

Inactivation of primate superior colliculus impairs covert selection of signals for perceptual judgments

Lee P Lovejoy^{1,2} & Richard J Krauzlis¹

Primates base perceptual judgments on some sensory inputs while ignoring others. The covert selection of sensory information for perception is often thought to be accomplished mostly by the cerebral cortex, whereas the overt orienting toward relevant stimuli involves various additional structures such as the superior colliculus, a subcortical region involved in the control of eye movements. Contrary to this view, we show that the superior colliculus is necessary for determining which stimuli will inform perceptual judgments, even in the absence of orienting movements. Reversible inactivation of the superior colliculus in monkeys performing a motion discrimination task caused profound inattention for stimuli in the affected visual field, but only when distracters containing counterinformative signals appeared in the unaffected field. When distracting stimuli contained no information, discrimination performance was largely unaffected. Thus, the superior colliculus is a bottleneck in the covert selection of signals for perceptual judgments.

The primate superior colliculus (SC) has long been implicated in the mechanisms of visual attention. For overt attention, the role of the SC is well established: we often look directly at attended objects, and the SC is a major component of the motor circuits that control how we orient our eyes and head^{1,2}. In addition to its well known role in guiding the motor output, the SC is also important for the preceding step of selecting which stimulus will be the target of an eye movement. When the region of the SC representing the target is reversibly inactivated, saccades are often misdirected to distracters appearing in unaffected parts of the visual field³. Conversely, electrical stimulation of the SC at currents too weak to directly evoke eye movements can nonetheless bias target selection toward the stimulus in the activated location, regardless of whether the target is acquired with a pursuit or saccadic eye movement⁴. We consider these effects on target selection to be a form of intentional neglect⁵ that may be related to the classic Sprague effect, in which deficits in orienting caused by lesion of parietal cortex on one side of the brain can be relieved by lesion of the SC on the other side⁶. Thus, the SC contributes to overt attention both by controlling the motor output and by participating in the selection process that determines where we look next.

However, we also attend covertly—without directing our gaze toward the attended object—and it is now clear that at least some components of the oculomotor system play a role in covert attention. In humans, imaging studies show that covert attention and eye movements activate a common set of areas in the parietal and frontal cerebral cortex⁷. The symptoms of spatial neglect in human patients are thought to arise from an imbalance of activity within this fronto-parietal regulatory network that drives attention to the unaffected side^{8–10}. Likewise, in nonhuman primates, cortical areas important for eye movements have also been implicated in the control of

covert attention. Reversible inactivation of the frontal eye fields causes temporary deficits in performance on covert attention tasks¹¹, and electrical stimulation of the frontal eye field improves performance on detection tasks and promotes the enhancement of visual processing in area V4 (refs. 12,13). The lateral intraparietal area is implicated in the control of both saccadic eye movements and spatial attention^{14,15} and is one of the few cortical areas known to contain neurons that represent the spatial decision variables¹⁶ important for guiding both overt and covert orienting.

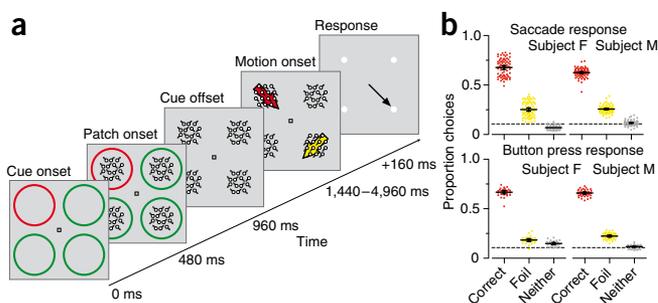
Nevertheless, it is not yet known whether the control of covert attention is restricted to the cerebral cortex or extends to subcortical structures such as the SC. The results so far are ambiguous. Some neurons in the SC increase their activity when a monkey attends into their response fields, even when the attended stimulus is not the target of a saccade^{17,18}; this activity could be related to the control of covert attention, or it could be related to oculomotor planning by the SC that occurs during covert attention. Microstimulation of the SC drives attention to a location in space almost as if the monkey had been cued to attend to that location^{19,20}; these effects show that the SC is part of the circuit for covert attention—perhaps through its connections to frontal and parietal cortex—but they do not distinguish whether the SC is crucial for the control of covert attention or simply updated about its current state.

We addressed this ambiguity by performing reversible inactivation in the SC of monkeys trained to perform a selective attention task. The task required subjects to ignore distracting stimuli while covertly attending to a cued stimulus that instructed them where to orient, thus distinguishing between control of gaze and control of attention. Inactivation of the SC caused extinction-like deficits: subjects ignored cued signals in the inactivated region when the cued signals

¹Systems Neurobiology Laboratory, Salk Institute for Biological Studies, La Jolla, California, USA. ²Graduate Program in Neurosciences, University of California, San Diego, La Jolla, California, USA. Correspondence should be addressed to L.P.L. (lovejoy@salk.edu).

Received 11 September; accepted 13 November; published online 20 December 2009; doi:10.1038/nn.2470

Figure 1 Selective attention task design. **(a)** Task sequence. After a brief fixation period, colored cue rings were presented. Stochastic motion patches appeared next, and then the cues disappeared. Following a delay, brief coherent motion pulses occurred in both the cued location (red arrow) and the diametrically opposite location (yellow arrow). When responding by saccade, monkeys reported the direction of the cued motion signal by making an eye movement to a response dot in the same direction; when responding by button push, monkeys pressed a button corresponding to the motion direction. **(b)** Normal behavioral task performance for both subjects in the saccade response version (top) and the button press response version of the task (bottom). Red dots represent proportion of correct choices (based on cued signal) in each session. Errors could be either driven by the foil signal (yellow dots) or by neither signal (gray dots). Scatter indicates variability across control sessions collected over several months before the inactivation experiments. Black lines, population averages; error bars, 95% multinomial confidence intervals; dashed line, proportion of responses consistent with the foil that would be expected by chance.



competed with distracting foils placed elsewhere, but discrimination ability was largely intact when the cued signal appeared alone. These effects reflected a generalized impairment in covert attention, because they were also observed using a manual-response version of the task without eye movements. Together, these results demonstrate a causal role for the SC in the control of covert attention.

