Good Looking…Better Looking! Performance Monitoring and Behavioral Adjustments in the Oculomotor System

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Executive control refers to the process of guiding action toward goals. Successful goal seeking agents cancel actions when changing circumstances render them inappropriate. Adaptive agents also track the frequency with which reinforcement is attained in order to adjust strategies when gains are too low. Response inhibition, or the ability to cancel action, has classically been investigated using a stop-signal task. Performance monitoring, or tracking gains and making behavioral adjustments, has been investigated using tasks with variable reward contingencies. These investigations are often carried out by observing monkeys performing saccade tasks. Since the input and output properties of the macaque oculomotor system are understood in comparatively great detail, it provides a simplified and useful model for investigating aspects of executive control. Discoveries suggest that several areas of the frontal and medial cortex are involved in oculomotor control and reward processing, including the frontal eye fields, the supplementary eye fields, and the anterior cingulate cortices. Of these, the supplementary eye fields have been further implicated in implementing behavioral adjustments during complex tasks. Neural activity in these areas, particularly in the anterior cingulate cortex, may contribute to human error related EEG signals. The behavioral relevance and physiological sources of these signals are poorly understood and animal models are sorely needed. Observations of monkeys performing asymmetrically rewarded tasks suggest that the mesencephalic dopamine system and basal ganglia may interact with frontal and medial cortices implementing a broad performance monitoring system.

Saccades
Accurate, high velocity eye movements used by primates to control gaze with precision.

Oculomotor system
Broadly, the areas of the brain, the nerves, and the muscles which play a direct role in controlling eye position and producing eye movements.

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THE STOP SIGNAL TASK AND OCULOMOTOR CONTROL

The stop-signal task (SST) was developed to investigate response inhibition[1-2]. In a typical version, subjects are required to discriminate between stimuli by making speeded manual responses. On a subset of trials, the stimulus to be discriminated is quickly followed by a second stimulus (the stop-signal) instructing subjects to cancel their prepared response. Logan and Cowan proposed a race model of the SST which provides a crucial estimate of the timing of the hidden, response inhibition process[3]. The ability to measure stop-signal reaction time (or SSRT) proved invaluable to the physiological investigation of cancelling action. It was subsequently demonstrated that the race model could fit behavior in a saccade version of the SST [4], and this version has been used with great success to investigate oculomotor control in monkeys [4-14]. Specifically, the logic of the race model identifies activation and timing criteria necessary for neurons to participate in preparing or cancelling eye movements. This framework allowed Hanes and colleagues to identify neural populations in the frontal eye field (FEF)[7] and superior colliculus (SC)[10] with activity necessary to produce or inhibit saccades during the SST. These findings led to the hypothesis that movement and fixation related cells in the FEF and SC may implement a process similar to the race model during the SST. By relaxing an assumption of independence, Boucher and colleagues provided an elegant link, showing that the race model can be extended in neurally plausible terms which fit both behavioral and physiological data[15]. Thus, a large body of established work provides a great deal of theoretical leverage for investigation of the oculomotor system using the SST. Special attributes of the SST which will be referred to in italics throughout the discussion also make it uniquely suited to investigate error detection and performance monitoring (**Figure 1**).

PERFORMANCE MONITORING IN EYE MOVEMENT FIELDS OF THE FRONTAL AND MEDIAL FRONTAL CORTICES

In macaque monkeys, eye movements are elicited by low-current, electrical stimulation of at least three areas of frontal and medial frontal cortex; the FEF[16], the supplementary eye field (SEF)[17], and the rostral cingulate motor area of the anterior cingulate cortex (ACC)[18]. As noted above, investigation using the SST

Race model
A class of dynamic systems models in which several processes accrue toward a threshold. The process which crosses threshold first determines the outcome of the process.

Superior colliculus
A midbrain structure where representations of visual, auditory, and tactile stimuli are combined with a map of eye movement coordiates.

Electrical stimulation
Electrical current injected (typically with a microelectrode) directly into cortex in order to cause local depolarization of neurons.

Speed accuracy tradeoffs
In many tasks, accurate performance is dictated by a balance between speed and accuracy. Slow responding ensures accuracy, but reduces the number of responses per unit time; fast responding ensures that more responses are generated, but may deteriorate accuracy. Speed and accuracy are therefore often used as measures of performance monitoring.

electroencephalogram (EEG)
A continuous record of voltage changes caused by neural activity measured at the scalp with passive electrodes.

