Current Biology, Vol. 15, 122–128, January 26, 2005, ©2005 Elsevier Ltd All rights reserved. DOI 10.1016/j.cub.2005.01.006

Volition and Conflict in Human Medial Frontal Cortex

Parashkev Nachev,[1] Geraint Rees,[2] Andrew Parton,[1,2] Christopher Kennard,[1] and Masud Husain[1,2,*]
[1]Department of Visual Neuroscience
Imperial College London
St Dunstan's Road
London W6 8RP
United Kingdom
[2]Institute of Cognitive Neuroscience
University College London
Alexandra House
17 Queen Square
London WC1N 3AR
United Kingdom

Summary

Controversy surrounds the role of human medial frontal cortex in controlling actions [1–5]. Although damage to this area leads to severe difficulties in spontaneously initiating actions [6], the precise mechanisms underlying such "volitional" deficits remain to be established. Previous studies have implicated the medial frontal cortex in conflict monitoring [7–10] and the control of voluntary action [11, 12], suggesting that these key processes are functionally related or share neural substrates. Here, we combine a novel behavioral paradigm with functional imaging of the oculomotor system to reveal, for the first time, a functional subdivision of the pre-supplementary motor area (pre-SMA) into anatomically distinct areas that respond exclusively to either volition or conflict. We also demonstrate that activity in the supplementary eye field (SEF) distinguishes between success and failure in changing voluntary action plans during conflict, suggesting a role for the SEF in implementing the resolution of conflicting actions. We propose a functional architecture of human medial frontal cortex that incorporates the generation of action plans and the resolution of conflict.

Results and Discussion

To understand conscious behavior, we need to understand how voluntary and reflexive actions differ. A defining feature of voluntary actions is that one can choose whether or not to execute them [13]. By contrast, although one may be able to suppress a reflexive action, its initiation is not the outcome of a choice but of an environmental—usually external—event. For this reason, studies that have attempted to isolate what is most distinctive about voluntary action have focused on the choice between two or more possible actions under conditions where that choice is least open to bias from external stimuli [12, 14–16]. The study of such "free-choice" or "underdetermined" [3] behavior is considered to be most revealing about the neural systems underlying volition—the capacity to choose between voluntary action plans.

However, an inevitable consequence of choosing between different action plans is the potential for conflict between them. This conflict may be greatest when no single action plan is preferable to another, as is necessarily the case in free-choice tasks. Thus, a neural system identified with a free-choice paradigm may actually be responsible for resolving conflict between incompatible action plans rather than for the volitional process of choosing between them. The use of free-choice paradigms to investigate volition may therefore be critically confounded by conflict.

Conversely, tasks such as the Stroop [17] and Eriksen flanker [18] paradigms, which were designed to probe the brain's response to behavioral conflict, typically place a well-learned or reflexive action in opposition to another action that is less potently specified by the environmental circumstances that prompt it. Therefore, if there is a distinct neural system dealing with choosing between voluntary actions, this system will be engaged to a lesser extent by the more automatic action. Consequently, the comparison of neural activity between these two actions potentially reveals not only activity related to conflict but also activity related to volition. Paradigms that traditionally have been used to assess conflict may thus be equally confounded by volition.

The medial-frontal-cortex activation widely reported in studies of conflict and free choice is therefore subject to a potential double confound, giving rise to several possible interpretations. First, activation attributed to conflict may be entirely due to a system subserving volition, or vice versa, suggesting that only one of these processes actually involves the medial frontal cortex. Second, the same system may be engaged identically by both processes, casting doubt on the theoretical distinction between them. Third, activation may be the consequence of an interaction between the two processes, either because one influences the other or because their combination triggers another process altogether. Finally, volition and conflict may independently engage closely neighboring neural substrates within medial frontal cortex.

To understand the role of this region in the control of voluntary action, we must therefore try to distinguish between these interpretations. Here, we sought to do this by using a factorial manipulation of volition and conflict in a novel oculomotor change-of-plan task involving balanced voluntary movements. We manipulated volition by asking subjects either to follow a specific movement plan or to choose freely between two alternatives. We manipulated conflict by asking them either to continue with their plan or to change it rapidly. If volition and conflict modulate different areas within medial frontal cortex, we can conclude that these processes are dissociated in the brain. Furthermore, we can also determine whether these processes operate