RESULTS

Monkeys normally attended to cued stimuli and ignored foils

Monkeys performed a motion discrimination task that required them to judge the direction of motion in one of four peripheral stochastic motion stimuli while ignoring distracting signals (Fig. 1a). The odd-colored ring cued the monkey to attend to one of the four stimuli. After a delay, brief pulses of coherent motion appeared simultaneously at both the previously cued location and the diametrically opposite ‘foil’ location. The direction of motion in the cued location was drawn at random from any of the four diagonal directions, and the direction in the foil was drawn from any of the remaining three. Monkeys were required to maintain fixation throughout the presentation of the motion stimuli, and, in separate versions of the task, they reported the direction of the motion pulse either by making a saccade or by pushing a button corresponding to the direction of motion. In the button-press version, they were required to maintain fixation for the entire duration of the trial, including the response interval.

After extensive training, both monkeys based their responses on the cued signal on a substantial majority of the trials (~75%), indicating that they were able to selectively attend to the cued stimulus (Fig. 1b). To achieve equivalent performance between the animals, we set the motion coherence at 0.1875 for subject F and at 0.25 for subject M. A preponderance of errors were consistent with the foil signal, indicating

that mistakes in the task were usually due to selecting the wrong stimulus, rather than simply guessing. Figure 1b shows behavioral data collected in the months before the inactivation experiments. In the saccade task, this includes 50,651 trials over 78 sessions with subject F and 33,170 trials over 82 sessions for subject M. In the button-press task, this includes 8,756 trials in 28 sessions for subject F and 20,265 trials in 44 sessions for subject M.

We assessed the degree to which the SC regulates selective attention by inactivating portions of the intermediate and deep layers of the SC corresponding to parts of the visual field in which motion stimuli were presented. Immediately before each inactivation, we collected control behavior. We then injected 0.5 μl of muscimol (0.5 $\mu\text{g m}^{-1}$), a GABA agonist, into the intermediate and deep layers of the SC to temporarily inactivate neurons in those regions (Supplementary Fig. 1 and Online Methods), although it is possible that neurons in the superficial layer might also have been affected. Muscimol spread laterally through these layers, and we assessed the spatial extent of the resulting inactivation effects by observing the decrease in peak velocity of visually guided saccades²¹ (Fig. 2a). In each session, the effects were restricted to a portion of the visual field that overlapped with either the cued or foil stimulus (Fig. 2b). Monkeys were cued to attend either into the affected quadrant or the diametrically opposite quadrant in alternating blocks of 40 trials. Because the motion direction was independent of the cued location, the locus of attention was independent of the orienting response. Any impact of SC inactivation on attention was therefore distinct from effects on saccades and could be distinguished by examining the subset of trials in which neither the cued signal nor the foil signal pointed into the affected quadrant of the visual field. In these trials, no response should be made into the affected quadrant and thus few responses should be affected by the inactivation. Consequently, we included only this subset of trials in further analysis. If the SC is necessary for selective attention, inactivation should decrease the ability of the monkeys to base judgments on cued signals in the affected visual field; the degree to which the foil intrudes upon the judgments will depend on the degree to which selective attention is biased into the unaffected visual field.

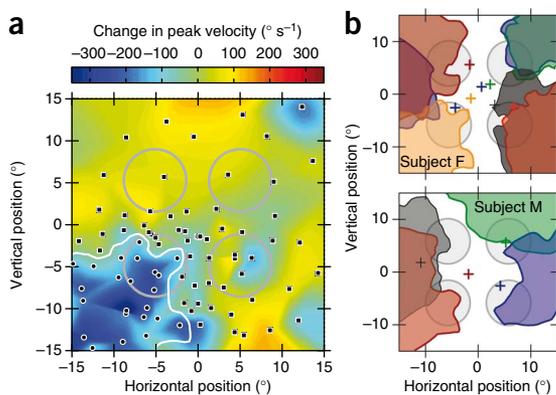


Figure 2 Map of inactivation effects. **(a)** Single session data from subject F. Black dots, saccade end points; interpolated color map, changes in peak velocity after muscimol injection. Cooler colors in the lower left quadrant indicate the decrease in peak velocity caused by SC inactivation; white contour delineates the affected region. Gray circles indicate the positions of the four stochastic motion stimuli, which were at fixed locations throughout the set of experiments. **(b)** Summary of SC injections for the saccade response task. Crosses, average end points of saccades evoked by microstimulation at the injection sites; shaded regions, extent of the visual field affected by each injection experiment.

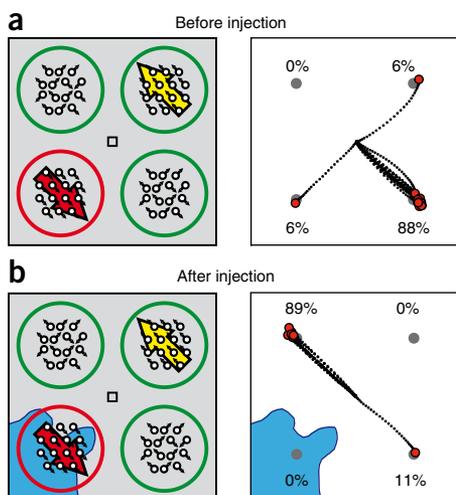


Figure 3 Sample data from one inactivation session. **(a)** Behavior of subject F in a representative stimulus condition before inactivation. Schematic of stimulus indicates cued signal position with red ring and directions of motion in the cued signal (red arrow) and foil signal (yellow arrow). Red dots indicate end-points of saccade trajectories. A majority of responses were correctly directed by the cued signal. **(b)** Behavior in the same condition after inactivation of the SC. Schematic of stimulus now indicates the affected portion of visual space as a blue shaded region. Only a minority of responses were correctly guided by the cued signal; instead, the majority of decisions were based on the foil.

