The forebrain cholinergic system tightly regulates higher cognitive function (Sarter and Bruno, 1997; Bartus, 2000). Losses in cognitive function with aging and Alzheimer's disease (AD) occur in parallel with degeneration of the brain's cholinergic systems, and cholinergic deficits correlate well with the degree of cognitive decline (Terry and Buccafusco, 2003). Cholinesterase inhibitors, which prolong the neurotransmitter's ability to stimulate post-synaptic receptors and amplify the natural pattern of acetylcholine release, are frontline medications for treating Alzheimer's disease (Sabbagh and Cummings, 2011). Improvement in cognitive functions can also be achieved by stimulation of the Nucleus Basalis (NB) of Meynert, the sole source of neocortical acetylcholine in primates and humans (Mesulam et al., 1983; Hendry et al., 1987). Recent studies in primates suggest that intermittent NB stimulation is equally or more effective in improving cognitive performance task as high doses of acetylcholinesterase inhibitors, with further effects that aggregate over time (Blake et al., 2017; Liu et al., 2017, 2018).

How cholinergic activation modulates neuronal activity to improve working memory is less understood. Stimulation of cholinergic forebrain neurons has been studied in the context of neuroplasticity (Bakin and Weinberger, 1996; Kilgard and Merzenich, 1998). More recently, optogenetic phasic stimulation of cholinergic neurons has been shown to improve visual perceptual discrimination (Pinto et al., 2013). Indirect evidence of neural effects with implications for working memory has been obtained from studies relying on systemic administration or micro-iontophoresis of muscarinic and nicotinic cholinergic antagonists, which have been shown to decrease firing rate specifically during the delay periods of working memory

tasks in the prefrontal cortex of nonhuman primates, while nicotinic agonists enhance it (Zhou et al., 2011; Yang et al., 2013).

We were therefore motivated to examine the effects of intermittent NB stimulation on neuronal activity during execution of a working memory task. We focused specifically on the prefrontal cortex, an area critical for working memory (Riley and Constantinidis, 2016), which receives innervation from a dedicated sub-region of the Nucleus Basalis (Gielow and Zaborszky, 2017). We implanted monkeys with NB stimulating electrodes and determined the effects of stimulation on behavioral performance and neural activity.

RESULTS

We recorded behavioral performance and neural activity from the dorsolateral prefrontal cortex in two monkeys implanted unilaterally with electrodes that targeted the Nucleus Basalis of Meynert (Fig. 1A). Electrode placement was guided by MR imaging and verified with CT scanning after implantation (see Methods). Electrode location was finally visualized with ChAT immunohistochemistry, post mortem. One monkey was implanted in the left, and the other in the right hemisphere. To obtain functional confirmation of the targeting, we collected LFP signals from the implanted electrode with the monkey at rest, with and without stimulation (Bjordahl et al., 1998). Continuous stimulation at 80 Hz produced LFP desynchronization (Fig. 1C and S1). Power in the 5-15 Hz range was significantly lower during stimulation than control (paired t-test, t_{17}=3.14, p=0.006 and t_{33}=2.5, p=0.02 for the two subjects, respectively).

Stimulation effects on behavioral performance

The monkeys performed a working memory task that required them to remember the location of either the first or second of two sequential stimuli, as instructed by the color of the fixation point – white or blue, respectively, and perform an eye movement towards the remembered location (Fig. 1D). Daily sessions without stimulation were interleaved with sessions during which intermittent electrical stimulation of the Nucleus Basalis was performed. Stimulation was applied during the inter-trial interval of the task for 15 s, at a frequency of 80 pulses per s (Fig. S2). Then the monkeys performed the task for 45 s (typically 4-5 completed trials), without stimulation. At the end of the trial that exceed the 45 s threshold, stimulation was applied anew and the cycle was repeated. This pattern of stimulation was elected based on recent results demonstrating the

intermittent stimulation improves working memory and attention performance (Blake et al., 2017; Liu et al., 2017, 2018).

Behavioral performance in our task generally improved with intermittent stimulation (Fig. 1E-H). Since stimulation was unilateral, we considered performance for two stimuli appearing at different locations with respect to the hemifield of the stimulus to be held in memory relative to the hemisphere of the implanted electrode. For monkey GR, stimulation improved performance for all conditions. A 3-way ANOVA on performance with factors stimulation (on or off), task (remember-first or remember-second) and location of stimuli (contralateral or ipsilateral stimulus to be remembered) revealed a significant main effect of stimulation ($F_{1,128}$=19.6, p=2.06x10^{-5}). The main effect of task was also significant for this animal ($F_{1,128}$=12.9, p=4.66x10^{-4}**)**. The effect of stimulus location as well as the three-way interaction term between stimulation, stimulus location, and task failed to reach significance. For monkey HE, this analysis revealed that stimulation improved performance specifically when the stimulus to be remembered was at a location contralateral to the site of the stimulation electrode (Fig. 1E, H). Stimulation was ineffective when the stimulus was ipsilateral to the stimulation (Fig. 1F, G). Performing the same 3-way ANOVA analysis revealed no net effect of stimulation, precisely because of this opposing effects in the two hemifields ($F_{1,204}$=0.27, p=0.6**)**, but now a significant three-way interaction between task, stimulation, and side of stimulus ($F_{1,128}$=6.04, p=0.015). Considering the contralateral conditions alone (Fig. 1E, H), the effect of stimulation was highly significant (3-way ANOVA with factors monkey, and stimulation: $F_{1,173}$ = 14.14, p= 0.0002 for remember-first task; $F_{1,173}$= 5.61 p=0.02 for remember-second task). The results of behavioral performance across all conditions demonstrated that stimulation improved

performance in the task, particularly for stimuli to be remembered appearing contralateral to the site of stimulation.

Effects on neural activity

We recorded from a total of 246 neurons (102 and 144 in the two monkeys, respectively) in areas 8 and 46 of the dorsolateral prefrontal cortex, as the monkeys performed the working memory task of Fig. 1D with and without Nucleus Basalis stimulation. Recording cylinders were implanted on the same side as the stimulation electrode. Blocks of 60 correct trials without stimulation were interleaved with blocks involving intermittent stimulation. Stimulation was always delivered in the inter-trial interval, as described above. Of those neurons, 112 (67 and 45 from the subjects, GR and HE respectively) responded to visual stimuli (evaluated with a paired t-test, at the $p<0.05$ significance level during the stimulus presentation or delay period) and had sufficient numbers of trials for comparisons between conditions. Most analyses that follow were based on these neurons; data from all neurons are shown in the supplementary material.