*Correspondence: m.husain@imperial.ac.uk

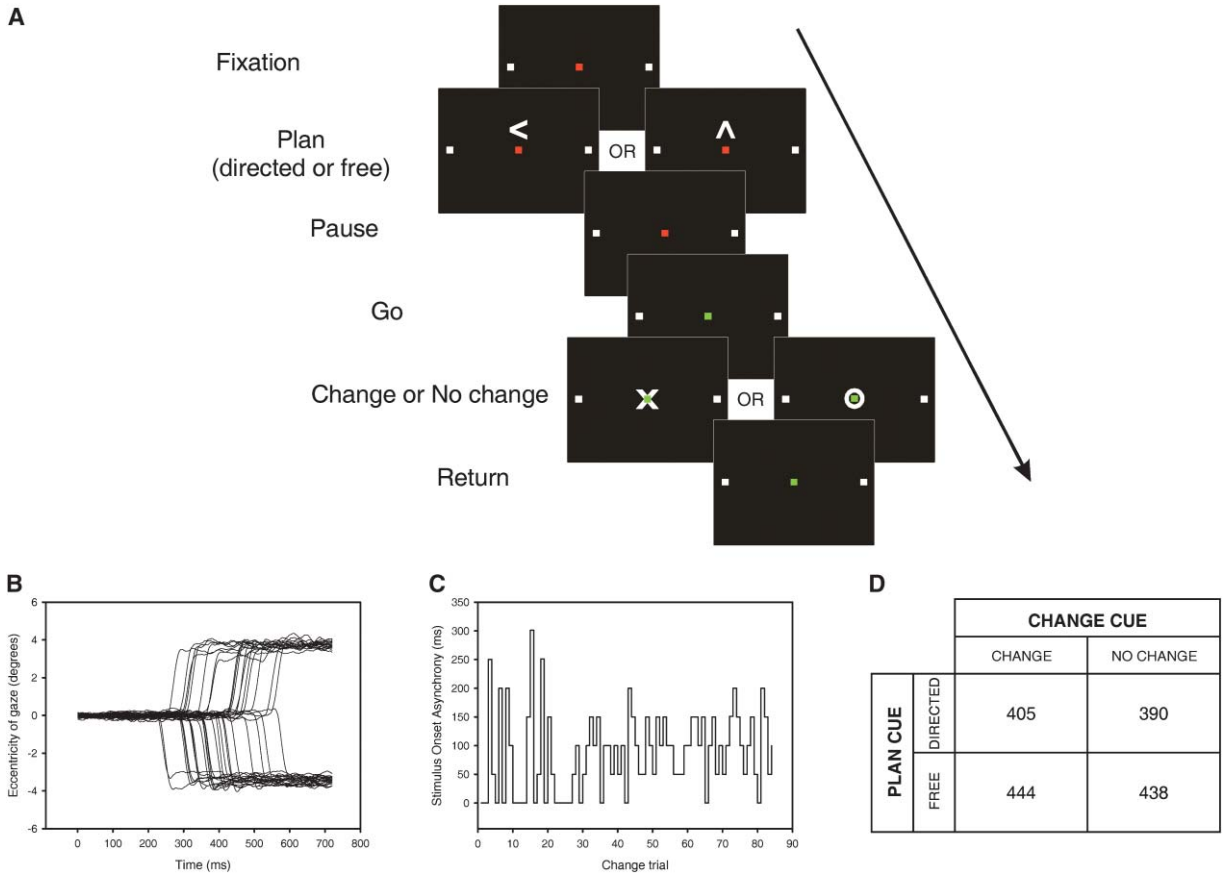

Figure 1. Experimental Paradigm and Behavior

(A) Temporal sequence of visual cues during each trial (not to scale). While fixating a red square, subjects planned a speeded saccade to one of two targets (white squares) that were either freely chosen (free plan) or specifically indicated (directed plan; here, a left plan is illustrated). A change in the fixation cue from red to green ("go" cue) signaled the execution of the saccade. After a variable interval (stimulus onset asynchrony) following the go cue, and before the saccade was executed, a "change" or "no-change" cue instructed subjects either to continue with their plan or to execute a saccade to the opposite target instead. The SOA was modulated online to target a 50% success rate in directed change trials.

(B) Raw saccadic traces from one subject performing the task in the scanner (negative eccentricity indicates leftward displacement). Data from left-directed change trials are shown.

(C) Plot of SOA for directed change trials performed by one subject. After each direct change trial, the SOA was automatically increased or decreased by 50 ms depending on whether the subject succeeded or failed in changing plans [40]. The algorithm sampled randomly from two independent threads starting at 0 and 300 ms.

(D) Group mean of individual subject median saccadic latencies (ms) collected during scanning for each trial type. At the group level, there was no significant main effect of choice ($p = 0.09$) or conflict ($p = 0.57$) on Friedman's test.

independently or not by looking for a statistical interaction between the factors used to manipulate them.

In addition, we predicted that the outcome of conflict between voluntary saccadic plans in our experiment would be reflected by activity within the SEF, a medial structure that is implicated in the control of saccades during conflict [19–22] and that has direct connections to brainstem oculomotor centers.

Nine subjects performed the change-of-plan task, which is related to saccadic countermanding [23, 24] and choice [25] paradigms (Figure 1; see Experimental Procedures). On each trial, subjects were instructed by a central cue to plan a saccade to one of two fixed targets placed horizontally on either side of central fixation. The target was either specifically indicated by the planning cue ("directed" trials) or freely chosen by the subject ("free" trials). After a variable short interval ($\sim$1 s) that allowed them to choose their target and prepare for the saccade, subjects were centrally cued to perform their planned saccade as quickly as they could ("go" cue). After another variable interval (stimulus onset asynchrony), a cue presented at fixation instructed subjects either to continue with their original plan ("no-change" trials) or to cancel it and execute a saccade as rapidly as possible to the opposite target ("change" trials).

In no-change trials there was no explicit competition between movement plans. By contrast, in change trials the movement plans cued by the go and change signals were placed in direct competition, with the level of conflict being critically biased by the SOA. In such race model paradigms [24–26], the two competing processes are envisaged as racing against each other independently, with the outcome being a monotonic function of

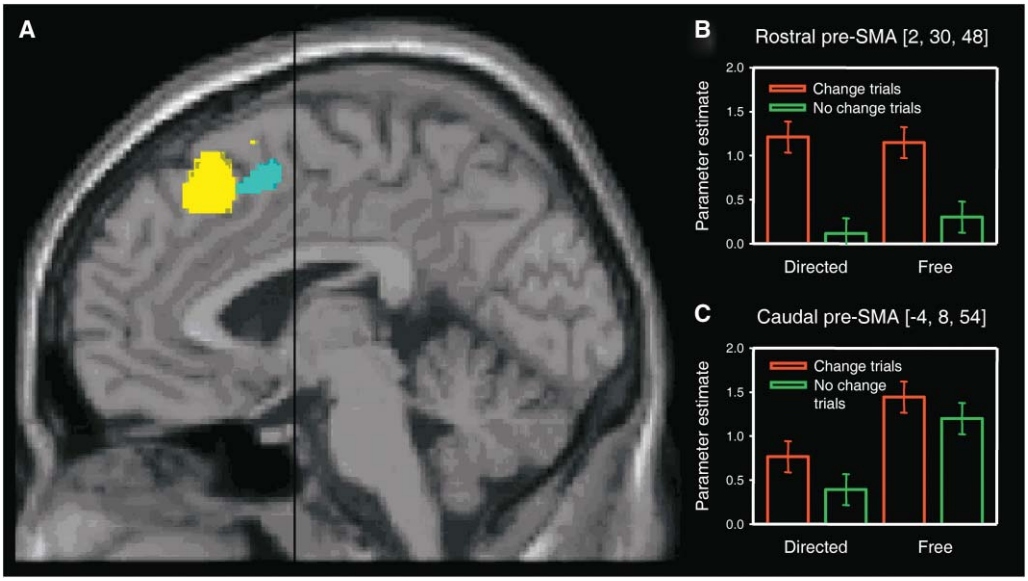

Figure 2. Pre-SMA Activation Associated with Changing Volitional Plans and with Free Choice

(A) Statistical parametric maps showing group main effects of changing plans in rostral pre-SMA (yellow, coordinates 2, 30, 48) and free choice in caudal pre-SMA (cyan, coordinates −4, 8, 54) at a threshold of $p < 0.001$ uncorrected are superimposed on a MNI standard single subject T1-weighted MRI scan. A black line indicates the position of the anterior commissure (VCA line).