SC inactivation impaired selective attention

After inactivation of the SC, both monkeys ignored the cued signal when it was presented in the affected quadrant. In a representative pair of cued and foil motion directions from the inactivation in **Figure 2a**, subject F was initially able to base the majority of its judgments on the cued signal and ignore the foil signal (**Fig. 3a**). After inactivation, it was unable to base judgments on the cued signal when that signal appeared in the affected quadrant of visual space (**Fig. 3b**). This outcome cannot be explained in terms of a deficit in target selection or saccade execution^{3,4} because the cued signal required a rightward response into an unaffected quadrant. Instead, SC inactivation caused the monkey to base its decisions on the foil signal even though this signal instructed a leftward movement, toward the affected side of the visual field. Inactivation also did not cause the monkeys to become unmotivated or to begin randomly guessing: the majority of decisions were still based on the presented stimuli but now incorrectly followed the foil. Although SC inactivation did cause deficits in saccade production, such as a reduction in the peak velocity of saccades made into the affected quadrant (**Fig. 2**), the changes in behavior indicate that the monkey could not selectively attend into the affected quadrant.

SC inactivation caused monkeys to ignore the signal in the affected quadrant of visual space in all experimental sessions. We summarize these effects for each session by plotting the overall proportion of choices driven by each signal after inactivation against the proportions before inactivation (**Fig. 4**). A decrease in the proportion of choices driven by a particular signal causes the corresponding points to lie below the unity line, whereas an increase causes them to lie above the unity line. When the cue appeared in the affected quadrant (**Fig. 4a,c** for each subject), the proportion of choices with the cued signal decreased from ~ 0.7 before injection to only ~ 0.2 after injection (red symbols). Conversely, the proportion of choices with the foil signal increased from ~ 0.2 before injection to ~ 0.7 after injection (yellow symbols). Notably, the proportion of choices with neither signal did

not increase (gray symbols). This indicates that the monkeys did not engage in more random guessing after the inactivation but instead still based their choices on signals present in the display.

A complementary effect often occurred when the foil signal was presented in the affected quadrant. The proportion of choices with the cued signal increased slightly after injection in many sessions, and the proportion of choices with the foil decreased (**Fig. 4b,d** for each subject). The amplitude of these improvements was limited by the high level of the monkeys' preinjection performance, and was more evident with subject M. Again, the proportion of choices with neither signal did not change. Thus, SC inactivation caused the monkeys to preferentially base decisions on the signal in the unaffected quadrant, regardless of the cue, as if selective attention were biased toward the signal in the unaffected region.

Deficits also occurred for manual response

To test whether SC inactivation caused a general impairment of selective attention rather than an effect restricted to the guidance of eye movements, we trained both subjects to perform the task by pushing buttons rather than by making saccades (**Fig. 5**). Just as in the saccade version of the task, SC inactivation again caused the subjects to ignore the cued signal when it was presented in the affected quadrant and instead to base their responses on the foil (**Fig. 5a,c**). When the foil signal was presented in the affected quadrant, performance was sometimes improved (**Fig. 5b,d**), although this effect was observed less often than in the saccade version of the task. We also performed a saline control experiment in subject M, which led to no changes in performance regardless of where the cued and foil signals were placed (**Fig. 5c,d**). Overall, these results rule out explanations based on the role of the SC in the control of saccades because the changes in performance occurred while the subjects

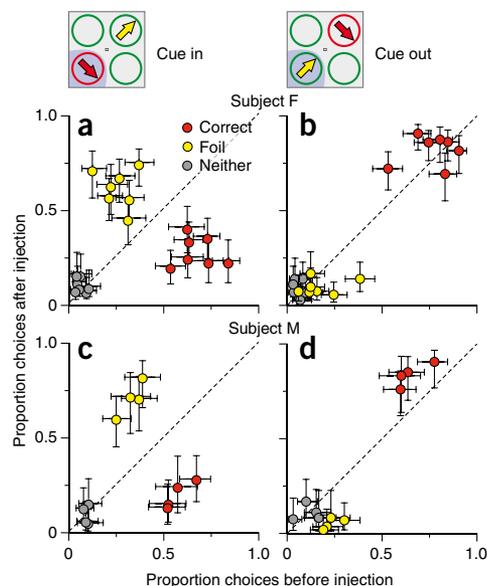


Figure 4 Summary results from inactivation sessions in saccade-response version of the task. The proportion of choices after injection is plotted against the proportion before injection. Red circles, correct choices matching the cued signal; yellow and gray symbols, errors driven by either the foil signal or neither signal. Error bars, 95% multinomial confidence intervals for each of the sessions, which included 176–264 trials per session. **(a,b)** Data for subject F. **(c,d)** Data for subject M. When the cued signal was in the affected region **(a,c)**, subjects ignored this signal and instead based their choices on the foil. Conversely, when the foil signal appeared in the affected region **(b,d)**, subjects tended to base their choices on the cued signal and ignore the foil.

