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Motivational influences on response inhibition measures

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Abstract

Psychological research has placed great emphasis on inhibitory control due to its integral role in normal cognition and clinical disorders. The stop-signal task, in conjunction with the stop-signal reaction time (SSRT) measure, provides a well-established paradigm for measuring motor response inhibition. However, the influence of motivation and strategic decision-making on stop-signal performance and SSRT has not been examined. In the present study, we conceptualize the stop-signal paradigm as a decision-making task involving the tradeoff between fast responding and accurate inhibition. In four experiments, we demonstrate that this performance tradeoff is influenced by inherent motivational biases as well as explicit strategic control, resulting in systematic differences in conventional measures of inhibitory ability, such as SSRT. Within subjects, we found that SSRT was lower when participants favored correct stopping over fast responding, and was higher when participants favored fast responding over correct stopping. We present a novel variant of the stop-signal task that uses a monetary incentive structure to manipulate motivated speed-accuracy tradeoffs. By sampling performance at multiple tradeoff settings, we obtain a measure of inhibitory ability that is not confounded with motivational or strategic bias, and thus, more easily interpretable when comparing across participants. We present a working theoretical model to explain the effects of motivational context on response inhibition.

Keywords

inhibitory control; SSRT; speed-accuracy tradeoffs

Inhibitory control refers to the ability to suppress a prepotent response, be it a behavioral process, impulse, or inappropriate thought. As a result, inhibitory control can be the difference between stepping back onto a curb and walking straight into traffic; between tasting desert and having a second piece of cheesecake; and between telling your spouse what she wants to hear and putting your foot in your mouth. There has been tremendous interest in inhibitory control, largely due to its apparent deficit in certain clinical disorders, such as ADHD (Barkeley, 1997; Schachar *et al.*, 1995). Furthermore, inhibitory control warrants considerable attention because it has broad applications to diverse spheres of psychosocial functioning, including decision-making (Bechara *et al.*, 2000), social competence (Eisenberg *et al.*, 1996; Kochanska *et al.*, 2000; Thorell *et al.*, 2004), and emotion regulation (Ochsner *et al.*, 2002; Phan *et al.*, 2005; Walcott & Landau, 2004).

Inhibitory control has been operationalized in laboratory paradigms that require inhibition of pre-potent motor responses, such as the stop-signal paradigm, which has been shown to differentiate between individuals with inhibitory deficits (e.g. ADHD) and controls (Schachar *et al.*, 2000) and is correlated with self-reported impulsivity (Logan, Schachar, & Tannock, 1997). The stop-signal paradigm provides a sensitive, quantitative measure of

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response inhibition, stop-signal reaction time (SSRT), that correlates with other measures of inhibition and executive control (Friedman & Miyake, 2004). In the stop-signal task, participants perform a speeded response task (e.g. indicating whether an arrow points to the left or right). On “go” trials, they are instructed to respond as quickly as possible. On “stop” trials, a stop-signal (e.g., a tone) is presented concurrently with or just after the target, and participants must withhold their response. SSRT (Logan, Cowan & Davis, 1984) is based on a simple ‘race’ model, which asserts that on a given stop-signal trial, a “go-process” races against a “stop-process.” If the stop-process is faster than the go-process, a response will be successfully inhibited. With extensive evidence of reliability and face validity, SSRT has become a standard measure of response inhibition, used to study inhibitory control across stages of normal development (Band *et al.*, 2000; Kramer *et al.*, 1994), as well as in the context of clinical populations (Badcock *et al.*, 2002; Nigg, 2001; Schachar *et al.*, 2000).

SSRT is assumed to provide reliable estimates of a fixed ability: inhibitory control. However, it is unclear the extent to which SSRT values reflect pure estimates of inhibitory control ability. Recently, Van den Wildenberg *et al.* (2002) found that go response times on the stop-signal task were slower when participants were cued of an upcoming stop-signal than when they received no warning, suggesting that participants slowed responses in anticipation of stopping. Additionally, Van der Schoot *et al.* (2005) found that SSRT was faster for more intense stop-signals (80 dB vs. 60 dB tones). However, they also found that participants responded more slowly on blocks on which the stop-signal was more intense, suggesting that they differentially prepared responses given the known intensity of the stop-signal. Taken together, these findings suggest that participants’ expectations and motivations may significantly influence stop-signal performance and subsequent estimation of inhibition ability. Given the wide acceptance of SSRT as a measure assessing inhibitory control ability, it is important to determine whether SSRT estimates are truly independent of external influences, such as motivational context.