(B) Signal change in rostral pre-SMA cluster indexed by the parameter estimates for each of the four main conditions. Note significant conflict-related activity on both free and directed trials. Error bars correspond to 90% confidence intervals.

(C) Corresponding plot for the caudal pre-SMA cluster showing a main effect of free choice and the absence of significant conflict-related activity. Neither rostral nor caudal pre-SMA showed a significant interaction (at a threshold of $p < 0.001$ uncorrected) between the effects of the two factors (choice and conflict), suggesting that volition does not modulate the activation of the conflict-related area and that conflict does not modulate the activation of the volition-related area.

their speed and the delay between them (the SOA). If the SOA is too short, subjects have ample time to change saccade direction, and little conflict ensues; if the SOA is too long, the change instruction occurs too late to interfere with the planned saccade and thus generate any conflict. We therefore maximized the conflict during change trials on an individual subject basis by automatically adjusting the SOA during the course of the experiment as performance varied, so that a successful change of plan occurred on approximately half of all direct change trials (Figure 1C). Thus, in this paradigm we were able to independently manipulate volition (free versus directed) and conflict (change versus no change).

Our paradigm offered a number of critical advantages over other paradigms specifically designed to study conflict or free choice. First, unlike "go-nogo" [27] and classical countermanding paradigms [23, 26], a single response occurred in all conditions, allowing for balance of response-related effects. Second, our performance-tracking algorithm ensured, independently of individual reaction times, that the level of conflict across subjects was similar. Third, our manipulation also resulted in approximately equal frequencies of errors and successes in the change task, ensuring that error-related activity was not confounded by "oddball" responses to the rarity of such events (another common problem in conflict tasks). Finally, because the no-change condition was signaled by an explicit cue—and therefore required active monitoring—our design allowed us to eliminate activation related to attention or arousal, or to an imbalance in the number of visual events.

The saccadic latencies obtained during scanning were consistent with a race model in which the response is determined by the outcome of competition between the "go" and "change" processes. Critically, directed trials on which subjects failed to change their planned saccade (i.e., errors) had significantly lower saccadic latencies than those on which they successfully changed plans (median difference = 107 ms; distributions significantly different within each subject, $p = 0.05$; one-tailed, two-sample Kolmogorov-Smirnov test; see Figure S1 in the Supplemental Data available with this article online). For each subject, plots of the probability of successfully changing plans against the SOA adjusted for individual variations in reaction time showed a monotonic relation as predicted by the race model (see Figure S2). Furthermore, the SOA manipulation successfully balanced the frequency of errors and successes on direct change trials (mean proportion of errors across subjects = 0.51; SE = 0.02). Although there was considerable variation between individuals, there was no systematic difference in latency between free and directed trials (Figures 1D and S3.) This is not unexpected because subjects in both types of trials were given ample time (between 800 and 1200 ms) to prepare a response (see Experimental Procedures).

Analysis of blood oxygenation level-dependent (BOLD) responses in medial frontal cortex revealed activation in the rostral pre-SMA (coordinates 2, 30, 48; $t = 5.53$; $p = 0.001$ corrected for multiple comparisons) specifically associated with changing plans (conflict factor). Importantly, conflict-associated activity here was

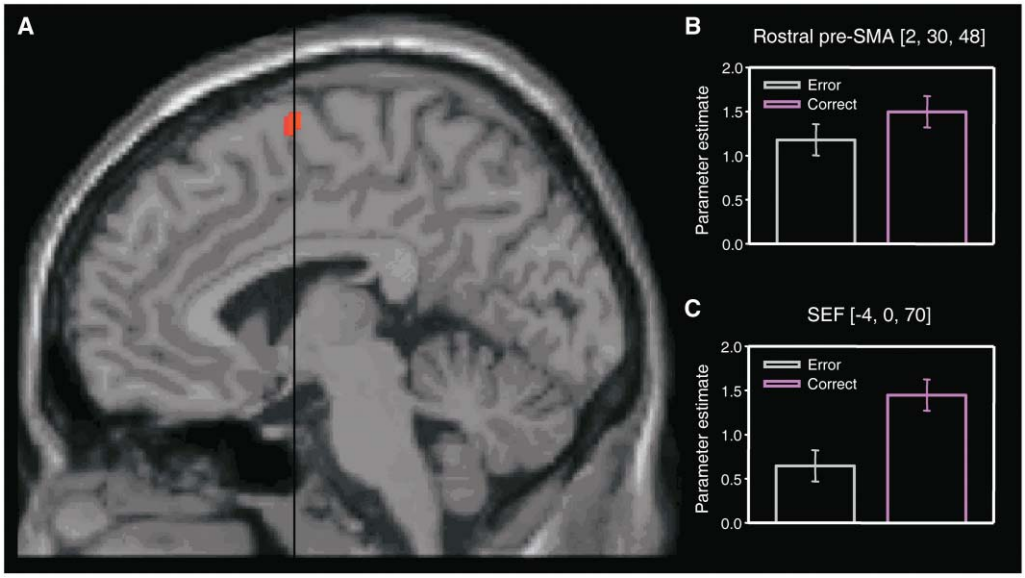

Figure 3. SEF Activation Associated with Successfully Changing Plans

(A) Comparison of successfully changed versus unsuccessfully changed directed trials reveals activity in the SEF. The statistical parametric map has been thresholded at $p < 0.001$ uncorrected and superimposed on a MNI standard single subject T1-weighted MRI scan. A black line indicates the position of the anterior commissure (VCA line).

(B) Signal change in the conflict-responsive rostral pre-SMA cluster (see Figure 2) indexed by the parameter estimates for unsuccessfully (yellow) and successfully (blue) changed directed trials. Note the absence of a significant difference (at $p < 0.001$ uncorrected). Error bars correspond to 90% confidence intervals.

(C) Corresponding plot for the SEF cluster showing that activity in this region discriminates between success and failure in changing oculomotor plans.

indistinguishable in the context of either free or directed choice (volition factor) (interaction, $t = 1.19$, $p = 0.121$ uncorrected, see Figure 2B). Activity in this rostral region of pre-SMA therefore reflected the level of conflict independently of volition. In contrast, a more caudal region of the pre-SMA (Figure 2A) was modulated by volition (coordinates -4, 8, 54; $t = 4.03$; $p = 0.043$ corrected) without being significantly influenced by conflict (interaction, $t = 0.59$, $p = 0.280$ uncorrected, see Figure 2C). Note that these two loci are separated by 23 mm, which is significantly greater than the spatial resolution afforded by the neuroimaging data and thus indicates a clear anatomical dissociation.