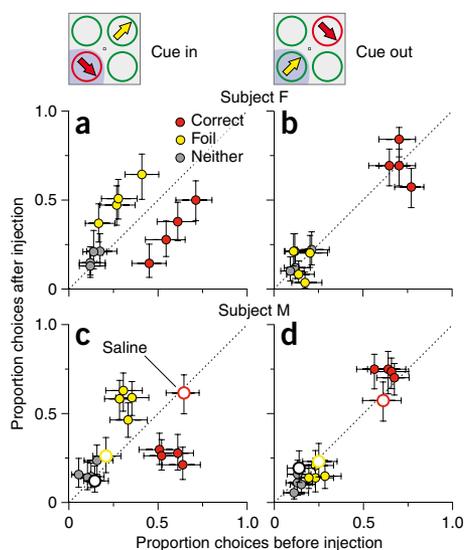


Figure 5 Summary results from inactivation sessions in button-press version of the task. Same conventions as in **Figure 4**. (**a,b**) Data for subject F. (**c,d**) Data for subject M. When the cued signal was in the affected region (**a,c**), subjects ignored this signal and instead based their choices on the foil, much as in the results from the saccade-response version. The injection of saline during a control experiment (large, open symbols in **c,d**) produced no significant changes in performance.

maintained fixation for the entire duration of each trial. Instead, they indicate that the changes in task performance after SC inactivation reflect a generalized impairment in covert attention.

SC inactivation slightly impaired motion discrimination

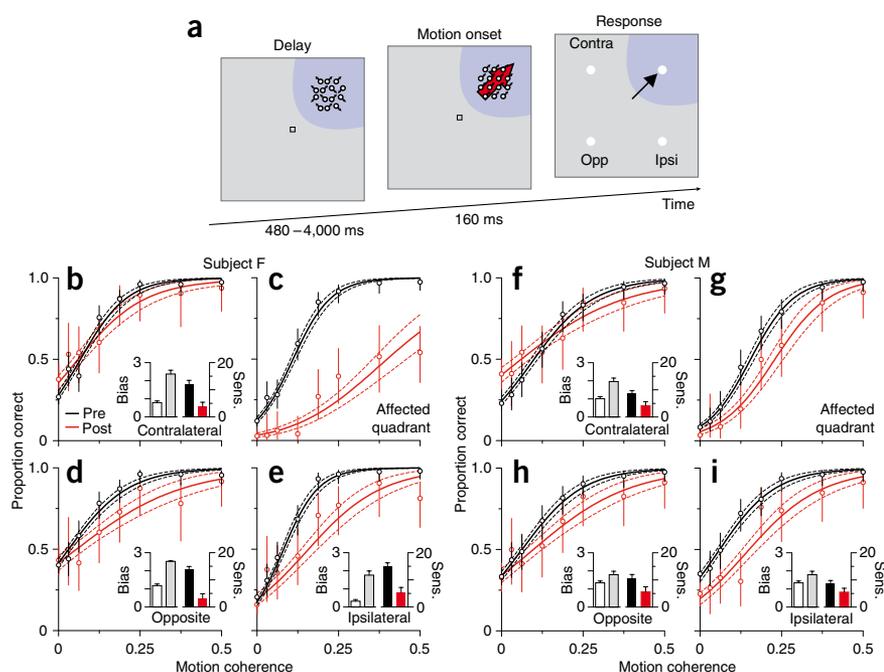
Although inactivation of the SC seemed to bias selective attention into the unaffected field, a local impairment of motion processing could have contributed to the change in behavior. To address this possibility, we tested motion discrimination on single stimuli concurrently with the inactivation sessions. Subjects reported the direction of motion in a single peripheral stimulus with a saccade (**Fig. 6a**). We pooled trials from all inactivation sessions and appropriately associated directions to maintain the spatial relationship of each direction to the inactivated region (contralateral, opposite and ipsilateral, as in **Fig. 6a**). This included for subject F 4,638 trials in 23 control

sessions and 1,283 trials in 9 inactivation sessions; for subject M, 3,873 trials in 20 control sessions and 1,293 trials in 8 inactivation sessions. Subject F's motion discrimination performance for each direction of motion as a function of coherence during both control and inactivation conditions appears in **Figure 6b–e**. Curves were fitted to the data using multinomial logistic regression²². The corresponding data and curve fits for subject M appear in **Figure 6f–i**.

SC inactivation impaired performance on the task, as evident by the decrease in proportion of correct responses. We quantified this impairment in terms of an increase in bias and a decrease in sensitivity to motion coherence. In probit analysis for two-alternative discrimination tasks, bias describes the relative preference for one option over another independent of signal strength, and sensitivity describes how the relative gain on signal strength contributes to the preference for one option over another. Similarly, in four-alternative discrimination, three relative bias terms and three relative sensitivity terms describe preference for each option over a single reference, which in this case was defined as the direction corresponding to the inactivated region. The insets in **Figure 6** show relative bias and sensitivity to coherent motion for each direction, before and after injection.

We found that subjects were biased to respond away from the affected quadrant of visual space, as expected from previous studies showing that SC inactivation affects saccade selection³. Subjects were normally biased slightly away from the region of the motion stimulus (**Fig. 6**, insets), and this tendency was exaggerated by inactivation of the SC. In addition, subjects showed a decrease in sensitivity to coherent motion after SC inactivation. The changes in sensitivity amount to a 66% decrease in the gain on the signal for

Figure 6 The effects of SC inactivation on local motion discrimination. (**a**) Task sequence. After a brief fixation period, a stochastic motion patch appeared in one quadrant of the visual field. After a random delay (480 ms plus a geometrically distributed interval with mean 480 ms), a brief (160 ms) coherent motion pulse occurred. The direction of motion was drawn at random from any of the four diagonal directions. Monkeys reported the direction of motion by making a saccade to a response dot in the same direction. Data were pooled across sessions on the basis of the direction of motion with respect to the affected quadrant: ipsilateral, other quadrant on the same side; opposite, diagonally opposite quadrant on the other side; contralateral, directly opposite quadrant on the other side. (**b–e**) Performance on motion discrimination task for subject F for each of the four motion directions. Black circles, correct task performance in control sessions; red circles, correct performance after injection. Error bars, 95% multinomial confidence intervals. Solid lines, fits by multinomial logistic regression; dashed lines, 95% confidence intervals on the fits. Insets: bias (control, white; after injection, gray) and sensitivity (control, black; after injection, red) relative to choices into the quadrant containing the stimulus. Error bars, s.e.m. of the fitted parameters. After inactivation, bias significantly increased away from the injection site and sensitivity significantly decreased for all directions of motion. (**f–i**) Performance on motion discrimination task for subject M. Same conventions as in **b–e**.