Nucleus Basalis stimulation had a predominantly excitatory effect (Fig. 2A). The distribution of firing rate differences computed in blocks of trials with or without 15 s of stimulation between them deviated significantly from a normal distribution (KS test for normalized rate differences, compared to normal distribution, $p=8.74\times10^{-6}$). For a total of 54 neurons, firing rate was significantly higher after stimulation (evaluated with a t-test at the $p<0.05$ level). An example is shown in Fig. 2B-E. However, stimulation also produced a significant decrease in firing rate in the fixation period for 16 neurons ($p<0.05$). To facilitate analysis of these opposing effects, we grouped neurons into those with a significant increase in

rate, and those without an increase (which included neurons with significant decreases, and no significant effect). We separately analyzed responses of neurons in these two groups.

For the neurons with an overall increase in activation, stimulation had no effect during the inter-trial interval (Fig. 3A, 2-way ANOVA with factors tasks and stimulation: main effect of stimulation F_1 =2.6, p=0.113). After the fixation point turned on, whose color signified the remember-first or remember-second rule, stimulation increased firing rate (Fig. 3A and Fig. S3, paired t-test, 2-way ANOVA with factors tasks and stimulation: main effect of stimulation F_1 =8.186, p=0.006). In blocks of stimulation trials, the effects were stable over the time course of ~1 min between cycles of repeated stimulation (see Fig. S2). The firing rate was elevated in the first trial following stimulation and no further increase was present in successive trials (Fig. 3H, red line). No systematic effects were present, either, in the sequential trials after an intertrial interval that did not contain stimulation, in blocks of trials when no stimulation was present (Fig. 3H, blue line).

The phasic response to the preferred stimulus itself (peak in the ~200 ms after stimulus) was largely unchanged between the control and stimulation conditions (Fig. 3A, 2-way ANOVA with factors tasks and stimulation: main effect of stimulation F_1 =0.397; p=0.53). The absence of an enhancement to the stimulus response was evident in both the remember-first and remember-second tasks (Fig. S4, S5), and for both the first and second presentation of a stimulus in the receptive field (Fig. 3A, and Fig. S3). On the other hand, the shift in firing rate baseline in trials with stimulation persisted during the delay periods after each of the stimuli and in the saccade period.

Although it did not improve responses for the best stimulus location, NB stimulation enhanced responses to stimuli at non-optimal locations, which resulted in an apparent broadening

of receptive fields during the cue presentation and delay period (Fig. 3B-E). Stimuli that appeared away from the peak of the response and elicited little or no response without stimulation generated a much stronger response with stimulation. Such examples in the remember-first task are the second stimulus in Fig. 3C-E and the first stimulus in Fig. S4F-J. The broadening of the receptive fields in the cue and delay periods was also evident in the remember-second task (see first stimulus in Fig. S5F-J). The population tuning curve based on the varying, second stimulus-location best illustrated the effect (Fig. 3I). In order to quantify differences in responsiveness to sub-optimal stimuli, we relied on a selectivity index (SI) defined as (Max-Min)/(Max+Min) where Max and Min represent the firing rate to the best and worst stimulus location for each neuron. The NB stimulation condition produced a significantly lower SI value (2-way ANOVA with factors tasks and stimulation: main effect of stimulation $F_{1,53} = 25.4$, $p = 5.7\text{x}10^{-6}$ for cue period, and $F_{1,53} = 24.2$, $p = 8.7\text{x}10^{-6}$ for delay period (Fig. S6). A time-resolved Receiver Operating Characteristic analysis revealed that the difference between best and worst stimulus responses declined with stimulation, for all task conditions (Fig. S7). Unlike the representation of stimulus location, selectivity for task was relatively unaffected by NB stimulation (Fig. S8-S9 and supplementary material).

The decrease in neuronal spatial selectivity we observed under stimulation can be conceptualized as broadening of the bump of activity in the population of prefrontal neurons, which is hypothesized to act as an attractor network during working memory (Wimmer et al., 2014; Inagaki et al., 2019). This model makes interesting predictions for behavioral performance under different combinations of remembered stimulus and distractor (see also Supplementary Material). Whereas a narrow bump in the control network may occasionally be interrupted by appearance of a distractor at a distant location (Fig. 4A), a wider bump under stimulation will

generally be more stable due to activation of a larger number of neurons, and therefore more resistant to the activation induced by a subsequent distractor (Fig. 4B). An exception to this pattern of behavioral enhancement under stimulation involves stimuli placed near the peak of the initial bump (Fig. 4C). Under such a scenario, it is more likely that the bumps of activity corresponding to the stimuli will "merge", resulting in more errors at the end of the delay period. We therefore reanalyzed the pattern of behavioral responses shown in Fig. 1E-H, based on the distance between the initial and second stimulus (Figure 4D-E). In the remember-first condition, stimulation improved performance in the conditions involving distant distractors (Figure 4D), however stimulation markedly *decreased* performance for stimuli appearing at adjacent locations (two-tailed t-test, t_{66}=2.83, p=0.006). Importantly, this pattern of responses was observed only for the remember-first condition. In the remember-second condition, stimulation improved performance for a second stimulus appearing at a close distance to the initial distractors (45° condition in Fig. 4E), as in this task it is beneficial to "pull" the initial bump of activity towards the second stimulus (Figure 4C). A network with a broader bump would also be expected to have lower variability in terms of behavioral output as more stable networks exhibit less drift of the peak from its initial location. This prediction was also validated in experimental results. The distribution of angular deviation from the mean endpoint of saccades in correct trials (Fig. 4F) was subtly but consistently lower under stimulation than in the control condition (Kuiper two-sample test, p=0.005), even after we had excluded the error trials, which exhibited the greater deviations from the mean.

NB stimulation in the remember-second task yielded another unexpected finding: responses in anticipation of a stimulus, even when no stimulus was presented at all (Fig. 3F-G). Our behavioral task involved a fixed duration of the fixation interval that the monkey could time.