Our findings suggest that previous reports [12, 15, 16] of pre-SMA/SMA activation in free-choice tasks are not related to conflict but instead arise from a functional segregation within the pre-SMA between a rostral region engaged by conflict and a more caudal region associated with volition. Moreover, the lack of an interaction between the effects of volition and conflict on the BOLD response suggests that these two processes engage distinct and independent systems within medial frontal cortex.

Some previous investigations of behavioral conflict [7, 8, 28] have implicated the anterior cingulate, rather than pre-SMA; however, they employed very different paradigms, such as the Stroop or "flanker" tasks, from the one used here. Equally, activation of the cingulate has been demonstrated when self-initiated and externally cued movements are compared [29], suggesting a role for this region in some aspect of voluntary movement. Although distinguishing between medial areas can be difficult as a result of peculiarities of the standard template used in functional imaging [4], the centers of conflict- and volition-related activation in our study lie outside the cingulate gyrus. It remains a possibility that conflict generated in tasks that are purely motoric, as here, engages different medial structures from conflict evoked by cognitive tasks such as the Stroop. Alternatively, response competition—even on cognitive tasks—may activate the pre-SMA [9, 10], and cingulate responses observed in previous studies may be related to task factors other than conflict [30, 31]. If the pre-SMA is indeed the critical region engaged by conflict, a simple "conflict monitoring" hypothesis [3] to explain its function would be hard to sustain in light of its involvement in other motor control aspects, such as selecting between different response sets [32, 33]. Instead, pre-SMA activity during conflict may be related to resolving competition between incompatible action plans so as to allow the desired plan to be performed.

If the rostral pre-SMA is engaged by conflict, it is natural to consider where the control necessary to successfully change an action plan is implemented. Such an area may be expected to show significantly greater activity on successful change trials compared with unsuccessful change trials. Within the medial frontal cortex we found this effect only in the vicinity of the SEF (coordinates -4, 0, 70; $t = 4.39$; $p = 0.018$ corrected; Figure 3). This suggests that in situations of response conflict in the oculomotor domain the SEF may be responsible for implementing the necessary control. An alternative

explanation for our findings is that SEF activity reflected more intensive saccadic planning during successful change trials (which necessarily involved two saccadic plans) because on some unsuccessful change trials subjects may not have even planned a change saccade. However, such an explanation is unlikely for two reasons. First, if subjects were simply not responding to the change cue on some trials, the SOA adapting algorithm would not have converged, as it did, on a threshold value. Second, the tracking algorithm had high temporal resolution (50 ms) and successfully targeted a 50% performance level. Hence, the change cue timings were very similar for successes and errors (mean difference in SOA = 46.7 ms [SE = 5.8 ms]), making it implausible that the change cue could have occurred too late for subjects even to attempt to make a plan.

Our findings converge with a recent report demonstrating a deficit in changing oculomotor plans in a patient with a highly focal SEF lesion [19]. However, the data presented here go considerably beyond that single case study by providing a direct insight into the mechanisms that are normally engaged by conflict and which clearly involve the pre-SMA (Figure 2). Another study has shown error-related activity in monkey SEF during a related conflict task known as saccadic countermanding [21]. However, because this involves withholding a response rather than making an alternative one, a direct comparison with our paradigm is not straightforward. Moreover, previous monkey and human studies, including those that have examined antisaccades [34, 35], have employed peripheral cues and therefore investigated suppression of reflexive behavior rather than conflict between voluntary action plans, as is the case here. In fact, using a fixed SOA variant of the change paradigm employed here, a recent microelectrode recording study in the macaque showed, in agreement with our finding, modulation of task-related activity by conflict in the SEF but no evidence of pure conflict-related activity in the SEF or ACC [31].

Conclusions

Taken together, our data suggest a new model of the role of dorsomedial frontal cortex in voluntary behavior. We propose that the rostral pre-SMA is engaged in resolving conflict between incompatible voluntary action plans. Resolution of such conflict (at least in the oculomotor domain) may be implemented via the SEF, with which rostral pre-SMA appears functionally interconnected [36] and which has direct connections to brainstem oculomotor centers [37]. We found that conflict-related modulation of rostral pre-SMA was not related to volition, suggesting that free voluntary action does not itself engender conflict. We propose that, in contrast to the role of rostral pre-SMA, generation of volitional plans engages the caudal pre-SMA. This area may also be involved in generating saccadic sequences [38] and attending to intentions [39]. The fractionation of medial frontal cortex function suggested by our experimental findings provides a testable framework for further experimentation in humans and other primates.

Experimental Procedures

Subjects

Twelve right-handed, 18- to 38-year-old volunteers with normal or corrected-to-normal vision gave informed consent to participate in the experiment, which was approved by the local ethics committee. The data from three subjects were not analyzed because these subjects were unable to perform the task in the scanner.

Procedure

The experiment employed a 2 × 2 factorial design, with saccadic plan (free or directed) and saccadic response (change or no change) as within-subject factors. Each subject performed a total of 378 trials in three equal runs during a single imaging session. The trial stimuli were back-projected onto a frosted glass screen at the bore of the magnet, which the subjects viewed via a mirror positioned above the head coil. Three horizontally arranged squares, each subtending 0.2°, were displayed against a dark background throughout the experiment. The two white outer squares (placed at 3.6° eccentricity) served as saccadic targets, and the central square served as the fixation point. Each trial began with a fixation period (400–600 ms duration), indicated by the fixation cue turning red in color. This was followed by an arrow "plan" cue (0.4° wide, 200 ms duration) displayed above the fixation point. The cue instructed subjects, with equal probability, to prepare a saccade either to a specific target (left/right arrow, directed trials) or to the target of their free choice (up arrow, free trials). Subjects maintained fixation for a further 800–1200 ms until a change in the color of the fixation point to green ("go" cue) instructed them to execute their prepared saccade as quickly as possible. After a variable interval following the go cue (SOA), a second cue was presented at fixation (0.4° wide, 200 ms duration) and instructed subjects, with equal probability, either to continue with their prepared saccade (circle, no-change trials) or to change their plan and execute a saccade in the opposite direction (cross, change trials). In cases of error, subjects were asked not to make a corrective movement. To optimize the difficulty of the change trials, we manipulated the SOA by a staircase adaptive algorithm [40] that responded to success or failure on each direct change trial by respectively increasing or decreasing the SOA by 50 ms on subsequent trials (see Figure 1C). To reduce predictability, the algorithm sampled randomly from two staircases starting at 0 ms and 300 ms. Catch trials (11% of total), where the plan cue was immediately followed by a go cue, were included to verify that subjects responded to the planning cue. Subjects in all trials had to return their gaze to the fixation point within 2000 ms of the go cue for the onset of the next trial. Trials were presented in a predetermined pseudorandomized order optimized for the contrasts of interest with a genetic algorithm procedure [41].