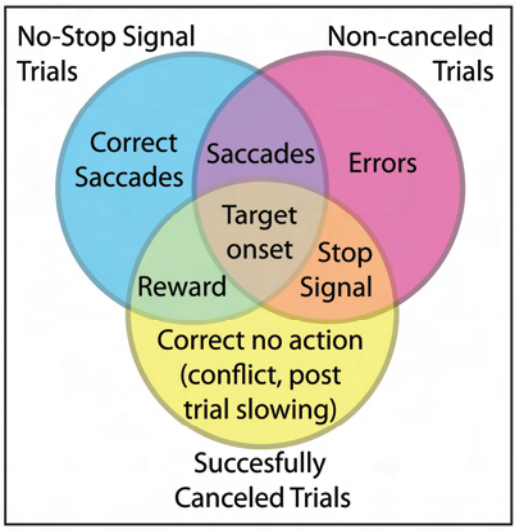

Figure 1 | **Venn diagramatic representation of trial types observed during the stop signal task.** Rings represent trial types. Areas of overlap represent commonalities between trial types. Note the response conflict and post trial slowing are observed in association with canceled trials in the stop signal task, breaking with their normal association with error trials in other tasks.

shows neural modulation in the FEF that is sufficient to play a role in producing or inhibiting eye movements [7]. Other work suggests that the FEF participates in decisions to make saccades to visual targets[19], and a direct link has been observed between the activity of movement related cells in the FEF and saccadic eye movements[8]. However, the contributions of the SEF and ACC to saccades are more nuanced.

During the SST, the majority of neurons in the SEF modulate too late to play a direct role in executing or withholding saccades. Interestingly, some neurons in the SEF exhibit post-saccadic activity when monkeys make errors in withholding saccades. Other neurons show activity before and during reinforcement on correct saccade trials, or when saccades are successfully cancelled[13]. *The SST dissociates actions from outcomes because two separate responses may be correct in different circumstances and identical responses may be either correct or erroneous.* Therefore, these error and reinforcement related signals cannot be explained as effects of visual stimuli or motor responses during the task, and they have led to the hypothesis that the SEF participates in performance monitoring of the oculomotor system[11-12,14]. Careful reading of the original description of the SEF reveals mention of reinforcement related cells, and cells which discharged rhythmically when the animal licked juice reward from a spout[17]. More than just monitoring performance, findings suggest that the SEF may play a direct role in influencing performance during saccade tasks. When monkeys make internally guided decisions during an asymmetrically rewarded free saccade task, nearly 50% of recorded visual neurons in the SEF show enhanced pre-target activity which may bias performance[20]. Moving from correlational measures to inferring causation, Stuphorn and Schall (2006) recorded behavior during the SST while delivering sub threshold intercranial stimulation to small areas within the SEF. While stimulation decreased reaction times (RTs) during simple visually guided saccades, RTs increased and overall accuracy improved in the context of the SST[13]. Taken together, these results suggest that the SEF plays a role in monitoring the outcome of saccades and making behavioral adjustments such as speed accuracy tradeoffs when necessary[11-12].

Cells in the ACC also show activity during errors and in relation to reinforcement, although the specific conditions under which they respond vary slightly from those observed in the SEF. Half of the observed ACC neurons which display error related modulation also display modulation when reward is unexpectedly withheld on correct trials. Of the neurons which respond to reinforcement, some respond when juice is delivered on correct trials, some respond to unexpected juice delivery, and some are modulated in both reinforcement conditions [9]. Thus, neuronal responses in the ACC tend to depend less on the animals behavior and more on trial outcome than those of the SEF. In humans, errors committed during speeded response tasks elicit a characteristic pattern of event related potential (ERP) waveforms (reviewed in more detail below) known as the error related negativity (ERN) and error related positivity (Pe)[21-22]. Dipole source localization has implicated the ACC as the probable source of the ERN signal[23], and local field potentials (LFPs) recorded from the macaque ACC show error related components with a form and time course similar to that of the human ERN[6]. Monkey homologues of human ERPs have been demonstrated in the past [24]. It remains to be seen if monkeys exhibit a homologue of the human ERN and Pe, but if so, the LFP data recorded in ACC may provide a crucial link between human EEG recordings and single cell recordings in monkeys. This development could pave the way for precise physiological characterization of the error related processes apparent in human EEG traces. We will now briefly discuss error related EEG components identified in humans.