A stimulus was presented after this interval, however in 20% of the trials no stimulus was presented and the trial continued with the presentation of the "second" stimulus at the time that was expected (see insets in Fig. 3F-G). We refer to that as the "null" condition. NB stimulation elicited elevated firing rate in the time interval that the first stimulus would have been expected in null trials (2-way ANOVA with factors tasks and stimulation: main effect of stimulation F_1=26.9, p=3.4x10^{-6}). Such an anticipatory signal was absent from the control trials, although presumably the monkey was anticipating a stimulus in these trials too. Appearance of such phantom bumps of activity in the absence of a real stimulus is also a consequence of a more stable attractor network.

Stimulation effects beyond increased firing rate

We finally examined effects of stimulation beyond the dominant pattern of increase in firing rate. Neurons that responded to stimuli but for which stimulation produced decreased activity were characterized by suppressed firing rate for both the remember-first (Fig. S10A,C) and remember-second tasks (Fig. S10B-D). Firing rate was reduced in the fixation period, but also in the stimulus presentation period and the delay period that followed it (Fig. S10A, C). Firing rate remained at low levels when the stimuli to be remembered were presented out of the receptive field (Fig. S10B, D).

Among neurons that did not respond significantly to visual stimuli a general increase in firing rate was observed during NB stimulation, similar to the effects of stimulation on task-responsive neurons. This was evident in both the remember-first and remember-second tasks, and throughout the duration of the trial (Fig. S11).

Although we emphasize firing rate differences that could account for the behavioral improvements in performance we observed under stimulation, alternative mechanisms of working memory have also been proposed, some identifying power in the gamma band of LFP as the critical variable predictive of maintenance (Constantinidis et al., 2018; Lundqvist et al., 2018). We therefore examined the LFPs recorded from the prefrontal cortex. Stimulation during task execution generally lower power in the alpha range and increased power in the beta-frequency band (Fig. S12).

DISCUSSION

Our study demonstrated that intermittent NB stimulation improves performance of monkeys in a working memory task that requires selective maintenance of a stimulus in memory, in agreement with recent studies that showed similar effects for other memory and attention tasks (Blake et al., 2017; Liu et al., 2017, 2018). We additionally show that the effect was associated with changes in the firing rate of neurons in the dorsolateral prefrontal cortex, most often increasing it. This increase was specific for task intervals, including the interval after the appearance of the fixation point, which signified the rule in our task and during the delay intervals over which a stimulus was needed to be maintained in memory. Stimulation also brought about changes in stimulus selectivity, suggestive of a broader peak of activation and more stable attractor network. Our results demonstrate the neural mechanisms through which NB stimulation affects neural activity and improves of cognitive performance.

Behavioral Effects of Stimulation

We have recently demonstrated that NB stimulation can improve cognitive performance in healthy adult monkeys, but only when administered in an intermittent fashion. Optimal stimulation parameters involve stimulation for 15-20 seconds per minute, and at a rate that delivers approximately a total of 1200 pulses of stimulation per minute (Liu et al., 2017). The current results expand the list of cognitive tasks that benefit from this protocol of stimulation. The behavioral effects of stimulation we report are also consistent with the known impairment of working memory caused by acetylcholine depletion in the prefrontal cortex (Croxson et al., 2011). Recent work established that the behavioral improvement induced by NB stimulation depends on acetylcholine release as cholinergic inhibitors abolish the performance benefits (Liu

et al., 2018). This is not to say that non-cholinergic projections do not play a role; it is well understood that GABAergic ascending projections are critical (Walker et al., 1989; Kim et al., 2015) and our protocol of stimulation is likely to activate them specifically, in contrast to systemic cholinergic drug administration.

Neural effects of NB Stimulation

The effects of NB stimulation we uncovered were generally consistent with the neural changes effected by systemic or microintophoretic administration of cholinergic agents in the prefrontal cortex of primates. Systemic administration of the muscarinic antagonist scopolamine generally depressed prefrontal firing rate during the baseline, had little effect on peak stimulus responses, and depressed delay period activity (Zhou et al., 2011), effects essentially opposite to those of stimulation we report here. Micro-iontophoresis of muscarinic and nicotinic-α7 inhibitors also depress prefrontal activity, particularly in the delay period of working memory tasks (Yang et al., 2013; Major et al., 2015), whereas cholinergic agonists increase activity in the prefrontal cortex (Yang et al., 2013; Sun et al., 2017). We should note that the effects of cholinergic agents in sensory areas are markedly different from those in the prefrontal cortex. Agonist administration in the primary visual cortex specifically enhances responses during stimulus presentation, and attended over unattended ones (Herrero et al., 2008).

Our results stand in contrast to the effects of dopamine agonists, which “sculpt” neuronal activity to improve spatial selectivity (Williams and Goldman-Rakic, 1995). We saw the opposite effect by NB stimulation. The apparent size of neuronal receptive fields expanded, and spatial selectivity decreased during stimulation. This effect is reminiscent of cholinergic

overstimulation with high doses of carbachol and M1R allosteric inhibitors administered iontophertically, which reduce prefrontal selectivity in the context of working memory tasks (Major et al., 2018; Vijayraghavan et al., 2018). Computational models (Compte et al., 2000; Wimmer et al., 2014) predict that activation of a larger population of neurons by a single stimulus resulting in a broader bump of activity render the network more resistant to distracting stimuli, although performance may be compromised in conditions involving distracting stimuli appearing in nearby locations. This was precisely the pattern of behavioral changes we observed (Fig. 4). We also observed prefrontal responses in anticipation of stimuli that did not appear, which is consistent with more stable attractors in which spurious activation may sometimes create "phantom" bumps. Neuronal responses in the Nucleus Basalis often signal novelty or surprise (Zhang et al., 2019), and in view of our results, such endogenous NB stimulation would have the effect of preferentially stabilizing activity elicited by unexpected stimuli.

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METHODS

Two male, rhesus monkeys (*Macaca mulatta*) weighing 7-10 kg were used in this study. The monkeys were trained to perform working memory tasks and baseline neurophysiological recordings were obtained from the prefrontal and posterior parietal cortex (Qi and Constantinidis, 2015; Qi et al., 2015). All experimental procedures followed guidelines by the U.S. Public Health Service Policy on Humane Care and Use of Laboratory Animals and the National Research Council's Guide for the Care and Use of Laboratory Animals and were reviewed and approved by the Wake Forest University Institutional Animal Care and Use Committee.