The stop-signal paradigm, like other basic reaction time tasks, involves making decisions about whether and when to initiate responses. The probability of a given action depends on the decision-maker’s response bias, or decision criterion, which reflects his/her subjective value of the potential outcomes. For example, an individual who values accurate inhibition of responses on “stop” trials over fast responses on “go” trials may be less likely to prepare motor responses to the go-stimuli than would an individual who places greater value on fast responding. Presumably, different tradeoff biases would produce differences in performance on a stop-signal task, though this has not been experimentally demonstrated. Such strategic tradeoffs (e.g. speed vs. accuracy) have been critically important in research on psychophysics (Green & Swets, 1966) and memory (Yonelinas, 1994), in which tradeoff biases are often controlled with rewards or other psychophysical manipulations. By contrast, studies of inhibitory control, and specifically the stop-signal task, have not experimentally controlled or measured stop-go tradeoff biases. As a result, it is unknown whether such tradeoffs influence measures of inhibitory ability, such as SSRT. If individual differences in tradeoff biases systematically influence SSRT, then differences in SSRT between individuals or even subject groups would not have the straightforward interpretation that makes the stop-signal task popular.

In this paper, we present empirical evidence from four experiments that reveal the effects of motivation and strategy on stop-signal performance and measures of inhibitory ability. In Experiments 1 and 2, we demonstrate that the existing approaches for minimizing strategic bias do not adequately constrain behavior, resulting in individual differences in performance bias that are predictive of individual differences in SSRT. These findings suggest that the SSRT measure depends on processes that may vary depending on context, including differences in the interpretation of task goals, or motivational orientation toward speed or accuracy. We tested this hypothesis experimentally in two additional studies. In Experiment 3, we present a novel variant of the stop-signal task that uses monetary reward and punishment schedules to vary the motivational context, effectively shifting stop-go tradeoff biases and producing systematic variations in SSRT. Experiment 4 explores some of the conditions necessary to elicit performance shifts in the stop-signal task, demonstrating the important roles of both explicit strategic control and performance feedback. Collectively, these findings provide experimental evidence that SSRT does not provide a measure of trait inhibitory ability, but rather is influenced by motivational state. In the General Discussion, we present a preliminary theoretical model to explain motivational influences on SSRT.

Experiment 1

For the most part, researchers have dealt with the threat of strategic influence on stop-signal performance by trying to prevent it. Some researchers have assumed that the influence of motivational bias should be negligible because participants are instructed to respond as quickly as possible, and to avoid delaying responses in order to improve accuracy on “stop” trials. However, we surveyed 110 stop-signal studies and found that participants usually receive no feedback on performance (104/110 studies), nor do they receive any explicit penalties for slowing responses (103/110 studies). A larger proportion of studies actually provide feedback that would inadvertently promote slowdown of responses (e.g. accuracy on the primary choice response task). While participants may be highly compliant, they may nonetheless perform differently on the task depending on inherent motivational orientations that are not constrained by the ambiguity of the task.

A second approach to constraining performance involves the use of an algorithm that targets the same stopping accuracy across all participants. This tracking procedure (Slater-Hammel, 1960) was adopted to ensure reliable estimates of SSRT. Simulations have shown that stop latency estimates from the SSRT model are unreliable when stop-signal response rates deviate substantially from 50%. Because SSRT is derived from the response time distribution on go trials, stop latency estimates are most reliable when sampling from the densest part of the response time distributions (50%) and are least reliable when sampling from the tails of the distribution. As a result, extreme tradeoff biases (e.g. error aversion resulting in 90% stop accuracy) may compromise the reliability of stop latency estimates from the SSRT model. The tracking procedure has become a popular solution to address this issue.

To achieve 50% stopping accuracy, the onset time of the stop-signal relative to the go stimulus, or the stop signal delay (SSD), is updated throughout the experiment to change the level of difficulty of the task. In theory, the tracking procedure should eliminate potential influences of motivational bias on SSRT by controlling the correct stopping rate across participants. However, the tracking procedure itself may introduce another type of motivational bias into SSRT estimates for some participants. Because successful response inhibition is more probable if the SSD is shorter rather than longer, the tracking procedure lengthens the SSD every time the subject successfully inhibits a response and decreases the SSD every time the subjects fails to inhibit a response to a stop-signal. A problem arises, however, if individuals increasingly slow down responses in order to ensure higher stopping accuracy, despite explicit instructions to avoid this type of behavior. In this case, the tracking procedure may actually undermine the face validity of the stop-signal task, by changing it from a task of response inhibition, to a task of pure decision making, where the subject decides to either respond immediately on half of all trials or to wait for a stop-signal to occur.