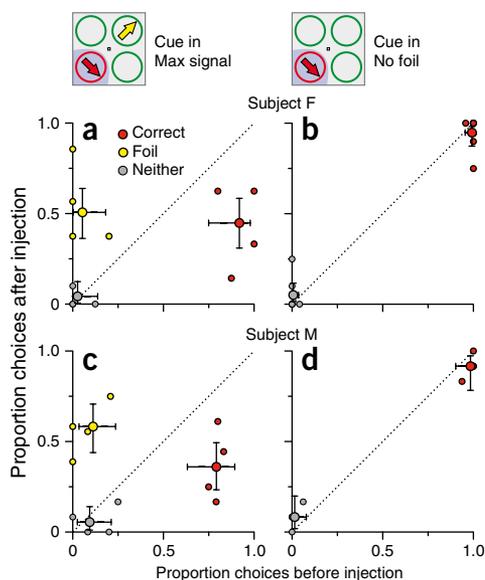


Figure 7 Impairments in selective attention after SC inactivation required the presence of a foil signal. **(a,b)** Data for subject F. **(c,d)** Data for subject M.

(a,c) After injection, monkeys tended to base judgments on the near-threshold foil signal in the unaffected region even when the cued signal in the affected region was set to maximal coherence. Individual symbols without error bars indicate performance on individual sessions; symbols with error bars indicate pooled performance. **(b,d)** When no foil signal appeared in the unaffected region, however, monkeys successfully ignored the three distracter stimuli with 0% motion coherence and based their choices on the cued signal.

subject F and a 50% decrease in the gain for subject M. Hence, SC inactivation impaired local motion discrimination, in addition to biasing saccade responses.

Sensory impairment did not cause deficits in attention

Although SC inactivation decreased sensitivity to local motion, discrimination performance could be recovered to control levels by simply increasing signal strength (Fig. 6). For example, discrimination performance using maximal signal strength during SC inactivation (~0.95 correct with 0.5 coherence; see Fig. 6) was equivalent or better for unaffected directions than that using near-threshold signal strengths without inactivation (~0.7 correct with ~0.2 coherence, see Fig. 1b). The impact of SC inactivation on local motion discrimination with single stimuli could therefore be equated with a reduction in effective signal strength. This equivalence provided a method for testing whether local changes in motion sensitivity contributed to the effects of SC inactivation on selective attention. Specifically, if the behavioral effects in the attention task were due to a local impairment in motion discrimination, then they should be entirely reversed by appropriately boosting the strength of the motion signal. In a set of additional inactivation experiments (Fig. 7), we therefore increased the coherence of stimuli in the affected quadrant to the maximum presentable while leaving the foil strength the same (0.5 cued / 0.1875 foil for subject F, 0.5 / 0.25 for subject M). Despite the increase in cued signal strength, we observed a qualitatively identical pattern of results as in the initial experiment: the monkeys ignored the cued signal and instead based responses on the foil (Fig. 7a,c). Therefore, increasing the strength of the cued stimulus could not reverse the behavioral changes observed after SC inactivation. It follows that a primary sensory impairment is insufficient to explain the observed effects and instead that the deficits observed after SC inactivation were caused by a disruption of selective attention.

Only misleading sensory information impaired performance

Finally, we tested whether the impairments in selective attention required the presence of a foil signal. Spatial neglect sometimes seems to involve an inability to disengage attention, implying that the deficit may involve not simply an impairment in directing attention into the affected field but instead an inappropriately hyperactive drive to attend to stimuli in the so-called unaffected field^{10,23,24}. We therefore considered whether the impairment in covert attention caused by SC

inactivation could be due to an inability to disengage attention from stimuli in the unaffected field. Under this hypothesis, the foil would drive choices after SC inactivation because attention is unavoidably engaged at that stimulus, thus permitting whatever signal was present there to drive the choice. If this were the case, then the mere presence of incoherent motion patches in the unaffected field should cause the monkeys to ignore the cued stimulus in the affected quadrant. Contrary to this prediction, however, when no foil signal competed with the cued signal, we observed no significant decrease in performance (Fig. 7b,d). This indicates that the presence of stimuli in the unaffected field was insufficient to impair performance. Thus the deficits in covert attention caused by SC inactivation were due to an inability to filter distracting or misleading sensory content, not simply the presence of distracting stimuli.

DISCUSSION

The primate SC has long been implicated in the control of attention and eye movements. Some of the first recordings in the primate SC showed that visual responses were enhanced with the shift of attention presumed to precede a saccadic eye movement²⁵, and older models of attention have outlined a role for the SC in the orienting of attention²⁶. More recently, neural activity in the superior colliculus has been correlated with both voluntary^{17,18} and stimulus-driven allocation of attention²⁷, although these observations could be due to an obligatory preparation of saccades that occurs concurrently with covert orienting. In addition, electrical stimulation of the superior colliculus caused mild enhancements in performance on a change-blindness task¹⁹ and motion-discrimination task²⁰, which shows that the SC is at least part of the circuit for covert attention. By showing that reversible inactivation of the SC causes a profound impairment in correctly selecting which visual stimulus will inform perceptual judgments, even in the absence of eye movements, our results demonstrate not only that the primate SC is part of this circuit but that its activity is crucial for the normal control of selective attention. Hence, the SC may form a bottleneck in the control of both overt orienting and covert attention.