Eye Tracking

Eye movements were recorded in the scanner with an ASL model 504 LRO infrared video-based eye tracker (Applied Science Laboratories, Bedford, MA) sampling at 240 Hz (see Figure 1B). Eye position was computed online by an ASL 5000 series controller and fed asynchronously into the stimulus-generating PC. Horizontal eye position was analyzed in the intertrial interval, and a lateral gaze shift of 2° was considered to be a response for the purpose of updating the adaptive thresholding algorithm. The latency and fidelity of eye movement responses were determined offline with custom routines written in Matlab (Mathworks, MA).

fMRI Data Acquisition

Scanning was performed on a 1.5T Siemens Magnetom Vision system at Charing Cross Hospital; a standard head coil was used. Functional data were collected with a T2*-weighted echoplanar sequence (TR = 3700 ms, TE = 60 ms, 34 axial slices, resolution 3.5 × 3.5 × 3.5, interleaved acquisition) in three sessions of 180 volumes each. The first five volumes of each session were discarded to allow for magnetic saturation effects.

Data Analysis

fMRI data were analyzed with SPM2 (http://www.fil.ion.ucl.ac.uk/spm). The images were realigned, "unwarped" to remove variance caused by movement-by-field-inhomogeneity interactions, normalized to a standard EPI template, and smoothed with a gaussian kernel of 10 mm full-width at half-maximum. The data were high-pass filtered (0.001953 Hz cutoff) to remove low-frequency signal drifts. As a test for task-related activations, the data were subjected to a two-level random-effects analysis via an epoch-based design.

The data were modeled voxel-wise, for which a general linear model (GLM) that included the experimental conditions with correct and incorrect trials modeled separately was used. The resulting parameter estimates for each regressor at each voxel were then entered into a second-level analysis, where each subject served as a random effect in a within-subject ANOVA. The main effects and interactions between conditions were then specified by appropriately weighted linear contrasts and determined with the t statistic on a voxel-by-voxel basis. A statistical threshold of $p < 0.001$ uncorrected for multiple comparisons was used to identify regions of activation within the entire medial frontal wall anterior to a line passing through the anterior commissure (VCA). This region of interest was then extended 10 mm posteriorly to include the entirety of the SEF cluster. Reported activations in the pre-SMA and SEF were corrected for multiple comparisons with a volume of interest generously defined a priori as the intersection of Brodmann areas 6, 8, and 9, and the medial frontal gyrus label in the Talairach Daemon database [42].

Supplemental Data

Supplemental figures are available with this article online at http://www/current-biology.com/cgi/content/full/15/2/122/DC1/.

Acknowledgments

This work was funded by the Wellcome Trust (M.H, C.K., G.R.)

Received: September 3, 2004
Revised: October 21, 2004
Accepted: November 5, 2004
Published: January 26, 2005