Although researchers acknowledge this is a potential problem, as it is common practice to caution participants to avoid such waiting strategies, there have been no reports of this type of behavior and how it influences SSRT. The tracking procedure targets 50% correct stopping rate, but does not constrain response times on the primary choice RT task. As a result, the stop-go tradeoff bias can vary between subjects even though stop accuracy may be controlled. In Experiment 1, we investigated whether individual differences in tradeoff bias predicted SSRT when a tracking algorithm was used to target 50% accuracy on stop trials. We expected that individual differences in stop-go performance tradeoffs would exist despite the use of a tracking procedure, and that differences in performance bias would explain differences in SSRT. Furthermore, we expected the tracking procedure to be unsuccessful at targeting 50% stopping accuracy for a subset of participants, suggesting that SSRT estimates cannot be easily interpreted for many healthy adults.

Method

Participants—Thirty-four individuals (16 females, 18 males) from the Columbia University community participated in Experiment 1 (median age = 22 years). All individuals received monetary compensation for their participation in this study. This research was approved by the Columbia University Institutional Review Board. All participants provided informed consent prior to participation.

Stimuli—All instructions and stimuli were presented on a monitor using Psychtoolbox for Matlab (Brainard, 1997). On “go” trials, a 1×1 inch go-signal (green arrow) was presented centrally. The direction of the arrow (50% left, 50% right) on any given trial was random, but appeared equally often for both go and stop trial types. The go-signal remained on the screen until the participant responded by pressing the “B” or “N” keys on the keyboard with their right index and middle fingers to indicate whether the arrow pointed toward the left or right, respectively.

On “stop” trials, the go-signal was presented centrally, and after a delay, a visual stop-signal was presented behind the go-signal: a yellow circle with a diameter 1.5 times the width of the arrow. Stop-signal onset time relative to arrow onset varied based on subject performance, as described in the procedure below. The stop-signal remained on the screen for 1000 ms.

Procedure

Speed Block: Participants first completed a speeded reaction time (RT) task, in which only go trials (n=70) were presented. Subjects were instructed to indicate the direction of the arrow as quickly and accurately as possible. During the speed block, an adaptive procedure was used to establish the RT cutoff, the point that divided fast and slow responses. If a response was faster than the RT cutoff, the message “Great!” was displayed for 500ms, but if the response was too slow (RT > RT cutoff), the message “Too Slow!” was displayed. After 25 trials, the cutoff was updated on every trial to the reflect the 70th percentile of the RT distribution for the last 25 trials. This tracking procedure encouraged participants to increase in speed throughout the block and provided a strategy-independent baseline measure of an individual’s RT distribution that could be compared with the RT distribution in the subsequent stop-signal task.

Tracking Block: Participants completed a mixed stop-signal block with 80 stop and 80 go trials randomly intermixed. A four-staircase procedure, described by Aron & Poldrack (2006), was used to titrate the SSD throughout the experiment. On a given stop-signal trial, the SSD was randomly chosen from one of the four staircases, with starting values of 100, 150, 200, and 250 ms. If inhibition was successful, the value of the current staircase was increased by 50 ms, making inhibition more difficult on a future stop trial. Conversely, if a response was made, the value of the current staircase was decreased by 50 ms, making inhibition more probable on a future stop-signal trial. These staircases are expected to converge around the SSD that results in stop-signal responses 50% of the time. Convergence should occur after about ten stop-signal trials. Examples of staircase movement throughout the block can be found in Figure 1.

Subjects were instructed to respond as quickly and accurately as possible to the direction of the arrow and to try to withhold a response if the stop-signal occurred. Subjects were told to avoid slowing down responses to try to improve stopping accuracy and explicitly instructed not to wait on any trials to see if a stop signal would occur. Go trials that were faster than the RT cutoff were awarded 10 points, and trials that were slower were penalized 10 points. Stop trials on which the subject successfully inhibited were awarded 10 points, and stop trials on which responses were made were penalized 10 points. Subjects were instructed to try to earn as many points as possible. On every trial, a 500 ms interval followed stimulus offset and preceded a feedback screen where the amount won or lost was displayed for 1000 ms. A randomly jittered interval (range: 500–1000 ms) followed each trial.