THE ERROR RELATED NEGATIVITY AND POSITIVITY

When humans commit errors while performing speeded response tasks, a negative ERP component with a frontocentral scalp distribution can be observed[21-22]. This ERN typically peaks around 100ms after the erroneous response and cannot be

Event related potential
A waveform created by aligning many EEG epochs to a common task related event (such as response) and then collapsing across epochs to produce a single averaged waveform. ERPs minimize random trial to trial fluctuations in the EEG through this averaging process to highlight task related components.

Dipole source localization
General term describing several methods used to localize EEG voltage fluctuations to one or several areas of the brain. Dipole source localization results must be interpreted with care since they are results of mathematically "ill posed, inverse" problems.

Local field potentials
Low frequency voltage fluctuations produced by the ensemble activity of local neurons recorded intercranially.

N2 and **P3**
Stimulus related ERP components. The N2 refers to the second negative component (usually occurring around 200ms) in a stimulus aligned ERP trace, and the P3 follows similar nomenclature. Both the N2 and the P3 really constitute families of components which can be observed in response to a wide variety of stimuli in multiple modalities.

explained in terms of task related stimulus or motor related processing[25]. A similar ERP component dubbed the feedback related negativity can be observed when subjects are informed of a failure to earn reinforcement[25]. The time course of the ERN is very similar to the time course observed in error related cellular modulation in the SEF and the ACC described above [6,9,13]. Dipole source localization generally implicates areas in or around the ACC as the ERN locus, and investigation using concurrent EEG and fMRI recordings show error related hemodynamic signals which fluctuate in correlation with trial to trial ERN variation[23]. It is generally accepted that the ERN and error related hemodynamic responses observed in the posterior medial frontal cortex reflect similar neural responses to errors [25]. The Pe follows the ERN, peaking at around 300 ms. It has a more parietal scalp distribution and also seems to be related to internal error processing [25]. Less is currently known concerning the anatomical source or hemodynamic correlates of the Pe.

Since their discovery, it has been hypothesized that error ERPs may reflect the activity of a neural network that is also involved in behavioral compensation. In one of the first descriptions of the ERN, Gehring and colleagues provided evidence that its amplitude could be attenuated when subjects were instructed to place emphasis on speed rather than accuracy, and that ERN amplitude also correlated with the force of manual response errors, as well as the probability of correcting an error or initiating a correct response on subsequent trials[22]. However, methodological concerns blunt the force of these findings, and attempts to replicate them have varied in their success [25]. Subsequent investigation has suggested that the amplitude of the ERN may be positively correlated with subsequent RTs on ambiguous trials[23,26]. In contrast to this finding, Nieuwenhuis and coworkers found RT adjustments that were correlated with the amplitude of the Pe, not the ERN. Furthermore, RT adjustments and Pe amplitude changes were only observed in association with trials on which participants reported awareness of errors[27]. The authors suggested that the ERN reflects error monitoring outside of conscious awareness, but recent findings by Woodman challenge this interpretation[28]. Klein and coworkers showed that activation of the supplementary motor area was associated with post-error slowing, reminiscent of the stimulation studies in SEF mentioned above[29]. Kerns and colleagues found evidence that error related activity in the ACC correlates with measures of behavioral adjustment independent of RT[30]. Adopting a different approach, Ridderinkhof and coworkers, found that correct trials preceding errors were characterized by greater positivity, which they interpreted as a failure of behavioral performance monitoring by the same network which gives rise to the ERN[31]. In sum, evidence for a link between error related activity and behavioral adjustments is currently contradictory and somewhat underwhelming given the scope of research. This may stem in part from task differences and variations in the operational definitions of behavioral adjustments themselves.