Surgery and neurophysiology. A 20-mm-diameter recording cylinder was implanted over the dlPFC (Fig. 1). A second cylinder was also implanted over the PPC of each monkey at the same time, but this was not used in the current experiment. Extracellular activity of single units was recorded from areas 8a and 46 of dlPFC. The anatomic location of electrode penetrations was determined on the basis of MR imaging. Recordings were obtained with arrays of two to four microelectrodes in the cylinder. These were epoxylite-coated tungsten electrodes with a 250 μm diameter and 1-4 MΩ impedance at 1 kHz (FHC, Bowdoin, ME). The electrical signal from each electrode was amplified, bandpass filtered between 500 Hz and 8 kHz, and recorded with a modular data acquisition system at 25-μs resolution (APM system; FHC, Bowdoin, ME). Waveforms that exceeded a user-defined threshold were sampled at 25 μs resolution, digitized, and stored for off-line analysis. LFP recordings were obtained from the same electrodes by

splitting the signal, filtering between 0.5 Hz and 100 Hz, and acquiring data at a 500 Hz sampling rate.

Deep Brain Electrode Implantation and Stimulation. Once the head-cap and recording cylinders had been implanted, a second surgery was performed to implant the stimulating electrode. Based on MR imaging, stereotaxic coordinates were obtained for targeted implantation. The animals were implanted unilaterally (one in the left, and one in the right hemisphere) at 8mm lateral, 16 mm anterior interaural, and 29 mm below the cortical surface in a vertical penetration. The lateral and anterior coordinates, and depth, were chosen to correspond to the center of the anterior portion of the Nucleus Basalis of Meynert, which would contain the highest density of projections to the prefrontal cortex (Mesulam et al., 1983; Gielow and Zaborszky, 2017). A small cylindrical titanium chamber (5-mm inner diameter and 7-mm outer) was mounted on the cranium and chamber was encased in bone cement, in continuity with the existing head-cap. A 26 ga. sharp hypodermic guide tube was lowered and the tip advanced 5 mm below the dura mater. The stimulation electrode was inserted into the guide tube, and a stylus was used to push it to the appropriate depth. The guide tube was then raised while the stylus depth maintained. The chamber was evacuated of fluid, flushed with ceftriaxone, and thereafter fluid evacuated a second time. Silicone was poured into the chamber to seal the fenestrations in the skull and the inside of the chamber. The rear end of the electrode could be continuously visualized to confirm proper depth. The electrode was fixed in depth with a drop of cyanoacrylate. One week after the surgery, the animals returned to behavioral studies. Placement of the electrode was verified with CT scanning, after implantation, in one animal.

The stimulation pulses were created by an isolated pulse stimulator (Model 2100, A-M Systems, Sequim WA), which was controlled by custom programed software, written on the

MATLAB platform. Impedances of electrodes were checked monthly during experiments. Intermittent stimulation was applied for 15 seconds at 80 pulses per second, followed by approximately 45 seconds with no stimulation. Stimulation was applied in the inter-trial interval, after a trial had completed, and a new trial began after stimulation had elapsed.

Stimulation electrodes were custom manufactured in our laboratory based on published specifications (McCairn and Turner, 2009). Conductors were 50 μm Pt/Ir, Teflon-insulated wire (A-M systems, Seattle, WA) embedded within a 30 ga. hypodermic tube, which was encased in a 28 ga. polyimide sheath. The wire extended from the end of the sheath into the brain tissue by roughly 1 mm, and the last 0.7 mm of insulation was stripped to achieve impedances of 5-10 kOhm at 1 kHz. The far end of the electrode was soldered to an extracranial connector fixed on the chamber outer wall. Preliminary experiments on electrode placement in the two pilot animals tested the effects of short periods of stimulation on EEG desynchronization. Stimulation was delivered with biphasic, negative first, unipolar 200 μA pulses with 100 μs per phase, and 80 Hz pulses were delivered for 100 msec. This resulted in LFP desynchronization obtained through the stimulation electrode when the electrode was at a depth corresponding to the atlas position of Nucleus Basalis. In pilot experiments, an electrode movement vertically in either direction of more than 1 mm was adequate to make desynchronization not possible using the same protocol (Liu et al., 2017). LFP recordings obtained through the stimulating electrode used the same filtering and sampling parameters as the recording electrodes (band pass filtering between 0.5Hz – 100 Hz, sampling at 500 Hz).

Behavioral tasks. The monkeys faced a computer monitor 60 cm away in a dark room with their head fixed. Eye position was sampled at 240 Hz, digitized, and recorded with an infrared eye position tracking system (model RK-716; ISCAN, Burlington, MA). The visual stimulus presentation and behavior monitoring were controlled by in-house software (Meyer and Constantinidis, 2005) implemented in the MATLAB computational environment (Mathworks, Natick, MA), using the Psychophysics Toolbox (Brainard, 1997).

The tasks used in the present study were variations of the Oculomotor Delayed Response task (Funahashi et al., 1989), but involving two stimuli appearing in sequence, requiring the monkey to remember and make an eye movement to the location of either the first or the second stimulus (Fig. 1). The monkeys were trained to saccade to the location of the remembered stimulus according to the color of fixation point. After the animals fixated at a white/blue square (0.2° in size) located at the center of the monitor for 1 second, two white squares (1.5° in size) were displayed sequentially for 0.5 s, with a 1 s intervening delay period (D1). The first stimulus (S1) was displayed at one of eight locations arranged along a circular ring of 12° eccentricity, with a 45° angular separation between neighboring stimuli. This was followed by a second stimulus (S2) which was displaced 0, 45, 90 or 135° relative to the first). After a second delay period of 1s (D2), the monkeys were required to saccade to the location of the first stimulus if the fixation point was white in color (remember-first condition), and to the location of the second stimulus if the fixation point was blue (remember-second condition). To minimize the uncertainty about the stimulus to be remembered, the remember-first and remember-second conditions were presented in blocks of trials. The animal was required to perform ten correct trials of the remember-first task, before the task alternated to the remember-second condition.

The monkeys were rewarded with juice after making a correct saccade. Breaking fixation led to the immediate termination of the trial without reward.

Behavioral Performance. We calculated behavioral performance as the percentage of trials that resulted in correct saccades into the target window, a 7° circle around the center of the stimulus. Trials that were aborted prior to end of the second delay period (due to premature saccades, or blinks) were not included in this analysis.