Analyses—From the tracking block, we calculated stop-signal response rate (RR), or the proportion of stop-signal trials on which the participants failed to inhibit a response. We identified subjects whose stop-signal RRs deviated at least 10% from the targeted 50%. These subjects (9/34) were classified as “noncompliant,” because the tracking procedure was unsuccessful at achieving the targeted 50% RR for these individuals. The remaining subjects who achieved RRs within 10% of the targeted 50% were classified as “compliant.” Stop-signal performance measures were compared for Compliant and Noncompliant subjects.

Mean RT was calculated for the speed block, for the first 40 go trials of the tracking block (Early), and for the second 40 go trials of the tracking block (Late). Incorrect go responses and Go trial RTs less than 50 ms or greater than three times the standard deviation of the block’s distribution were excluded from RT analysis. We also calculated the absolute amount of slowdown for the two halves of the tracking block – referred to as Early and Late Slowdown – by subtracting the mean Go RT of the Speed block from Early Go RT and from Late Go RT, respectively. We examined the effects of Compliance (Compliant vs. Non-compliant) and Block (Speed vs. Early vs. Late) on Go RT in a 2-between × 3-within subjects ANOVA. By comparing Go RT for these separate epochs, we can demonstrate the extent that responses increasingly slow over the duration of the tracking block. We expected that Late Go RT would be significantly greater than Early Go RT, demonstrating that slowdown experienced in the tracking block relative to the speed block is more than would be expected simply by adding an additional task component (go + stop). Furthermore, we expected Non-compliant subjects to demonstrate this effect to a greater extent than Compliant subjects.

SSRT was calculated for each motivation block according to the method outlined by Logan (1994). If the finishing time of the go-processes is faster than the finishing time of the stop-processes on a given stop trial, then a response should occur. In practice, the relative finishing time of the stop-processes is modeled as the percentile of the Go RT distribution equal to the observed stop-signal RR. For example, if a subject responded on 50% of stop-signal trials, then the stop finishing time would be equal to the median RT on go trials. SSRT, an estimate of stop latency, is equal to the difference between the stop finishing time and the stop-signal onset time. Because the tracking procedure is assumed to target RR = 50%, researchers have adopted the practice of subtracting the central SSD from the median of the Go RT distribution to estimate SSRT. The central SSD, estimated by averaging the last 10 values in each of the four staircases, is assumed to be the delay time that results in correct stopping 50% of the time (Aron & Poldrack, 2006).

SSRT was compared for Compliant and Non-compliant subjects using an independent samples t-test. Increasing slowdown of go responses over the course of the tracking block can be interpreted as a shift in performance bias favoring accuracy over speed, potentially mediated by explicit strategy or implicit motivational bias. Correlations between SSRT and mean Go RT on the speed block and Slowdown measures demonstrate probable motivational biases in SSRT from the tracking procedure.

Results

Across all participants in Experiment 1, the average correct stopping rate was 0.56 (SD = 0.093), which was significantly different from the targeted 0.5 ($t_{(33)} = 3.67$, $p < 0.001$). Table 1 compares performance for Compliant and Non-compliant participants.

One-way repeated measures ANOVA revealed that mean Go RT significantly slowed from the speed block (M = 343 ms, SD = 31 ms) to Early Go RT trials (M = 463 ms, SD = 95 ms), and slowed even further for Late Go RT trials (M = 488 ms, SD = 124 ms; $F_{(2,66)} = 46.01$, $p < 0.001$). An increase in RT from the speed block to the tracking block is expected since the inclusion of stop-signal trials increases the task's complexity. However, the continued increase in RT from Early trials to Late trials on the tracking block suggests strategic slowdown. Indeed, by comparing RTs between the compliant (n=25) and noncompliant participants (n=9), we observed a significant interaction between Compliance and Block on RT ($F_{(2,66)} = 31.1$, $p = < 0.001$), indicating that participants who deviated from the target 50% RR were also those that slowed down most during the course of the tracking procedure, presumably to wait for the stop signal.

SSRT values were not correlated with Go RT on the speed block ($r = 0.11$, $p = 0.53$), or with Early slowdown (r = −.26, p = .15), but were highly correlated with Late slowdown ($r = -0.58$, $p < 0.001$), suggesting that more effective inhibition (shorter SSRT) was not associated with basic processing speed but was associated with strategic slowdown during the tracking procedure. This relationship was largely driven by the noncompliant subjects, who demonstrated significantly greater RT slowdown as well as significantly lower SSRT scores than compliant subjects ($t_{(32)} = 6.2$, $p < 0.001$).