Error related components elicited during the SST have been identified, but varying degrees of rigor have been applied in these studies complicating their interpretation. Ridderinkhof and coworkers investigated stimulus driven ERPs (N2 and P3 components) elicited by the stop-signal itself on canceled and non-canceled trials. These investigators found larger amplitude components with longer latencies when subjects failed to cancel their responses[32]. Further investigation showed that decreasing the percentage of stop-signal trials caused subjects to speed up and the P3 to increase in amplitude[33]. These studies were taken as evidence that the P3 component plays a role in stopping behavior, but a role for the N2 and P3 in error monitoring was also considered, and it was suggested that they may overlap with ERN and Pe components in the SST. Interesting as these findings are, it must be acknowledged that motor response related EEG activity on non-cancelled trials was not removed by the subtraction procedure utilized in these studies which may have influenced the results[32]. Later research was carried out using "ignore" stimuli on trials without stop signals to control for stimulus related confounds introduced by stop-signal presentation. These studies demonstrated robust error related components untainted by stimulus or motor responses[34-35]. Other investigators have attempted to characterize the ERN in the SST in terms of its relationship to autonomic responses[36] or awareness[37], but failed to control for stimulus related confounds of stop-signal presentation (see **Figure 1**). Thus, while error related effects are readily apparent in the stop-signal paradigm, we know very little about their relation to behavior in this task. This is particularly unfortunate since *the unique structure of the SST causes participants to slow responses after successfully cancelled trials instead of errors*[5], a dissociation which may prove useful in correlating error ERPs with behavior.

Several theories have been proposed concerning the cognitive and physiological mechanisms reflected by the ERN. In one of the first descriptions of the ERN, Falkenstein and coworkers suggested that it indexed processing of the mismatch between executed and appropriate responses[21]. This mismatch is essentially one definition of an error. The source of the putative correct response representation during error commission is, however, uncertain. Current

Executive control
The set of cognitive functions which allow complex behavior to be generated beyond simple stimulus and response arcs.

Movement and fixation related cells
Neurons in the SC and FEF which fire maximally before the eyes move or while they are still respectively.

Mesencephalic dopamine system
A collection of cells in the midbrain which provide diffuse input of the modulatory neurotransmitter dopamine to frontal and medial cortices.

Basal ganglia
Several collections of cell bodies which lie at the base of the cerebrum and form a system crucial to generation of movement as well as normal emotional function and cognition.

Mesolimbic Dopamine pathways
A collection of cells in the midbrain which provide diffuse input of the modulatory neurotransmitter dopamine to various areas classically defined as "limbic" areas.

Self-stimulation studies
Experiments in which subjects are implanted with stimulating electrodes which allow them to deliver current intercranially to themselves by carrying out behaviors (such as pressing levers).

Memory guided saccade task
A task in which subjects must make an eye movement to the remembered location of a visual stimulus at the end of a delay period.

theories seek to describe the ERN in terms of more general monitoring processes. Of these, the response conflict theory[38-39] and dopamine (DA) related reinforcement learning theories [40-42] have had broad influence. The response conflict theory suggests that uncertain circumstances produce coactivation of conflicting responses along with high probabilities of errors. This response conflict is continuously monitored by the ACC, which outputs the signal to areas in the prefrontal cortex in order to recruit increasing or decreasing levels of executive control as the situation warrants[38]. An intuitively appealing model of ACC function, conflict monitoring also provides satisfactory fits to behavioral data, as well as explaining many puzzling aspects of observed ERN activity[39]. But it is not entirely clear how this model generalizes to tasks which may not engender conflicting responses. *The SST provides a dissociation of error and response conflict since movement and fixation neurons are maximally coactivated on correct canceled trials*[7]. Studies using the SST have found conflict monitoring responses in the SEF[14], but direct physiological evidence for conflict monitoring in the ACC is lacking[6,9]. Reinforcement learning theories of ACC function take an alternate approach by suggesting that phasic signals from the mesencephalic DA system are responsible for the observed ERN[40]. It is well known that the mesencephalic DA system exhibits a phasic decrease in DA signaling in conjunction with failure to obtain reinforcement[43] (discussed below). Through projections to the ACC, this phasic decrease may disinhibit apical dendrites of pyramidal neurons and mediate synaptic plasticity[40]. The supposed DA "training signal" may then be used by ACC neurons to provide motor influence to an appropriate cortical controller[40] or to learn context dependant predictions of error likelihood[42]. Models of reinforcement learning are successful in fitting behavioral data, and make many predictions concerning ERN signaling which have been observed in the laboratory[41-42]. Additionally, this theory dovetails with physiological findings suggesting a key role for the basal ganglia in oculomotor performance monitoring.