References

1. Picard, N., and Strick, P.L. (2001). Imaging the premotor areas. Curr. Opin. Neurobiol. *11*, 663–672.
2. Paus, T. (2001). Primate anterior cingulate cortex: Where motor control, drive and cognition interface. Nat. Rev. Neurosci. *2*, 417–424.
3. Botvinick, M.M., Braver, T.S., Barch, D.M., Carter, C.S., and Cohen, J.D. (2001). Conflict monitoring and cognitive control. Psychol. Rev. *108*, 624–652.
4. Rushworth, M.F., Walton, M.E., Kennerley, S.W., and Bannerman, D.M. (2004). Action sets and decisions in the medial frontal cortex. Trends Cogn. Sci. *8*, 410–417.
5. Gehring, W.J., and Fencsik, D.E. (2001). Functions of the medial frontal cortex in the processing of conflict and errors. J. Neurosci. *21*, 9430–9437.
6. Laplane, D., Talairach, J., Meininger, V., Bancaud, J., and Orgogozo, J.M. (1977). Clinical consequences of corticectomies involving the supplementary motor area in man. J. Neurol. Sci. *34*, 301–314.
7. Botvinick, M., Nystrom, L.E., Fissell, K., Carter, C.S., and Cohen, J.D. (1999). Conflict monitoring versus selection-for-action in anterior cingulate cortex. Nature *402*, 179–181.
8. Carter, C.S., Braver, T.S., Barch, D.M., Botvinick, M.M., Noll, D., and Cohen, J.D. (1998). Anterior cingulate cortex, error detection, and the online monitoring of performance. Science *280*, 747–749.
9. Garavan, H., Ross, T.J., Kaufman, J., and Stein, E.A. (2003). A midline dissociation between error-processing and response-conflict monitoring. Neuroimage *20*, 1132–1139.
10. Ullsperger, M., and von Cramon, D.Y. (2001). Subprocesses of performance monitoring: a dissociation of error processing and response competition revealed by event-related fMRI and ERPs. Neuroimage *14*, 1387–1401.
11. Thaler, D., Chen, Y.C., Nixon, P.D., Stern, C.E., and Passingham, R.E. (1995). The functions of the medial premotor cortex. I. Simple learned movements. Exp. Brain Res. *102*, 445–460.
12. Lau, H.C., Rogers, R.D., Ramnani, N., and Passingham, R.E. (2004). Willed action and attention to the selection of action. Neuroimage *21*, 1407–1415.
13. Passingham, R.E. (1995). The Frontal Lobes and Voluntary Action (Oxford: Oxford University Press).
14. Frith, C.D., Friston, K., Liddle, P.F., and Frackowiak, R.S. (1991). Willed action and the prefrontal cortex in man: A study with PET. Proc. R. Soc. Lond. B. Biol. Sci. *244*, 241–246.
15. Deiber, M.P., Passingham, R.E., Colebatch, J.G., Friston, K.J., Nixon, P.D., and Frackowiak, R.S. (1991). Cortical areas and the selection of movement: A study with positron emission tomography. Exp. Brain Res. *84*, 393–402.
16. Playford, E.D., Jenkins, I.H., Passingham, R.E., Nutt, J., Frackowiak, R.S., and Brooks, D.J. (1992). Impaired mesial frontal and putamen activation in Parkinson's disease: A positron emission tomography study. Ann. Neurol. *32*, 151–161.
17. Stroop, J.R. (1935). Studies of interference in serial verbal reactions. J. Exp. Psychol. Gen. *18*, 643–662.
18. Eriksen, B.A., and Eriksen, C.W. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. Percept. Psychophys. *16*, 143–149.
19. Husain, M., Parton, A., Hodgson, T.L., Mort, D., and Rees, G. (2003). Self-control during response conflict by human supplementary eye field. Nat. Neurosci. *6*, 117–118.
20. Schall, J.D., Stuphorn, V., and Brown, J.W. (2002). Monitoring and control of action by the frontal lobes. Neuron *36*, 309–322.
21. Stuphorn, V., Taylor, T.L., and Schall, J.D. (2000). Performance monitoring by the supplementary eye field. Nature *408*, 857–860.
22. Schlag-Rey, M., Amador, N., Sanchez, H., and Schlag, J. (1997). Antisaccade performance predicted by neuronal activity in the supplementary eye field. Nature *390*, 398–401.
23. Hanes, D.P., and Schall, J.D. (1995). Countermanding saccades in macaque. Vis. Neurosci. *12*, 929–937.
24. Hanes, D.P., and Carpenter, R.H. (1999). Countermanding saccades in humans. Vision Res. *39*, 2777–2791.
25. Leach, J.C., and Carpenter, R.H. (2001). Saccadic choice with asynchronous targets: Evidence for independent randomisation. Vision Res. *41*, 3437–3445.
26. Logan, G.D., Cowan, W.B., and Davis, K.A. (1984). On the ability to inhibit simple and choice reaction time responses: a model and a method. J. Exp. Psychol. Hum. Percept. Perform. *10*, 276–291.
27. Simson, R., Vaughan, H.G., Jr., and Ritter, W. (1977). The scalp topography of potentials in auditory and visual Go/NoGo tasks. Electroencephalogr. Clin. Neurophysiol. *43*, 864–875.
28. Kerns, J.G., Cohen, J.D., MacDonald, A.W., III, Cho, R.Y., Stenger, V.A., and Carter, C.S. (2004). Anterior cingulate conflict monitoring and adjustments in control. Science *303*, 1023–1026.
29. Deiber, M.P., Honda, M., Ibanez, V., Sadato, N., and Hallett, M. (1999). Mesial motor areas in self-initiated versus externally triggered movements examined with fMRI: Effect of movement type and rate. J. Neurophysiol. *81*, 3065–3077.
30. Critchley, H.D., Mathias, C.J., Josephs, O., O'Doherty, J., Zanini, S., Dewar, B.K., Cipolotti, L., Shallice, T., and Dolan, R.J. (2003). Human cingulate cortex and autonomic control: converging neuroimaging and clinical evidence. Brain *126*, 2139–2152.
31. Nakamura, K., Roesch, M.R., and Olson, C.R. (2004). Neuronal activity in macaque SEF and ACC during performance of tasks involving conflict. J. Neurophysiol., in press. Published online August 4, 2004. 10.1152/jn.00305.2004.
32. Shima, K., Mushiake, H., Saito, N., and Tanji, J. (1996). Role for cells in the presupplementary motor area in updating motor plans. Proc. Natl. Acad. Sci. USA *93*, 8694–8698.
33. Rushworth, M.F., Hadland, K.A., Paus, T., and Sipila, P.K. (2002). Role of the human medial frontal cortex in task switching: A combined fMRI and TMS study. J. Neurophysiol. *87*, 2577–2592.
34. Curtis, C.E., and D'Esposito, M. (2003). Success and failure suppressing reflexive behavior. J. Cogn. Neurosci. *15*, 409–418.
35. Amador, N., Schlag-Rey, M., and Schlag, J. (2004). Primate antisaccade. II. Supplementary eye field neuronal activity predicts correct performance. J. Neurophysiol. *91*, 1672–1689.
36. Fujii, N., Mushiake, H., and Tanji, J. (2002). Distribution of eye- and arm-movement-related neuronal activity in the SEF and in the SMA and Pre-SMA of monkeys. J. Neurophysiol. *87*, 2158–2166.
37. Huerta, M.F., and Kaas, J.H. (1990). Supplementary eye field as defined by intracortical microstimulation: Connections in macaques. J. Comp. Neurol. *293*, 299–330.
38. Isoda, M., and Tanji, J. (2004). Participation of the primate presupplementary motor area in sequencing multiple saccades. J. Neurophysiol. *92*, 653–659.

39. Lau, H.C., Rogers, R.D., Haggard, P., and Passingham, R.E. (2004). Attention to intention. Science *303*, 1208–1210.
40. Levitt, H. (1971). Transformed up-down methods in psychoacoustics. J. Acoust. Soc. Am. Suppl. 2. *49*, 467-477.
41. Wager, T.D., and Nichols, T.E. (2003). Optimization of experimental design in fMRI: A general framework using a genetic algorithm. Neuroimage *18*, 293–309.
42. Maldjian, J.A., Laurienti, P.J., Kraft, R.A., and Burdette, J.H. (2003). An automated method for neuroanatomic and cytoarchitectonic atlas-based interrogation of fMRI data sets. Neuroimage *19*, 1233–1239.

Supplemental Data

Volition and Conflict in Human Medial Frontal Cortex

Parashkev Nachev, Geraint Rees, Andrew Parton, Christopher Kennard, and Masud Husain

Supplemental References

S1. Wichmann, F.A., and Hill, N.J. (2001). The psychometric function: I. Fitting, sampling, and goodness of fit. Percept. Psychophys. *63*, 1293–1313.

S2. Wichmann, F.A., and Hill, N.J. (2001). The psychometric function: II. Bootstrap-based confidence intervals and sampling. Percept. Psychophys. *63*, 1314–1329.