Discussion

Although the tracking procedure may be successful in targeting 50% correct stops for many compliant participants, it proved to be unsuccessful for a substantial proportion of participants in Experiment 1. Despite instructions to weigh stop and go trials equally and to avoid strategic slowdown, some individuals demonstrated extreme error aversion and strategic slowdown of responses. Though researchers have not reported this type of behavior, to our knowledge, it has been acknowledged by other researchers as a potential concern, and some researchers have developed enhanced feedback procedures to further constrain strategic influences on the stop-signal task using the tracking procedure (Swylan, 2004). Thus, it is likely that the "non-compliance" observed in our sample is generalizable to other healthy adult populations.

Examination of individual subjects' Go RT distributions suggests that some participants engaged in deliberate decision-making, resulting in a bimodal Go RT distribution (see Figure 1). As a result, even for subjects who were successfully tracked with the paradigm to 50% correct stops, it is unclear whether SSRT actually reflects response inhibition ability, given subjects may have been performing a qualitatively different task.

Because we did not collect subject reports of strategy used in this task, we cannot conclude whether the subjects identified as "noncompliant," intentionally disregarded the instructions to avoid strategic slowdown or whether their performance was influenced by implicit motivational biases. In Experiment 2, we compared explicit reports of strategy to performance to address this question.

Experiment 2

In Experiment 1, we demonstrated limitations to the tracking procedure when used in a stop-signal task with stop-signals occurring on 50% of all trials and performance feedback after each trial. By making stop and go trials equally probable and providing feedback after both trial types in Experiment 1, individual differences in tradeoff bias were perhaps more apparent than they might have been had we used another design. Typically, researchers who use the tracking procedure do not provide trial-by-trial speed-related feedback and include a lower proportion of stop trials (e.g. 25%). In Experiment 2, we administered the same tracking procedure described in Experiment 1, but did not provide any performance feedback and lowered the stop-signal probability to 25% of all trials. We expected stop-signal RR and Go RT slowdown to be lower than what we observed in Experiment 1, since this version of the task disproportionately favors the go response. Despite the shift in these outcome measures, we nonetheless expected to observe similar patterns of bias that would be predictive of SSRT. To determine whether noncompliance or extreme tradeoff bias was due to explicit strategy or implicit bias, we obtained participant reports of strategic bias. If noncompliant behavior was intentional, we would expect explicit reports of behavior to match stop-signal performance trends in response time.

Methods

Participants—Thirty-two healthy adults (18 female, 14 male) ages 18–33 (median = 22) participated in Experiment 2.

Stimuli & Procedure—All stimuli and procedures were identical to those used in Experiment 1, with two exceptions: (1) Feedback was not displayed after every trial to indicate whether go responses were fast enough or too slow, or whether inhibition was successful or not for stop-signal trials; and (2) A total of 360 trials were included in the tracking block, including 180 go trials and 80 stop-signal trials (25%). Because of the extended format of this version, a pause screen was inserted every 80 trials to prevent subject fatigue.

At the end of the block, half of the subjects were asked the following: "About what percent of your total effort on the task was focused on accurately inhibiting responses to the stop-signal (relative to effort focused on responding quickly to the arrow)?" The other half of the participants was asked the question in terms of effort focused on responding quickly relative to accurate inhibition. To respond, subjects typed a single number from 0–100. Responses made in terms of quick responding were subtracted from 100 to establish the effort for accuracy. Explicit reports of effort for stop-signal accuracy were used for all subjects.

Analyses—Because we expected stop-signal RR to be within 10% of the targeted 50%, due to the task's emphasis on speed, we used different criteria for identifying noncompliance than those used in Experiment1. In Experiment 2, we simply compared stop-signal performance and SSRT between those individuals who demonstrated the greatest slowdown across the task (top 25%, N = 8) to the remaining participants (N = 24). Stop-signal performance measures described in Experiment 1 were all included in the present analyses.

Results

Across all participants in Experiment 2, the average correct stopping rate was 0.53 (*SD* = 0.059), which was significantly different from the targeted 0.5 ($t_{(31)} = -2.74$, $p < 0.01$). Individuals identified as Noncompliant demonstrated significantly higher correct stop rates (*M* = .59, *SD* = .07) than did Compliant subjects who demonstrated less extreme slowdown of responses (*M* = .51, *SD* = .04; $t_{(31)} = 3.3$, $p < .005$).