Neural Data Analysis. All data analysis was implemented with the MATLAB computational environment (R2012-2015, Mathworks, Natick, MA). Recorded spike waveforms were sorted into separate units using an automated cluster analysis relying on the KlustaKwik algorithm (Harris et al., 2000), which relied on principal component analysis of the waveforms. Mean firing rate was then determined in each task epoch. Neurons responsive to the stimuli during either the cue period or the delay period, evaluated with a repeated measures ANOVA, at the $p < 0.05$ significance level were used for most analyses in the main text, however analyses including all neurons were also performed. Neural data from correct trials were used only in these analyses.

We identified neurons with a significant excitatory or inhibitory effect of stimulation by comparing baseline firing rate during the fixation period between the control and stimulation conditions (evaluated with a t-test at the $p<0.05$ level). To study separately effects of stimulation on the remember-first and remember-second task, we performed a 2-way ANOVA with factors tasks and stimulation. We repeated this 2-way ANOVA for other task intervals, including the

stimulus presentation and delay period. In a similar fashion, a 3-way ANOVA was performed in order to determine the main effect of task, location of first stimulus, and location of second stimulus. This analysis was performed in a time-resolved fashion, in successive 250 ms windows spanning the entire trial.

We quantified selectivity for different stimulus location using a Selectivity Index (SI) defined as (Max-Min)/(Max+Min) where Max and Min represent the firing rate corresponding to the best and worst stimulus location for each neuron. Discriminability between stimulus conditions does not only depend on mean firing rates, on which SI depends, but also their variance. We therefore compared the full distributions of firing rates between the worst and best condition using a Receiver Operating Characteristic analysis. This was performed in a time-resolved fashion, in successive 250 ms windows.

The endpoint of saccades towards the targets were analyzed in correct trials. For each monkey and stimulus condition, the mean saccadic endpoint was calculated for the target location (using circular mean statistics). We then computed the angular deviation of the saccadic endpoint in every trial, relative to the mean saccadic endpoint for that condition. We applied the Kuiper two-sample test, a circular analogue of Kolmogorov-Smirnov test, to compare the distributions of angular deviations around the mean, with and without stimulation.

We performed a power spectrum analysis of LFP recordings, using the Chronux package. Power at different frequency bands was compared between the control and stimulation conditions. Comparison of LFP power obtained through the stimulation electrode was determined at rest, and following 6 seconds of intermittent stimulation. Multiple sessions were obtained to determine desynchronization in this fashion.

Immunohistochemistry and Fluorescence Imaging. Free floating 50 micron sections of fixed monkey brain were stained with Anti-ChAT antibody (MilliporeSigma, MAB5270), Goat Anti-Mouse-Biotin-SP antibody (Jackson ImmunoResearch Laboratories, 115-067-003), Streptavidin-HRP (PerkinElmer, NEL750), and SuperGlo Green fluorescein tyramide (Fluorescent Solutions, FS101). Stained sections were mounted on slides and z-stack images were collected at 10X and 20X magnification using a Zeiss AxioImager microscope. The coronal section displayed in Figure 1B was corresponded to a plane approximately 16 mm anterior to the interaural line.

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FIGURE LEGENDS

Figure 1. Localization and effects of stimulation. A. Anatomical MR scan from one monkey obtained prior to implantation. The approximate location of the implanted electrode is indicated with the solid/dashed vertical line. The dotted area represents the cortical region sampled with neurophysiological recordings. Abbreviations, AS: arcuate sulcus; PS: principal sulcus. **B**. Histology and ChAT Immunohistochemistry. Left, a 50 micron thick coronal plane section viewed in light microscopy displaying the most inferior track of the electrode cannula. The red box surrounds the cannula track (red arrow) and indicates the area enlarged in the middle panel. The dashed line marks the floor of the Nucleus Basalis. Middle, the marked area enlarged at 10X magnification shown under merged green and blue fluorescence. Blue color marks nuclei with DAPI, and the green marks antibody to ChAT. White arrows mark blood vessel autofluorescence. The dashed line is the same as in A and marks the floor of the basal forebrain. Right, Nucleus Basalis at 20X magnification. DAPI (blue), Anti-ChAT (green), Anti-ChAT-containing neurons (red arrows), Blood vessel autofluorescence (white arrows). **C.** Power Spectrum of Local Field Potential recorded from the implanted electrode during rest (solid line) and following 80 Hz stimulation. **D.** Successive frames illustrate the sequence of events in the behavioral task. Depending on the color of the fixation point, white or blue, the monkey has to remember either the first or the second of two stimuli presented in sequence, respectively. At the end of the trial, the fixation point turns off and the monkey needs to perform an eye movement towards the location of the correct stimulus in order to receive a liquid reward. **E-H**. Percentage of correct trials is shown for each of the two monkeys, for different stimulus types (n=18 sessions for stimulation, 17 for control for monkey GR; n=19 stimulation and 35 control for

monkey HE). **E**, Mean performance (and sem) for trials in which first stimulus appears contralateral to the stimulation site, when the monkey is executing the remember-first task, and needs to remember the first stimulus. **F**. Performance in the remember-first task when the first stimulus appears ipsilateral to the stimulation site. **G**. Performance in the remember-second task when the second stimulus appears ipsilateral to the stimulation site. **H**. Performance in the remember-second task, when the second stimulus appears contralateral to the stimulation site.

Figure 2. Distribution and example of stimulation effects. **A**. Distribution of firing rate differences between stimulation and control conditions. Positive values indicate higher fixation period firing rate in the stimulation condition. Each neuron is represented twice in this diagram; once for the remember-first, and once for the remember-second task. Mean firing rate of neurons with significant increase in activation by NB stimulation (n=112 neurons). **B-E**. Raster plots and Peri-Stimulus Time Histograms represent responses of a single neuron in the remember-first (B-C) and remember-second task (D-E), under control and stimulation conditions. Trials are pooled from conditions when the first stimulus appeared inside the receptive field (B, D) or outside (C, E). Insets to the right of the PSTH represent schematically the location of stimulus relative to the receptive field; the actual locations and receptive field locations varied in each neuron.