THE BASAL GANGLIA PLAY AN IMPORTANT ROLE IN OCULOMOTOR PERFORMANCE MONITORING

The basal ganglia (BG) form reentrant loops with virtually every area of cortex through the thalamus, and project to several midbrain and brainstem nuclei [44-45]. Consensus has emerged that behaviorally relevant information converges with control over motor output in the BG, placing them in a key position to guide goal directed responses. In addition to their well-known role in orchestrating movements of the trunk and limbs through the skeletomotor circuit, the BG contribute to normal emotional and cognitive function, and they are vital in regulating saccadic eye movement. The oculomotor circuit of the BG exerts tonic, GABAergic inhibition on the SC via the substantia nigra pars reticulata (SNpr). The caudate (CD) can release tonic inhibition on the SC through the "direct" pathway or potentiate inhibition through the "indirect" pathway which projects through the subthalamic nucleus (STN)[46]. DA cells of the substantia nigra pars compacta (SNpc) project to the CD. They facilitate signaling along the direct pathway and inhibit signaling along the indirect pathway by targeting projection neurons with D1 like and D2 like receptors respectively. The FEF and SEF project excitatory input to the CD as well as directly to the STN. This so-called "hyper-direct" pathway may provide fast, potent, cortically driven inhibition of the SC through the STN which may aide in canceling planned responses[47]. Taken together, these observations describe a mechanism by which dopaminergic signaling in the BG can influence oculomotor output[48].

A large body of evidence suggests that the mesoncephalic and mesolimbic DA pathways play a role in signaling the presence of reward and facilitating motivated behavior. Qualitatively, patients with Parkinson's disease (which depletes DA) exhibit paucity of spontaneously generated movements including gaze shifts[48]. Empirically, the classic medial-septal area, self stimulation studies of Olds and Milner are generally taken to demonstrate the ability of the DA system to reinforce behavior[49]. More recently, Schultz and colleagues have provided evidence that the DA systems may provide an ongoing "reward-prediction error signal" by comparing the probability of reward given an animal's behavior in the current context to actual outcomes and signaling deviations[43]. The phasic increases and decreases that DA cells exhibit in response to reward or its absence resemble the output of a simple machine learning algorithm called the method of temporal differences, and could be used to increase the frequency of behaviors leading to reward and update future reward prediction[50]. Redgrave and Gurney have put forth the alternate view that phasic DA responses signal the presence of biologically salient events, including reward related and unexpected stimuli. They argue that contextual and motor cues coexist in the BG and the phasic DA signal serves to synaptically strengthen responses in the current context when they produce unexpected events. Thus, the DA signal may allow an animal to discover new actions which lead to novel outcomes and expand its behavioral repertoire[51-52]. Although the scope of the phasic DA signal is still in question, it is clear that DA signaling is related to reward.

Receptive fields
The spatial extent in which a stimulus encourages a neuron to fire action potentials.

In an important series of experiments, Hikosaka and coworkers showed that visual and saccade related neurons in the CD modulate their firing rates to reflect changing reward contingencies in a memory guided saccade task[53-55]. Animals were required to make memory guided saccades to one of 2 or 4 target locations, but during one condition only a single target location was rewarded. Animals made saccades with shorter latencies and higher peak velocities to rewarded locations, and the receptive fields of visual and memory related neurons in the CD shifted dramatically in response to changing reward contingencies[54]. Moreover, changes in discharge rate of saccade related CD cells were temporally correlated with reward related behavioral adjustments made by the animal, suggesting that CD cell responses could help facilitate the observed changes in saccade speed and latency[55]. Not only are cellular responses in the CD enhanced when receptive fields contain rewarded targets, but CD neurons often exhibit responses that specify the size of the upcoming reward. These effects may be mediated by DA dependent long term potentiation arising from SNpc input[53]. If this were verified, it would provide an elegant example of goal directed behavior under the guidance of dopaminergic signaling through the BG. Variants of a sequential probability ratio test are commonly used to model decision making processes[56-57]. These models maximize reward rates when decision thresholds are set optimally [58-59]. Behaviorally, this is equivalent to making speed/accuracy tradeoffs, and there is circumstantial evidence to suggest that the BG may implement equations required to make these adjustments through a hard-wired circuit[60].