The primary deficit we observed after SC inactivation was an inability to filter out distracting or misleading sensory information. These effects on selective attention have a somewhat different character than those typically observed in areas of cerebral cortex, which are normally associated with increases in the detectability or discriminability of stimuli at the attended location^{28–32}. Instead, our results are reminiscent of visual extinction, a phenomenon observed in less florid cases of spatial neglect in which stimuli in the affected side of the visual field are perceived so long as there are no competing stimuli in the unaffected side³³. In the present experiment, misleading information, not simply distracters, was necessary to induce the deficits in performance. This observation suggests that a competition occurs, not simply between visual stimuli, but between the potential sources of information to guide the subject's perceptual judgment. This type of mechanism is compatible with the biased competition model of spatial attention, which holds that a

biasing signal weights stimuli in a spatially specific manner before a divisive normalization stage^{34–36}. The extinction-like deficits we observed suggest that SC inactivation disrupts the normal weighting of signals in the affected quadrant but leaves the process of divisive normalization intact. The SC is not necessarily the source of the biasing signal, but given its anatomical connections¹, it could serve as a site of convergence and integration of many potential biasing signals from various cortical and subcortical sources and then broadcast the results to appropriate targets in thalamus, cortex and elsewhere^{26,37,38}.

We also found that SC inactivation caused a mild impairment in the ability to discriminate motion signals. This more subtle effect could be due to changes in sensory processing. The discrimination of motion signals depends on neurons in the middle temporal area, which show modulation with spatial attention^{29,39} and receive indirect inputs from neurons in the more superficial layers of the SC⁴⁰. However, lesion of the SC has been shown not to lead to changes in the response properties of neurons in cortical area MT (ref. 41), suggesting that other mechanisms might be involved. In particular, changes in discrimination performance could be due to changes in how sensory signals are pooled when making decisions, with no changes in sensory processing. For instance, in monkeys learning a motion discrimination task, increases in discrimination performance were not associated with changes in the response properties of neurons in MT but instead with the association of motion signals with response directions in cortical area LIP (ref. 42). In our experiments, disruption of the normal spatial weighting of signals by SC inactivation might have allowed perceptual judgments to be influenced by irrelevant activity originating from outside the motion patch, possibly illustrating the hazards of internal noise that is not properly suppressed by selective attention⁴³.

This study demonstrates that the primate SC is not simply updated about covert selective attention but is necessary for its normal operation. The pattern of extinction-like deficits provides an outline of the possible mechanisms by which the SC makes its contribution and shows that the fronto-parietal network in cerebral cortex is insufficient on its own to allocate selective attention. Given its evolutionary history and its interconnectedness with other brain regions, identifying how the SC exerts its control over perceptual judgments is likely to be central to understanding what selective attention is and how it works.

METHODS

Methods and any associated references are available in the online version of the paper at <http://www.nature.com/natureneuroscience/>.

Note: Supplementary information is available on the Nature Neuroscience website.

ACKNOWLEDGMENTS

We thank E. Boehle and N. Dill for technical assistance. This work was supported by the Simons Foundation (R.J.K.), the Institute for Neural Computation (L.P.L.) and an Aginsky Scholars Award (L.P.L.).

AUTHOR CONTRIBUTIONS

L.P.L. and R.J.K. designed and conducted the experiments and wrote the manuscript. L.P.L. analyzed the data.

Published online at <http://www.nature.com/natureneuroscience/>.

Reprints and permissions information is available online at <http://npg.nature.com/reprintsandpermissions/>.

- Wurtz, R.H. & Albano, J.E. Visual-motor function of the primate superior colliculus. *Annu. Rev. Neurosci.* **3**, 189–226 (1980).
- Sparks, D.L. Conceptual issues related to the role of the superior colliculus in the control of gaze. *Curr. Opin. Neurobiol.* **9**, 698–707 (1999).
- McPeck, R.M. & Keller, E.L. Deficits in saccade target selection after inactivation of superior colliculus. *Nat. Neurosci.* **7**, 757–763 (2004).
- Carello, C.D. & Krauzlis, R.J. Manipulating intent: evidence for a causal role of the superior colliculus in target selection. *Neuron* **43**, 575–583 (2004).