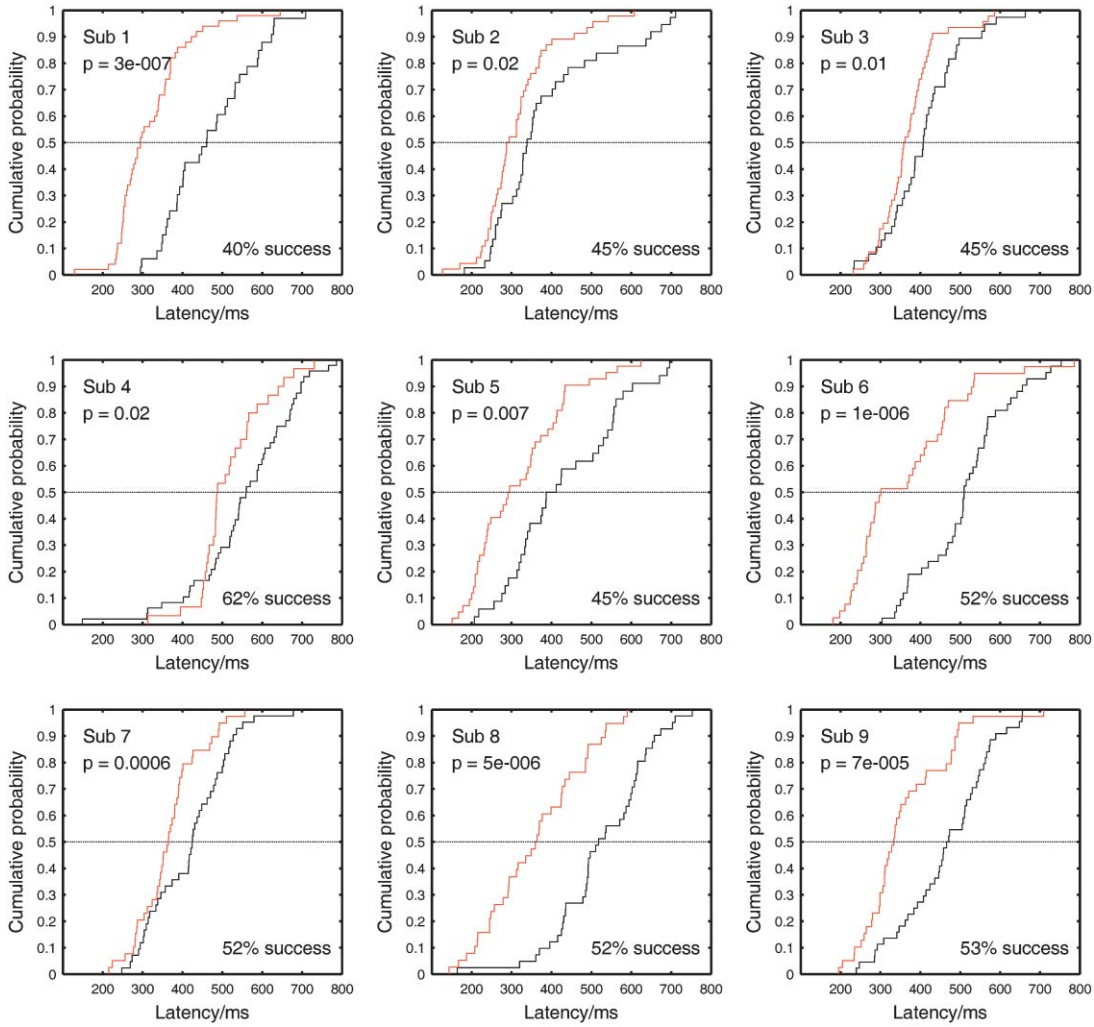

Figure S1. Behavioral Analysis of Successes and Errors

Latency distributions for unsuccessful direct change trials (red) and successful direct change trials (black) obtained in the scanner based on a mean of 81 observations per subject (STD = 2.71). For each subject, the distributions are significantly different on a two-sample Kolmogorov-Smirnov test at $p = 0.05$ (asymptotic p values given in plots). These results are consistent with the outcome of each trial being decided by a race between the two competing processes. The overall probability of successfully changing direction is also given for each subject.