CONCLUDING REMARKS

In sum, intercranial recordings from monkeys guided by computational modeling efforts are providing an increasingly comprehensive view of oculomotor performance monitoring circuits. This work may shed much needed light on human error related activity observed in EEG and fMRI recordings. The SST provides several unique behavioral dissociations related to performance monitoring. Its creative use will continue to provide compelling tests of model predictions and answer lingering questions about error detection and behavioral adjustments.

REFERENCES

1. Helson H and Steger JA (1962). On the inhibitory effects of a second stimulus following the primary stimulus to react. *J of Exp Psy.* **64** (3): 201-205.
2. Lappin JS and Eriksen CW (1966). Use of a delayed signal to stop a visual reaction-time response. *J of Exp Psy.* **72** (6): 805-811.
3. Logan GD and Cowan WB (1984). On the ability to inhibit thought and action: a theory of an act of control. *Psy Rev.* **91** (3): 295-327.
4. Hanes DP and Carpenter RHS (1999). Coutermanding saccades in humans. *Vis Res.* **39**: 2777-2791.
5. Emeric EE, Brown JW, Boucher L, Carpenter RHS, Hanes DP, Harris R, Logan GD, Mashru RN, Pare` M, Pouget P, Stuphorn V, Taylor T and Schall JD (2007). Influence of history on saccade countermanding performance in humans and macaque monkeys. *Vis Res.* **47**: 35-49.
6. Emeric EE, Brown JW, Leslie M, Pouget P, Stuphorn V and Schall JD (2008). Performance monitoring local field potentials in the medial frontal cortex of primates: anterior cingulate cortex. *J Neurophysiol.* 99: 759-772.
   Demonstrates that local field potentials in the anterior cingulate cortex exhibit error related components that are similar in timing and appearance to the error related negativity and positivity observed in humans. So doing, it goes a long way toward bridging the gap between intracranial single cell recordings of error and reinforcement related activity in monkeys and error relate ERP components observed in humans.
7. Hanes DP, Patterson WF and Schall JD (1998). Role of frontal eye fields in countermanding saccades: visual, movement, and fixation activity. *J Neurophysiol.* **79**: 817-834.
8. Hanes DP and Schall JD (1996). Neural control of voluntary movement initiation. *Science*. **274**: 427-430.
9. Ito S, Stuphorn V, Brown JW and Schall JD (2003). Performance monitoring by the anterior cingulate cortex during saccade countermanding. *Science*. **302**: 120-122
10. Pare` M and Hanes DP (2003). Controlled movement processing: superior colliculus activity associated with countermanded saccades. *J Neurosci*. **23**(16): 6480-6489.
11. Schall JD and Boucher L (2007). Executive control of gaze by the frontal lobes. *Cog, Affect, & Behav Neurosci*. 7(4): 396-412.
    Reviews findings from a range of investigations using the stop-signal task in order to build a broad theory of executive control in the oculomotor system carried out by the frontal lobes. Integrates data from physiological recordings with the neurally plausible "interactive race model" of Boucher, Palmeri, Logan, and Schall (2007).
12. Schall JD, Stuphorn V and Brown JW (2002). Monitoring and control of action by the frontal lobes. *Neuron*. **36**: 309-322.
13. Stuphorn V & Schall JD (2006). Executive control of countermanding saccades by the supplementary eye field. *Nat Neurosci*. **9**(7): 925-931.
14. Stuphorn V, Taylor TL and Schall JD (2000). Performance monitioring by the supplementary eye field. *Nature*. **408**: 857-860.
15. Boucher L, Palmeri T, Logan GD and Schall JD (2007). Inhibitory control in mind and brain: an interactive race model of countermanding saccades. *Psy Rev*. **114**(2): 376-397.