- Heilman, K.M. Intentional neglect. *Front. Biosci.* **9**, 694–705 (2004).
- Sprague, J.M. Interaction of cortex and superior colliculus in mediation of visually guided behavior in cat. *Science* **153**, 1544–1547 (1966).
- Corbetta, M. & Shulman, G.L. Control of goal-directed and stimulus-driven attention in the brain. *Nat. Rev. Neurosci.* **3**, 201–215 (2002).
- Driver, J. & Mattingley, J.B. Parietal neglect and visual awareness. *Nat. Neurosci.* **1**, 17–22 (1998).
- Mort, D.J. *et al.* The anatomy of visual neglect. *Brain* **126**, 1986–1997 (2003).
- Corbetta, M., Kincade, M.J., Lewis, C., Snyder, A.Z. & Sapir, A. Neural basis and recovery of spatial attention deficits in spatial neglect. *Nat. Neurosci.* **8**, 1603–1610 (2005).
- Wardak, C., Ibos, G., Duhamel, J. & Olivier, E. Contribution of the monkey frontal eye field to covert visual attention. *J. Neurosci.* **26**, 4228–4235 (2006).
- Moore, T. & Armstrong, K.M. Selective gating of visual signals by microstimulation of frontal cortex. *Nature* **421**, 370–373 (2003).
- Moore, T. & Fallah, M. Control of eye movements and spatial attention. *Proc. Natl. Acad. Sci. USA* **98**, 1273–1276 (2001).
- Snyder, L.H., Batista, A.P. & Andersen, R.A. Coding of intention in the posterior parietal cortex. *Nature* **386**, 167–170 (1997).
- Bisley, J.W. & Goldberg, M.E. Neuronal activity in the lateral intraparietal area and spatial attention. *Science* **299**, 81–86 (2003).
- Gold, J.I. & Shadlen, M.N. The neural basis of decision making. *Annu. Rev. Neurosci.* **30**, 535–574 (2007).
- Kustov, A.A. & Robinson, D.L. Shared neural control of attentional shifts and eye movements. *Nature* **384**, 74–77 (1996).
- Ignashchenkova, A., Dicke, P.W., Haarmeier, T. & Thier, P. Neuron-specific contribution of the superior colliculus to overt and covert shifts of attention. *Nat. Neurosci.* **7**, 56–64 (2004).
- Cavanaugh, J. & Wurtz, R.H. Subcortical modulation of attention counters change blindness. *J. Neurosci.* **24**, 11236–11243 (2004).
- Müller, J.R., Philiastides, M.G. & Newsome, W.T. Microstimulation of the superior colliculus focuses attention without moving the eyes. *Proc. Natl. Acad. Sci. USA* **102**, 524–529 (2005).
- Quaia, C., Aizawa, H., Optican, L.M. & Wurtz, R.H. Reversible inactivation of monkey superior colliculus. II. Maps of saccadic deficits. *J. Neurophysiol.* **79**, 2097–2110 (1998).
- McCullough, P. & Nelder, J. *Generalized Linear Models* (Chapman & Hall, New York, 1990).
- Halligan, P. & Marshall, J. Toward a principled explanation of unilateral neglect. *Cogn. Neuropsychol.* **11**, 167–206 (1994).
- Joanette, Y. & Brouchon, M. Visual allesthesia in manual pointing—some evidence for a sensorimotor cerebral organization. *Brain Cogn.* **3**, 152–165 (1984).
- Goldberg, M.E. & Wurtz, R.H. Activity of superior colliculus in behaving monkey. II. Effect of attention on neuronal responses. *J. Neurophysiol.* **35**, 560–574 (1972).
- Posner, M.I. & Petersen, S.E. The attention system of the human brain. *Annu. Rev. Neurosci.* **13**, 25–42 (1990).
- Fecteau, J.H., Bell, A.H. & Munoz, D.P. Neural correlates of the automatic and goal-driven biases in orienting spatial attention. *J. Neurophysiol.* **92**, 1728–1737 (2004).
- Reynolds, J.H. & Chelazzi, L. Attentional modulation of visual processing. *Annu. Rev. Neurosci.* **27**, 611–647 (2004).
- Cook, E.P. & Maunsell, J.H.R. Attentional modulation of behavioral performance and neuronal responses in middle temporal and ventral intraparietal areas of macaque monkey. *J. Neurosci.* **22**, 1994–2004 (2002).
- Yeshurun, Y. & Carrasco, M. Attention improves or impairs visual performance by enhancing spatial resolution. *Nature* **396**, 72–75 (1998).
- Luck, S.J., Chelazzi, L., Hillyard, S.A. & Desimone, R. Neural mechanisms of spatial selective attention in areas V1, V2, and V4 of macaque visual cortex. *J. Neurophysiol.* **77**, 24–42 (1997).
- Williford, T. Effects of spatial attention on contrast response functions in macaque area V4. *J. Neurophysiol.* **96**, 40–54 (2006).
- Rafal, R.D. Neglect. *Curr. Opin. Neurobiol.* **4**, 231–236 (1994).
- Desimone, R. & Duncan, J. Neural mechanisms of selective visual attention. *Annu. Rev. Neurosci.* **18**, 193–222 (1995).
- Reynolds, J.H., Chelazzi, L. & Desimone, R. Competitive mechanisms subserve attention in macaque areas V2 and V4. *J. Neurosci.* **19**, 1736–1753 (1999).
- Reynolds, J.H. & Heeger, D.J. The normalization model of attention. *Neuron* **61**, 168–185 (2009).
- De Weerd, P., Desimone, R. & Ungerleider, L.G. Generalized deficits in visual selective attention after V4 and TEO lesions in macaques. *Eur. J. Neurosci.* **18**, 1671–1691 (2003).
- Rossi, A.F., Bichot, N.P., Desimone, R. & Ungerleider, L.G. Top down attentional deficits in macaques with lesions of lateral prefrontal cortex. *J. Neurosci.* **27**, 11306–11314 (2007).
- Treue, S. & Maunsell, J. Attentional modulation of visual motion processing in cortical areas MT and MST. *Nature* **382**, 539–541 (1996).
- Berman, R. & Wurtz, R. Exploring the pulvinar path to visual cortex. *Prog. Brain Res.* **171**, 467–473 (2008).
- Rodman, H.R., Gross, C.G. & Albright, T.D. Afferent basis of visual response properties in area MT of the macaque. II. Effects of superior colliculus removal. *J. Neurosci.* **10**, 1154–1164 (1990).
- Law, C.-T. & Gold, J.I. Neural correlates of perceptual learning in a sensory-motor, but not a sensory, cortical area. *Nat. Neurosci.* **11**, 505–513 (2008).
- Doshier, B.A. & Lu, Z.L. Mechanisms of perceptual attention in precuing of location. *Vision Res.* **40**, 1269–1292 (2000).



ONLINE METHODS

Behavioral tasks. The selective attention task required monkeys to maintain fixation while attending to a stochastic motion stimulus (**Fig. 1a**). Each trial began with the appearance of a fixation dot. Four colored circles appeared for 480 ms. The odd-colored ring indicated the cued location. Stochastic motion stimuli appeared within the circles, and, after an additional 480 ms, the cue circles disappeared. Stimuli remained on the screen for 480 ms plus a geometrically distributed delay of mean 480 ms. The hazard function remained flat for nearly the entire duration of the trial so that the monkeys were not provided with information that could allow them to predict the onset of the motion pulses. Coherent motion pulses (160 ms) occurred in both the cued location and the diametrically opposite location. Motion was transitioned from incoherent to coherent by assigning newly appearing dots into the pool of coherently moving dots. The monkeys' task was to report the direction of motion in the cued location (by saccade or button press, in separate experiments). Monkeys received a liquid reward only for correct responses in completed trials. If the monkey broke fixation midtrial, such as making a saccade toward one of the motion stimuli, the trial was aborted and repeated later in the session. Motion coherence of the pulses was titrated for each subject to maintain 65%–70% correct performance (0.1875 for subject F and 0.25 for subject M).