Figure 3. Population responses under stimulation. **A**. Mean firing rate with and without stimulation is shown during the intertrial interval, fixation interval, first stimulus presentation involving the best stimulus of each neuron, second stimulus presentation involving the best stimulus of each neuron, and saccade towards best stimulus. Results from the remember-second task are shown, for of neurons with significant increase in activation by NB stimulation (n=54

neurons). **B-E**. Mean firing rate in the remember-first task, in conditions involving presentation of the first stimulus in the receptive field, followed by a second stimulus at progressively less responsive locations. Gray rectangles represent the times of stimulus presentations. Insets to the right of PSTH represent location of the stimuli relative to each neuron's receptive field; results from neurons with different receptive field locations have been averaged together, but only one stimulus location is indicated. **F-G**. Mean firing rate in the remember-second task, in conditions involving no first stimulus, followed by a second stimulus in or out of the receptive field. Horizontal lines illustrate the times that a first stimulus would have been delivered relative to the onset of the fixation point, had one been present in these trials. **H.** Firing rate in sequential trials in blocks of trials when stimulation was applied or not. X axis represents time after the offset of stimulation, or sham inter-trial interval. **I**. Population tuning curve, obtaining by averaging responses of individual neurons to stimuli relative to each neuron's preferred location (depicted at 0°).

Figure 4. Attractor network behavior. A. Schematic diagram of theoretical bump of activity in an attractor network. Abscissa represents time after initial stimulus onset, ordinate neurons with preference for different stimulus locations, indicated by location varying between 0 and 360°. Activity of neurons with different preference is indicated based on color scale. The first stimulus appearance at 270° (indicated by horizontal line on top of the panel) elicits a bump of activity which is maintained during the delay period, after the stimulus is no longer present. Appearance of the second stimulus at the 90° location causes the initial bump of activity to terminate and a new bump to be maintained at 90°. The subject retrieves this location at the end of the delay period (black triangle, to the right of the panel). **B.** A network with neurons with broader

selectivity results in a wider bump of activity, which is more resistant to the interference of the second stimulus, and the subject is able to retrieve the location of the original stimulus at 270°. **C**. When the second stimulus appears at location near the first, the bumps of activity are more likely to merge in the network with the broader bump. The recalled location (black triangle) is thus "pulled" towards the location of the second stimulus. **D.** Mean performance (and sem) in the remember-first task, for trials grouped by distance between the first and second stimulus (180, 90, or 45°), under stimulation or control conditions. Data from both monkeys pooled together (n=35 stimulation sessions with sufficient trials for this analysis, 51 for control). **E.** Mean performance (and sem) in the remember-second task, for trials grouped by distance. **F.** Distribution of angular deviations from mean endpoint, under stimulation and control conditions.

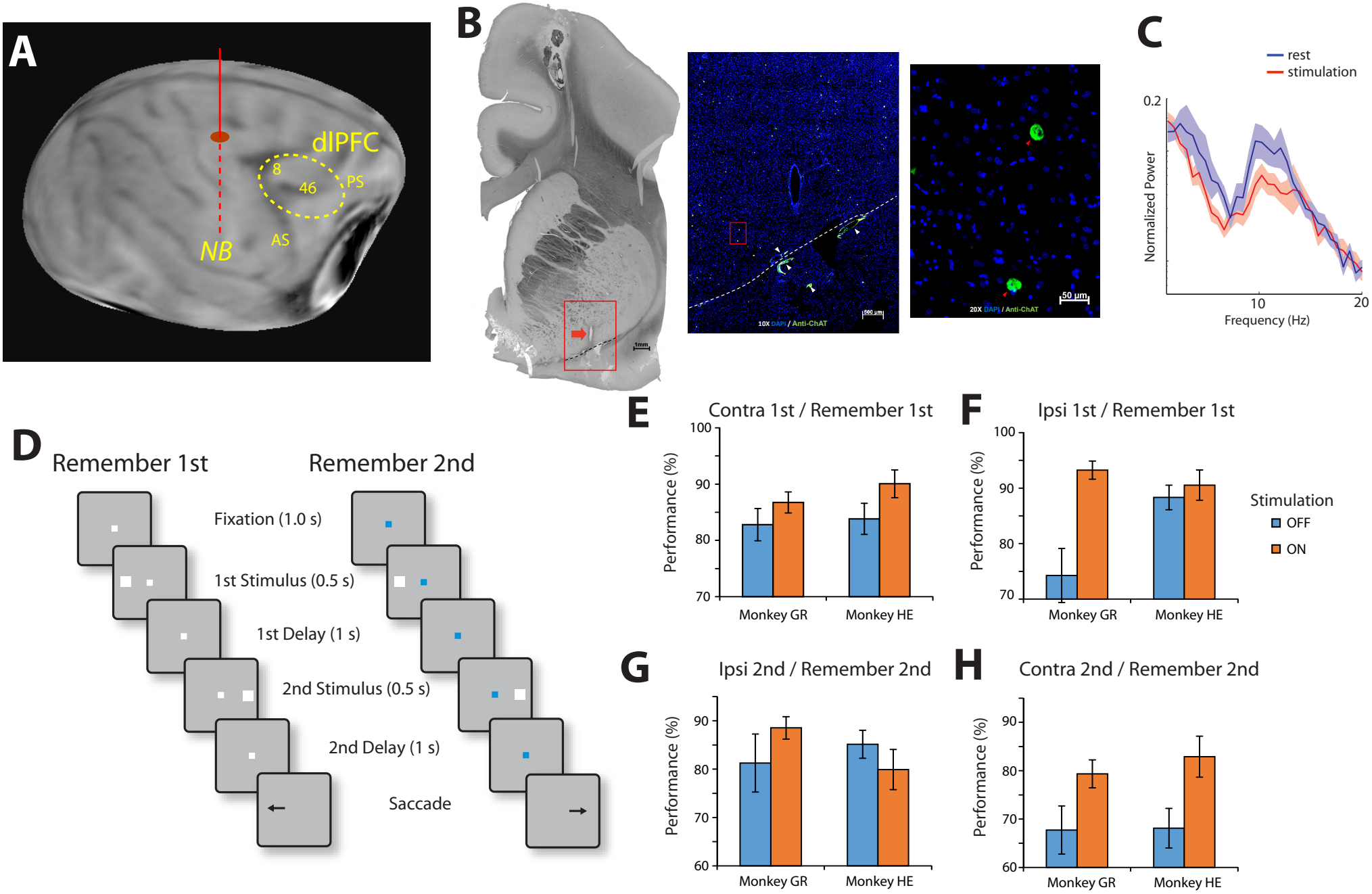
A
dlPFC
8
46
PS
AS
NB
B
1mm
500 µm
10X DAPI / Anti-ChAT
50 µm
20X DAPI / Anti-ChAT
C
rest
stimulation
0.2
Normalized Power
10
20
Frequency (Hz)
D
Remember 1st
Remember 2nd
Fixation (1.0 s)
1st Stimulus (0.5 s)
1st Delay (1 s)
2nd Stimulus (0.5 s)
2nd Delay (1 s)
Saccade
E
Contra 1st / Remember 1st
F
Ipsi 1st / Remember 1st
G
Ipsi 2nd / Remember 2nd
H
Contra 2nd / Remember 2nd
Performance (%)
Monkey GR
Monkey HE
Stimulation
OFF
ON