16. Bruce CJ and Goldberg ME (1985). Primate frontal eye fields. I. single neurons discharging before saccades. *J Neurophysiol*. **53**(3): 603-635.
17. Schlag J and Schlag-Rey M (1987). Evidence for a supplementary eye field. *J Neurophysiol.* **57**(1): 179:200.
18. Mitz AR and Wise SP (1987). The somatotopic organization of the supplementary motor area: intracortical microstimulation mapping. *J Neurosci*. **7**(4): 1010-1021.
19. Schall JD and Thompson KG (1999). Neural selection and control of visually guided eye movements. *Annu Rev Neurosci*. **22**: 241-259.
20. Coe B, Tomihara K, Matsuzawa M and Hikosaka O (2002). Visual and anticipatory bias in three cortical eye fields of the monkey during an adaptive decision-making task. *J Neurosci*. **22**(12): 5081-5090.
21. Falkenstein M, Hohnsbein J, Hoormann J and Blanke L (1990) Effects of errors in choice reaction tasks on the ERP under focused and divided attention. *Psychophysiol Brain Res*. **1**: 192-195.
22. Gehring WJ, Goss B, Coles MGH, Meyer DE and Donchin E (1993). A neural system for error detection and compensation. *Psy Science*. **4**(6): 385-390.
23. Debener S, Ullsperger M, Siegel M, Fiehler K, von Cramon D and Engel AK (2005). Trial-by-trial coupling of concurrent electroencephalogram and functional magnetic resonance imaging identifies the dynamics of performance monitoring. *J Neurosci.* **25**(50): 11730-11737.
24. Woodman GF, Kang MK, Rossi AF and Schall JD (2007). Nonhuman primate event-related potentials indexing covert shifts of attention. *PNAS*. **104**(38): 15111-15116.
25. Ridderinkhof KR, Ullsperger M, Crone E and Niewenhuis S (2008). The role of the medial frontal cortex in cognitive control. *Science*. **306**: 443-447.
26. West R and Travers S (2008). Tracking the temporal dynamics of updating cognitive control: and examination of error processing. *Cerebral Cortex*. **18**: 1112-1124.
27. Nieuwenhuis S, Ridderinkhof KR, Blom J, Band GPH and Kok A (2001). Error-related brain potentials are differentially related to awareness of response errors: evidence from an antisaccade task. *Psychophysiol.* **38**: 752-760.
28. Woodman GF (in press). Masked targets trigger event-related potentials indexing shifts of attention but not error detection. *Psychophysiology*.
29. Klein TA, Endrass T, Kathmann N, Neumann J, von Cramon DY and Ullsperger M (2007). Neural correlates of error awareness. *NeuroImage*. **34**: 1774-1781.
30. Kerns JG, Cohen JD, MacDonald AW, Cho RY, Stenger VA and Carter CS (2004). Anterior cingulate conflict monitoring and adjustments in control. *Science*. **303**: 1023-1026.
31. Ridderinkhof KR, Nieuwenhuis S and Bashore TR (2003). Errors are foreshadowed in brain potentials associated with action monitoring in cingulate cortex in humans. *Neurosci Letters*. **348**: 1-4.
32. Kok A, Ramautar JR, De Ruiter MB, Band GPH and Ridderinkhof KR (2004). ERP components associated with successful and unsuccessful stopping in a stop-signal task. *Psychophysiol*. **41**: 9-20.
33. Ramautar JR, Kok A and Ridderinkhof KR (2004). Effects of stop-signal probability in the stop-signal paradigm: the N2/P3 complex further validated. *Brain and Cog*. **56**: 234-252.
34. Stahl J and Gibbons H (2007). Dynamics of response-conflict monitoring and individual differences in response control and behavioral control: an electrophysiological investigation using a stop-signal task. *Clinical Neurophysiol*. **118**: 581-596.
35. Dimoska A, Johnstone SJ and Barry RJ (2006). The auditory-evoked N2 and P3 components in the stop-signal task: indices of inhibition, response-conflict or error-detection?. *Brain and Cog*. 62: 98-112.
Shows clear error related negativity and positivity in the event related potentials of humans performing a stop-signal task with appropriate controls. Thus the peculiar behavioral dissociations of the stop signal task which make it an attractive paradigm for studying performance monitoring do not render it incompatible with error ERP studies.
36. van Boxtel GJM, Molen MW, Jennings JR and Bruian CHM (2001). A psychophysiological analysis of inhibitory motor control in the stop-signal paradigm. *Bio Psy*. **58**: 229-262.
37. Endrass T, Franke C and Katmann N (2005). Error awareness in a saccade countermanding task. *J Psychophysiol*. **19**(4): 275-280.
38. Botvinick MM, Braver TS, Carter CS and Cohen JD (2001). Conflict monitoring and cognitive control. *Psy Rev.* **108**(3): 624-652.
39. Yeung N, Botvinick MM, Cohen JD (2004). The neural basis of error detection: conflict monitoring and the error-related negativity. *Psy Rev.* **111**(4): 931-959.
40. Holroyd CB and Coles MGH (2002). The neural basis of human error processing: reinforcement learning, dopamine, and the error-related negativity. *Psy Rev*. **109**(4): 679-709.
41. Nieuwenhuis S, Holroyd CB, Mol N, Coles MGH (2004). Reinforcement-related brain potentials from medial frontal cortex: origins and functional significance. *Neurosci and Biobehav Rev*. **28**: 441-448.
42. Brown JW, Braver TS (2008). Learned predictions of error likelihood in the anterior cingulate cortex. *Science*. **307**: 1118-1121.
43. Schultz W, Dayan P and Montague R (1997). A neural substrate of prediction and reward. *Science*. **275**: 1593-1599.
44. DeLong MD (2000). The basal ganglia. In: *Principles of Neural Science* 4th ed, (Kandel ER, Schwartz JH and Jessell), 853-867. New York: McGraw-Hill.
45. Mink JW (2008). The basal ganglia. In: *Fundamental Neuroscience* 3rd ed, (Squire LR, Berg D, Bloom FE, du Lac S, Ghosh A and Spitzer NC), 725-750. Amsterdam: Elsevier.
46. Hikosaka O and Wurtz RH (1989). The basal ganglia: In *The Neurobiology of Saccadic Eye Movements*, (Wurtz RH and Goldberg ME). Amsterdam: Elsevier.
47. Aaron AR and Poldrack RA (2006). Cortical and subcortical contributions to stop signal response inhibition: role of the subthalamic nucleus. *J Neurosci*. **26**(9): 2424-2433.
48. Hikosaka O, Bromberg-Martin E, Hong S and Masayuki M (2008). New insights on the subcortical representation of reward. *Curr Op in Neurobio*. **18**: 203-208.