One-way repeated measures ANOVA revealed that mean Go RT significantly slowed from the speed block to Early Go RT trials (*M* = 71.8 ms, *SD* = 33.8 ms) and slowed even further for Late Go RT trials (*M* = 91.8 ms, *SD* = 57.9 ms; $F_{(1,31)} = 12.85$, $p < 0.001$). The amount of continued slowdown from Early to Late was significantly higher for the Noncompliant group (*M* = 68.9 ms, *SD* = 24.01 ms) than the Compliant group (*M* = 5.1 ms, *SD* = 15.8 ms; $t_{(31)} = -7.1$, $p < 0.001$), confirming the basis of our classification of subjects as compliant or noncompliant by the extent of this slowdown.

SSRT values were not correlated with Go RT on the speed block ($r = -.08$, $p = 0.65$), but were significantly correlated with Early slowdown (r = −.56, p = .001), and even more highly correlated with Late slowdown ($r = -0.65$, $p < 0.001$). Like in Experiment 1, this relationship was largely driven by the noncompliant subjects, who demonstrated significantly greater RT slowdown as well as significantly lower SSRT scores (*M* = 126.8 ms, *SD* = 75.6 ms) than compliant subjects (*M* = 200.6 ms, *SD* = 42.1 ms; $t_{(31)} = 2.8$, $p = 0.02$).

On average, participants in Experiment 2 reported spending 33.5% of their effort on stopping accurately, and 66.5% of their effort on responding quickly to the arrow. Reports of explicit tradeoff bias did not significantly differ between Noncompliant subjects (*M* = 42%, *SD* = 20.6%) and Compliant subjects (*M* = 30.6%, *SD* = 20%; $t_{(31)} = -1.4$, $p > 0.1$), suggesting that differences in behavior were not necessarily driven by differences in explicit strategy. Consistent with this finding, explicit reports of tradeoff bias did not significantly correlate with extent of RT slowdown during the task ($r = .3$, $p = 0.1$) or with SSRT ($r = -.17$, $p = .34$).

Discussion

Experiment 2 revealed that individual differences in stop-go tradeoff biases predicted differences in SSRT estimates, even when the stop-signal probability is relatively low (25%). Thus, the findings presented in Experiment 1 likely are not representative of a special case of motivational bias induced by high stop-signal probability (50%) and thus greater bias toward accurate inhibition. Even under experimental conditions that promote speeded responses, a subset of individuals demonstrate an accuracy bias that undermines the utility of the tracking procedure to target 50% correct stops, and effectively compromises the validity of the SSRT measures based on performance on the task.

In Experiment 2, the low probability of stop-signals should favor fast responding over accurate inhibition. Participants reported favoring speed over accuracy on the task, yet a subset of participants demonstrated strategic slowdown that would suggest accuracy on stop trials was more important than speed on go trials. These findings indicate that performance tradeoffs may be driven by implicit motivational biases rather than by explicit strategic control. This is important because researchers have only acknowledged the potential role of *consciously* executed strategy on stop-signal performance. Although the tracking procedure may attempt to constrain the influence of explicit strategy, findings from Experiment 2 suggest it does not constrain implicit motivational biases which not only impact stop-signal task performance, but also influence SSRT estimates.

The findings from the SSD procedure do not imply a criticism of the tracking procedure as a whole, but merely illustrate that the procedure does not completely eliminate the influence of motivational bias for all individuals. Many groups have used it successfully, and a key factor may be the selection and training of participants. The tracking procedure has become popular because it helps eliminate potential bias in SSRT estimates that can occur when performance deviates substantially from 50% stop trial accuracy. Although the tracking procedure may be able to match stopping accuracy across most participants, individual differences in motivational bias still exist, and can influence SSRT estimates, as we observed in Experiments 1 and 2. Thus, by only controlling the stop-signal RR, the tracking procedure solves one source of bias in SSRT (estimating from the center of the distribution), but it also introduces another form of bias into SSRT estimates. We make this point with extreme cases of noncompliance, yet it is unknown how even minor variations in motivational bias could impact estimates of SSRT. It is important to point out the existence of this pattern of ‘non-compliant’ behavior in a formal empirical study because, to our knowledge, no studies using the tracking procedure have reported any sort of quality assurance check of individual subjects’ data to confirm that the tracking procedure was even successful at achieving 50% RR. Thus, we cannot be entirely confident that SSRT is measuring the same construct – inhibitory ability – for every subject.