FIGURE 1

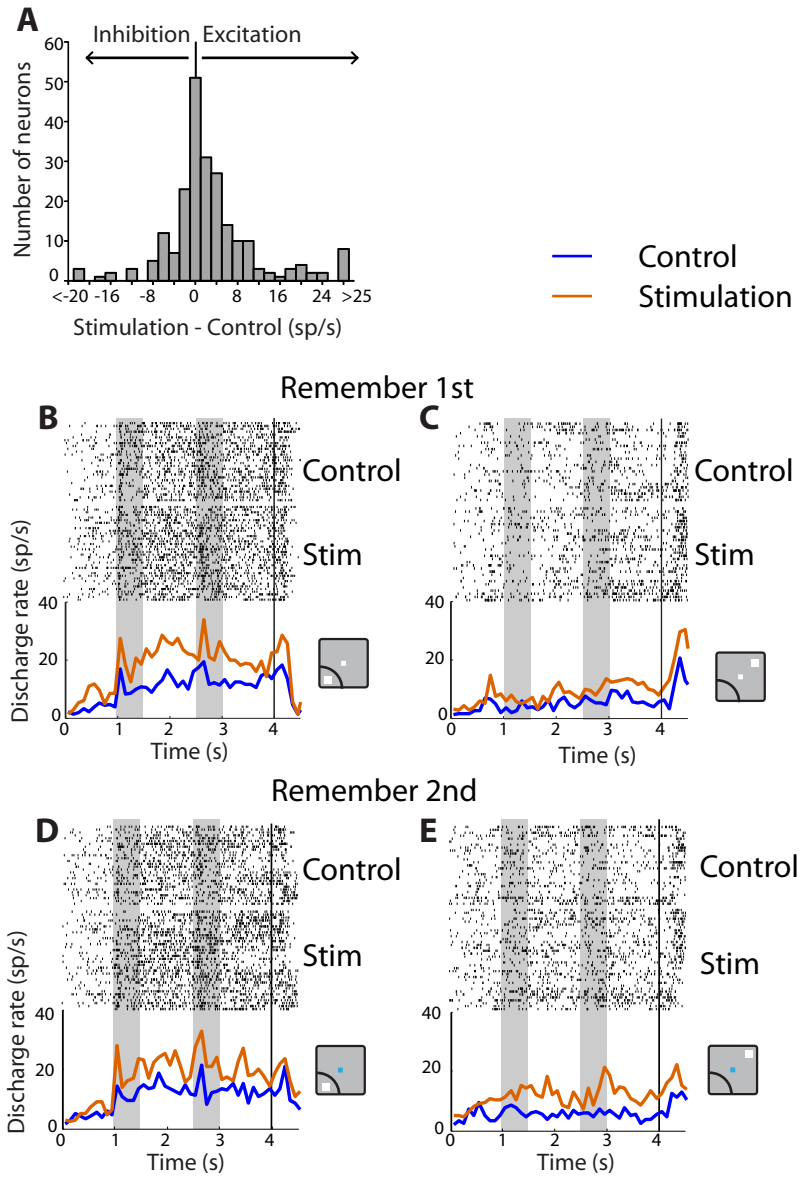
A
Inhibition
Excitation
Number of neurons
60
50
40
30
20
10
0
<-20 -16 -8 0 8 16 24 >25
Stimulation - Control (sp/s)
Control
Stimulation
Remember 1st
B
C
Control
Stim
Discharge rate (sp/s)
40
20
0
0 1 2 3 4
Time (s)
Remember 2nd
D
E