49. Olds J and Milner P (1954). Positive reinforcement produced by electrical stimulation of septal area and other regions of rat brain. *J Exp Psy*. **47**(6):419-427.
50 Motague PR, Hyman SE and Cohen JD (2004). Computational roles for dopamine in behavioral control. *Nature*. **431**: 760-767.
51. Redgrave P, Gurney K and Reynolds J (2008). What is reinforced by phasic dopamine signals?. *Brain Res Rev*. **58**:322-339.
52. Redgrave P and Gurney K (2006). The short-latency dopamine signal: a role in discovering novel actions?. *Nat Rev Neurosci*. **7**: 967-975.
53. Ding L and Hikosaka O (2006). Comparison of reward modulation in the frontal eye field and caudate of the macaque. *J Neurosci*. **26**(25): 6695-6703.
54. Kawagoe R, Takikawa Y and Hikosaka O (1998). Expectation of reward modulates cognitive signals in the basal ganglia. *Nat Neurosci*. **1**(5): 411-416.
55. Lauwereyns J, Watanabe K, Coe B and Hikosaka O (2002). A neural correlate of response bias in monkey caudate nucleus. *Nature*. 418: 413-417.
Although not the first use of the "one directional reward" (1DR) task this study demonstrates how powerful the paradigm can be. A simple manipulation of spatial reward contingencies in a visually guided saccade task leads to anticipatory activity in caudate neurons which may be sufficient to explain speeded reaction time effects.
56. Ratcliff R and McKoon G (2008). The diffusion decision model: theory and data for two-choice decision tasks. *Neural Computation*. **20**: 873-922.
57. Roitman JD and Shadlen MN (2002). Response of neurons in the lateral intraparietal area during a combined visual discrimination reaction time task. *J Neurosci*. **22**(21): 9475-9489.
58. Simen P, Cohen JD and Holmes P (2006). Rapid decision threshold modulation by reward rate in aneural network. *Neural Networks*. **19**: 1013-1026.
59. Sugrue LP, Corrado GS and Newsome WT. (2009). Matching behavior and the representation of value in the parietal cortex. *Science*. **304**: 1782-1787.
60. Bogacz R, Brown E, Moehlis J, Holmes P and Cohen J (2006). The physics of optimal decision making: a formal analysis of models of performance in two-alternative forced-choice tasks. *Psy Rev*. **113**(4): 700-765.

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FURTHER INFORMATION

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