SSRT is generally accepted as a highly reliable and valid measure of response inhibition ability. However, the findings suggest that inhibitory ability, as measured by SSRT, depend on motivational context. As a result, measures of inhibitory ability that do not account for Motivational Context and SGT bias may not reliably reflect a trait inhibitory ability. Although studies have demonstrated that SSRT has high test-retest reliability (Kindlon, Mezzacappa, & Earls, 1995; Tannock, *et al.*, 1989), SSRT may be reliably measuring something other than inhibitory ability. Individual differences in interpretation of instructions and task goals, as well as noncompliant behavior observed on the tracking procedure for some subjects in Experiments 1 and 2, suggest that people have inherent motivational biases, and it is probable that people approach the task with the same inherent biases in a reliable manner. As a result, experimentally manipulating and measuring variables like motivational bias and strategic control over performance may substantially improve our ability to produce reliable and valid measures of inhibitory ability.

Experiment 3

The previous studies demonstrated that stop-signal performance and measures of inhibitory control (e.g. SSRT) are influenced by motivational bias, reflected in the individual differences in the tradeoff between fast responding and accurate inhibition. In the present study, we conceptualize the stop-signal paradigm as a decision-making task involving strategic allocation of resources. While strategic tradeoff is inherent to the task, it can be constrained by feedback and explicit consequences for behavior, so that the validity of the task is not compromised. The experimental design was inspired by previous research that demonstrated the influence of decision-making on measurements of simple cognitive processes such as perception and memory. Such applications of signal detection theory (Green & Swets, 1966) suggest that tradeoff bias should be independent of the measured ability. In Experiment 3, we adopted a model similar to the receiver operating characteristic (ROC) curves of signal detection theory to calculate response curves for varying strategic go speed and stop accuracy tradeoffs. By examining stop-signal performance under multiple decision criteria, we aimed to calculate an inhibition sensitivity measure that explains performance accounting for motivational bias and strategic control.

In this experiment, we tested the hypothesis that shifts in Motivational Context would produce shifts in response inhibition measures (e.g. SSRT). We manipulated the

Motivational Context for three trial blocks by differentially varying rewards and penalties for each trial type (stop vs. go), resulting in the systematic tradeoff between accuracy on stop trials and speed on go trials. We examined the effect of Motivational Context on stop-signal performance measures and SSRT in two versions of the stop-signal task, which differed only by the proportion of stop-signal trials (25% vs. 50%).

To examine tradeoff between speed and accuracy, ideally we would use equal numbers of stop and go trials (50%), which would allow tradeoff bias to be unconstrained by trial frequencies. However, most stop-signal studies report using fewer stop-signal trials (e.g. 25%). Thus, it is important to determine if motivational context can influence stop-signal performance measures when stop trials are relatively infrequent. We hypothesized that Motivational Context would significantly influence stop-signal performance measures regardless of stop-signal probability. However we expect the magnitude of this effect would be smaller when the stop-signal probability was relatively low, since in the 25% stop-signal condition, there is an existing bias toward speed due to the disproportionate number of go trials.

Methods

Participants—Twenty-one individuals (15 females, 7 males) from the Columbia University community participated in Experiment 3 (median age = 23 yrs). Participants were randomly assigned to one of two versions of the stop-signal task. One version (n=11) had 50% stop trials in each block and the other version (n=10) had 25% stop trials in each block. Instructions and procedures were identical for both task versions.

Stimuli—All stimuli and trial timing were identical to those used in Experiment 1.

Procedure

Speed block: Subjects first completed a speed block of 70 go trials, with RT cutoff titrated as in Experiment 1. Subsequent task parameters were derived from each individual’s speed block RT distribution, allowing for perceived task difficulty to be controlled across subjects. The RT cutoff for subsequent blocks was set to 1.5 times the median of the speed block RT distribution. In Experiment 3, SSD was fixed rather than titrated as in Experiments 1 and 2: the stop-signal was presented 200 ms before the individual’s RT cutoff on all stop trials.

Mixed blocks: Participants then completed three stop-signal blocks. For the 50% stop-signal task, each mixed block had 60 go trials and 60 stop trials. For the 25% stop-signal task, each mixed block had 90 go trials and 30 stop trials. Participants were instructed to respond as quickly as possible on all trials, but to try to withhold responses if a stop-signal occurred. They were explicitly instructed to avoid slowing down responses on go trials to improve stopping accuracy, as go and stop trials were equally important. On each trial, feedback was provided, as described in the tracking block of Experiment 1. On go trials, responses faster than the RT cutoff were rewarded with monetary gains and responses slower than the RT cutoff were penalized with monetary losses. On stop trials, participants received monetary gains for successfully inhibiting a response and were penalized with monetary losses for failing to do so. If participants responded before the go-signal appeared, they were penalized 100 points to discourage premature responses and to promote attentive performance. Participants were instructed to earn as many points as possible, for points were translated into bonus reward money. The point total was displayed at the end of each block. On average, participants earned $4.00 bonus money (range = $0.00–$9.00).