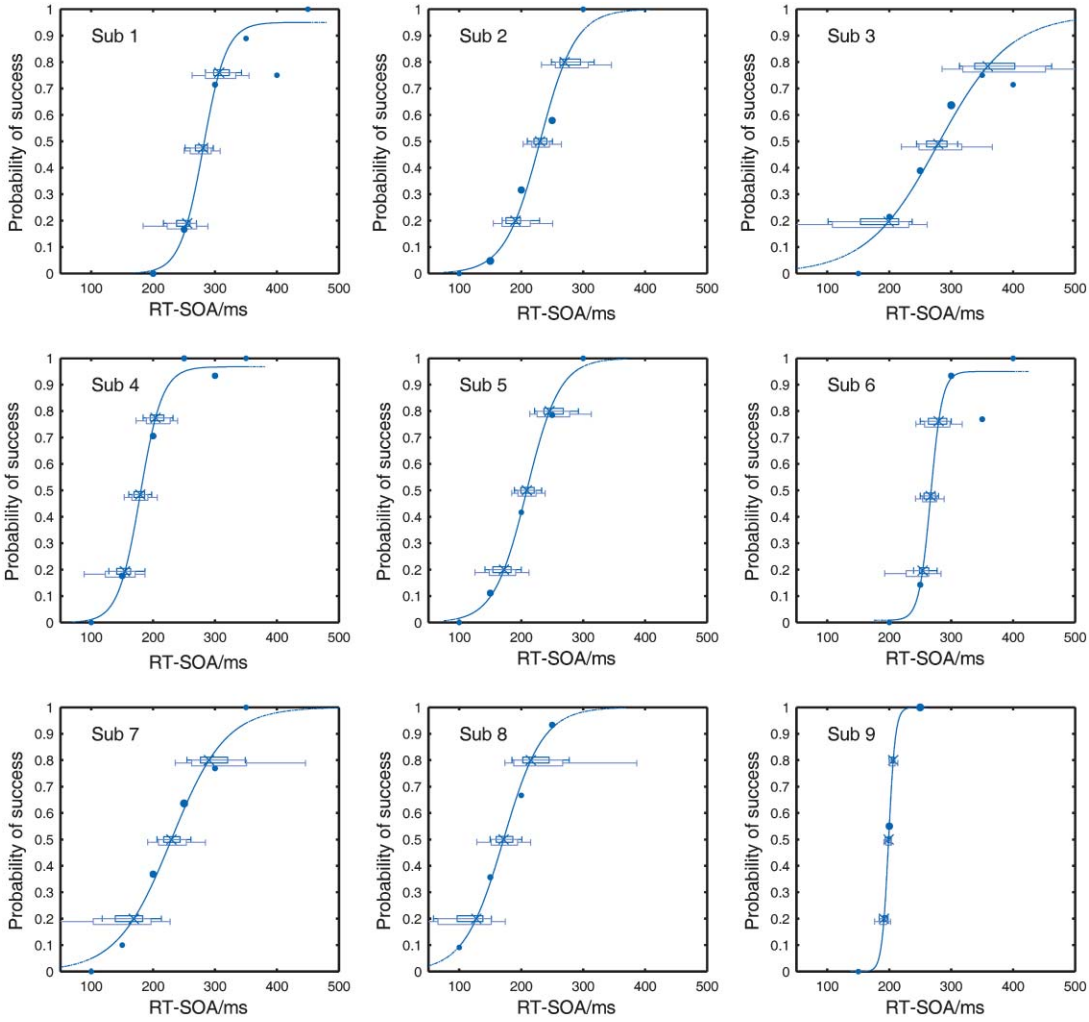

Figure S2. Inhibition Functions for Each Subject Showing the Relationship between Changing Plans and the Change Signal Delay in the Scanner

The probability of successfully changing direction is plotted as a function of the SOA-adjusted reaction time (effectively, the time the subject had to change direction) on each trial. The data have been distributed in 50 ms bins (to match the 50 ms step size of the SOA-tracking algorithm), and uninformative values (latencies shorter than the slowest 0% bin and longer than the shortest 100% bin) have been removed. Logistic functions were fitted to the data with psignifit toolbox version 2.5.41 for Matlab (see http://bootstrap-software.org/psignifit/), which implements the maximum-likelihood method described by Wichmann and Hill [S1]. Confidence intervals were found by the bias-corrected accelerated bootstrap method implemented by psignifit, based on 4999 simulations (see Wichmann and Hill [S2]). Error bars correspond to $\pm$ 1 standard deviation (dark blue) and $\pm$ 2 standard deviations (light blue). Each plot is based on a mean of 62 observations (STD = 10.6). Note that, because the adaptive staircase targeted the 50% performance level, there were relatively few observations at the extremes of the functions, making reliable slope estimates difficult to obtain.

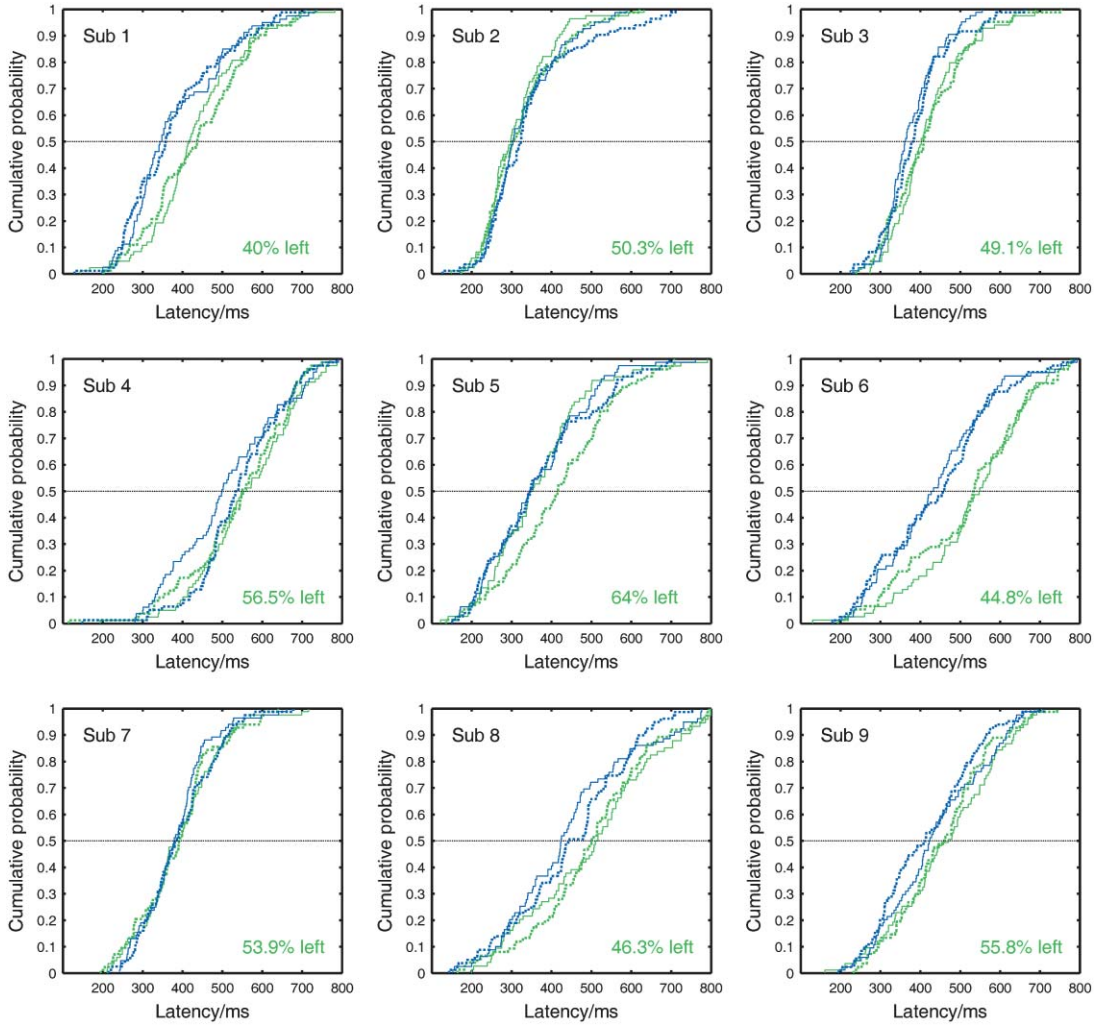

Figure S3. Behavioral Analysis of Experimental Factors

Latency distributions obtained in the scanner subdivided by choice (blue, directed; green, free) and conflict (solid, no change; dashed, change). An average of 322 saccades per subject is included (STD = 11.5). At the group level, there was no significant main effect of choice ($p = 0.09$) or conflict ($p = 0.57$) on Friedman's test. The proportion of left saccades on free trials for each subject is shown in green. The mean proportion of left responses was 51.2% (SEM = 2.4).