FIGURE 2

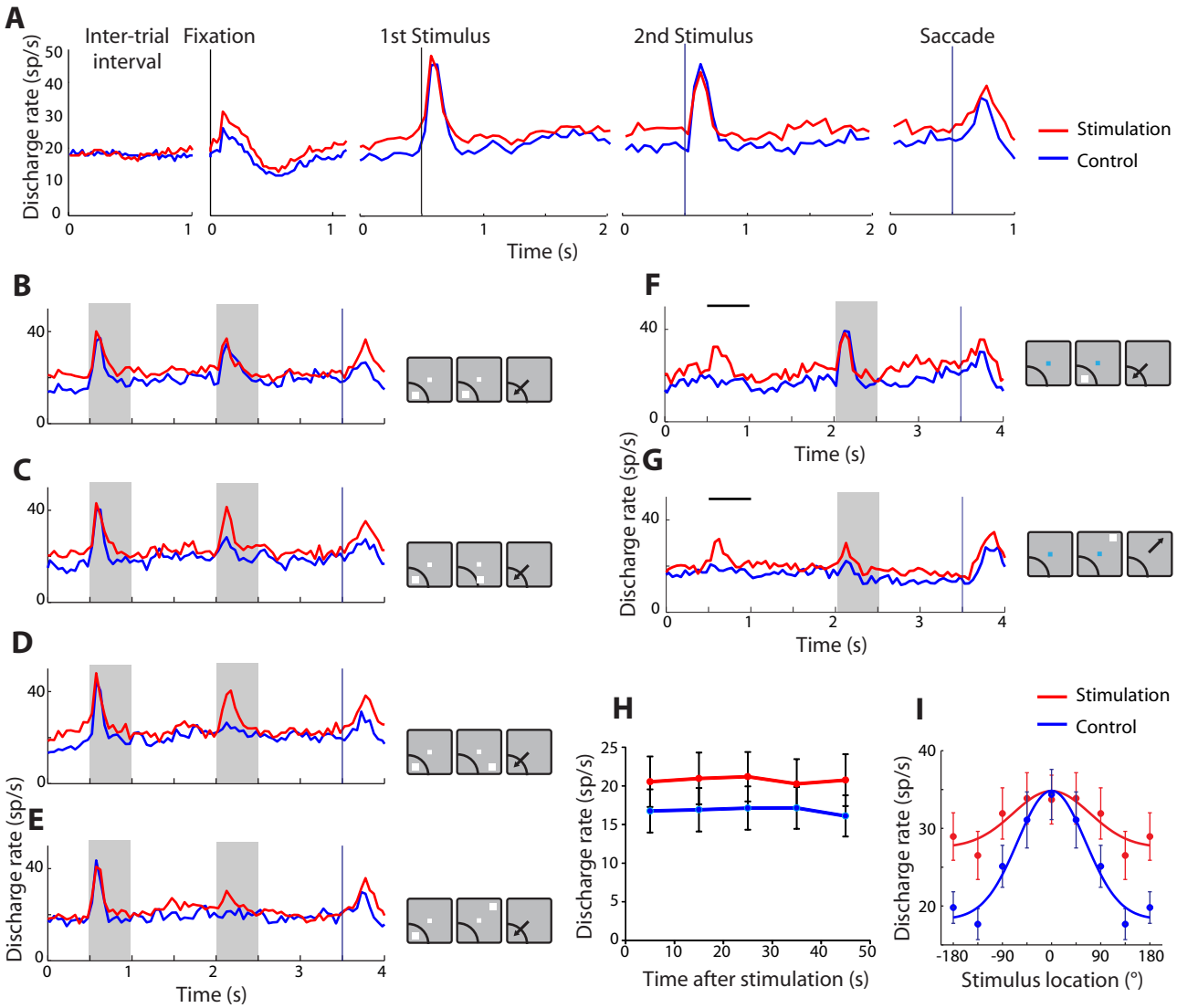
A
Inter-trial interval
Fixation
1st Stimulus
2nd Stimulus
Saccade
Discharge rate (sp/s)
Time (s)
Stimulation
Control
B
C
D
E
F
G
H
I
Time after stimulation (s)
Stimulus location (°)

FIGURE 3

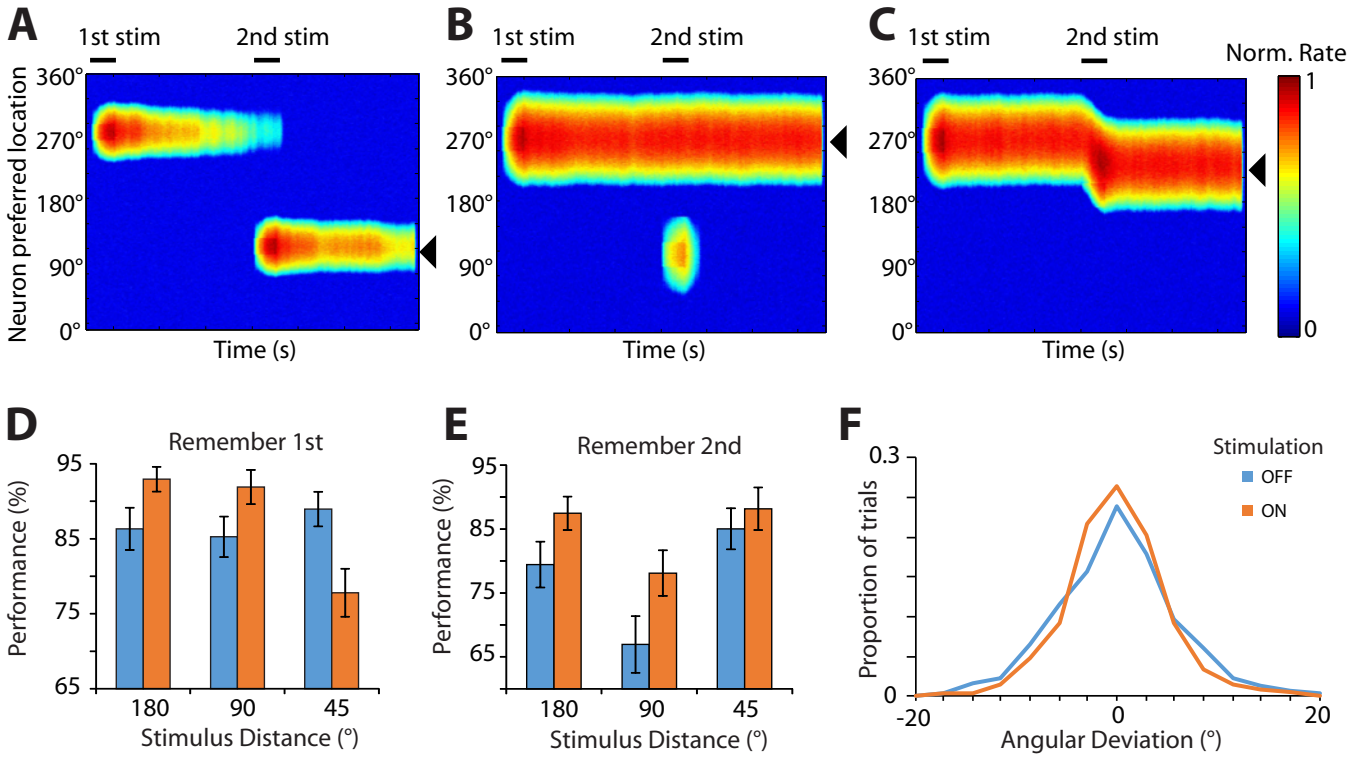
A
1st stim
2nd stim
Neuron preferred location
360°
270°
180°
90°
0°
Time (s)
B
1st stim
2nd stim
360°
270°
180°
90°
0°
Time (s)
C
1st stim
2nd stim
Norm. Rate
1
0
360°
270°
180°
90°
0°
Time (s)
D
Remember 1st
Performance (%)
95
85
75
65
180
90
45
Stimulus Distance (°)
E
Remember 2nd
Performance (%)
95
85
75
65
180
90
45
Stimulus Distance (°)
F
Stimulation
OFF
ON
Proportion of trials
0.3
0
-20
0
20
Angular Deviation (°)

FIGURE 4