During both control behavior and inactivation, monkeys fixated on a small, stationary spot presented at eye level directly in front of them at the center of a cathode ray tube (CRT) display with a refresh rate of 75 Hz. The fixation spot consisted of a single pixel of background luminance surrounded by a 1-pixel-thick white square. With our display geometry and distance, this 3×3 pixel stimulus corresponded to $\sim 9 \times 9$ min arc of visual angle. The background luminance of the monitor was 14 cd m^{-2} . Luminance of the fixation dot was 50 cd m^{-2} . The cue rings appeared at an eccentricity of 8.2 degrees of visual angle (fixation point to ring center), had a diameter of 8.8 degrees of visual angle, and had a thickness of 0.25 degrees of visual angle. The ring luminance was 25 cd m^{-2} green or red. The stochastic motion stimuli appeared centered within the cue rings and had a radius of 4.25 degrees of visual angle. The stimuli consisted of limited lifespan dots²⁹. The dot lifespan was 2 refreshes. At each refresh, each dot either appeared at a random location within the patch or was displaced by 4 pixels (~ 0.2 degrees). The coherence was the proportion of total dots moving in the same direction; the remainder moved in uniformly distributed random directions. Each dot had a peak luminance of 50 cd m^{-2} . Responses were conveyed with saccades made to choice dots appearing at an eccentricity of 8.2 degrees of visual angle and with a radius of 0.2 degrees and peak luminance of 50 cd m^{-2} .

On the same day as each inactivation session, we collected preinjection control behavior on both the single-stimulus motion discrimination task (192 trials) and the selective attention task (352–528 trials). During this phase of the session, we advanced the tip of the injection cannula into the quadrigeminal cistern. After collecting preinjection control data, we advanced the injection cannula into the intermediate and deep layers of the SC and verified our position as described below. After completing the injection, we mapped the extent of the inactivation effects with visually guided saccades (80 trials). We then assessed motion discrimination performance with the single-stimulus discrimination task (192 trials) before proceeding with the selective attention task (352–528 trials). For the single-stimulus discrimination task, we randomly interleaved stimuli with a range of motion coherences (0.625, 0.125, 0.1875, 0.25, 0.375, 0.50); for the

selective attention task, we used a single coherence just above threshold for each of the monkeys (0.1875 for subject F, 0.25 for subject M).

In the button-press version of the task, subjects pushed buttons mounted at waist level on the left side of the chair within easy reach of the left hand. Four buttons were arranged in a square and each button corresponded to a direction of motion. Each subject used only its left hand to push buttons. As in the initial version of the attention task, monkeys were required to maintain fixation during the trial; in the button-press version, they were required to maintain fixation during the response period and push the button corresponding to the judgment of motion direction. They could only push buttons during this interval and were rewarded for the first button pushed.

Muscimol injections. We injected muscimol ($0.5 \mu\text{l}$, $5 \mu\text{g} \mu\text{l}^{-1}$), a GABA agonist, into the intermediate and deep layers of the SC using an injection cannula with an electrode threaded down its barrel⁴⁴. Three methods allowed us to localize the cannula tip within the SC before injection (**Supplementary Fig. 1**). First, we advanced the cannula to a depth (1.5–3 mm below the SC surface) corresponding to the intermediate and deep layers based on a history of microelectrode recordings and histological studies¹. Second, we recorded activity during saccades consistent with known responses in the SC, thus confirming the depth in the SC. The location of the units' movement fields also indicated our placement within the SC's retinotopic map. Third, we evoked saccades with microstimulation. The current required to evoke saccades (typically $10 \mu\text{A}$ in the intermediate and deep layers) provided a further indication of depth, and the direction and amplitude of the evoked saccades indicated the position within the map. Nonetheless, we cannot be certain that our effects are due solely to inactivation of neurons in the intermediate and deep layers of the SC because some drug may have diffused vertically through the layers or tracked up the shaft of the injection cannula to affect neurons in the overlying superficial layers.

We performed a total of 35 SC inactivation experiments in the two monkeys. The saccade response version included seven for subject F and four for subject M; this version of the task also included the single-patch control experiment. For the button-press version of the task, we inactivated at four sites for subject F and four sites for subject M; we also conducted one saline control experiment with the button-press task in subject M. Finally, for the experiments varying the coherence in both the foil and cue patches, we conducted four sessions in each of the two subjects and pooled the data across those sessions separately for each subject. Injection sessions are detailed in **Supplementary Tables 1–3**.

Monkey preparation. We performed reversible inactivation of the intermediate and deep layers of the superior colliculus in two adult rhesus monkeys (subjects F and M) that were 10–15 years of age and weighed 12–15 kg. The monkeys were prepared using standard surgical techniques described in detail previously⁴⁵. All experimental protocols were approved by the Institutional Animal Care and Use Committee and complied with US Public Health Service policy on the humane care and use of laboratory animals. The laboratory setup for behavioral control and monitoring was identical to that described previously⁴⁵.

44. Chen, L.L., Goffart, L. & Sparks, D.L. A simple method for constructing microinjectrodes for reversible inactivation in behaving monkeys. *J. Neurosci. Methods* **107**, 81–85 (2001).

45. Hafed, Z.M., Goffart, L. & Krauzlis, R.J. Superior colliculus inactivation causes stable offsets in eye position during tracking. *J. Neurosci.* **28**, 8124–8137 (2008).