Monetary rewards and punishments were titrated adaptively during task performance, depending on the difference between an individual’s current tradeoff bias and the targeted tradeoff for each of three Motivational Contexts: Go Bias, No Bias, and Stop Bias. Block order was counterbalanced across subjects. On each trial, the stop-go tradeoff (SGT) bias was defined as the average of the success rate on the last ten stop trials (correct stops) and the failure rate on the last ten go trials (RT > RT cutoff). SGT values closer to zero reflect a stronger bias for responding quickly on go trials, and values closer to one reflect a stronger bias for stopping correctly on stop trials. Each Motivational Context block targeted a different tradeoff bias (Go Bias = 0.3, No Bias = 0.5, Stop Bias = 0.7). In practice, if a participant initially demonstrated a tradeoff bias toward stopping accuracy in the Go Bias block, then rewards and penalties for “stop” trials would be decreased in magnitude and rewards and penalties for “go” trials would increase in magnitude. [1]The titration began with equal rewards (+50) and penalties (−50) for both trial types, and was bounded at a maximum of 100 points and a minimum of 0 points for rewards, and a maximum of 0 points and a minimum of −100 points for penalties. Rewards and punishments initially varied as the participants adapted to the payoffs, but increasingly stabilized over time.

Participants were explicitly trained to strategically trade off between speed and stop accuracy in response to changes in rewards and punishments. For example, participants were told, “If you notice that you are receiving larger rewards and penalties for your performance on go trials than on stop trials, you should focus on making speeded responses on go trials to earn the most money possible.” Three practice blocks of 20 trials each preceded the three mixed blocks. Participants were not informed of the number of trials in a block, or of the probability of stop trials in a block.

Analyses—One-way repeated measures ANOVA models were used to examine the influence of Motivational Context (3 levels: Stop-bias, No-bias, Go-bias) on four outcome variables: SGT, stop-signal RR, RT slowdown relative to the speed block, and SSRT. Separate analyses were conducted for each task version (25% vs. 50% stop trials), and combined data were also analyzed with 2-between (Task Version) × 3-within (Motivational Context) mixed effects ANOVAs. Huynh-Feldt corrected p-values are reported as well as partial eta squared values (h_p^2).

To determine the amount of “strategic” slowdown for each participant, we calculated the differences between the mean of the RT distribution for each motivation block and the mean of the RT distribution for the speed block. Incorrect go responses and Go trial RTs less than 50 ms or greater than three times the standard deviation of the block’s distribution were excluded from RT analysis.

For each block, a subject’s average SGT was defined as the average of the stop trial accuracy rate and the go trial failure rate across the entire block. Thus, a given SGT value reflects a particular tradeoff between time-outs and correct stops, shown by the diagonal lines in Figure 2 for three SGT values (0.3, 0.5, and 0.7). SGT values vary between 0 and 1, with lower values reflecting a stronger speed bias, and higher values reflecting a stronger accuracy bias. An SGT of 0.5 indicates no bias toward speed or accuracy. As Figure 2 illustrates, holding SGT constant, better inhibitory efficacy would lead to higher correct stop rates and lower time-out rates. Thus, the diagonal lines in Figure 2 reflect performance at a constant SGT but for varying levels of inhibitory efficacy. As a result, SGT is a measure comparable to the bias measure used in signal detection theory, and the each SGT value approximates a position along a tradeoff curve (similar to an ROC curve) defined by the subject’s SSRT. However, the curves in Figure 2 differ critically from typical ROC curves,

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[1] Amount of change in rewards depended on (1) trial number: initial reward jump size was 25 and exponentially decayed to a minimum jump size of 5; and (2) difference between true tradeoff bias and targeted tradeoff: jump size was multiplied by this difference to determine shift in rewards and penalties.

because here, response curves can be both concave (good inhibitor) and convex (poor inhibitor) due to the nonlinear tradeoff between correct stop rate and time-out rate.

For each of the three blocks, correct stopping rate (y) was plotted against the timeout rate (x), which is the proportion of go trials that were penalized for being too slow. From the data, we estimated the subject's speed-accuracy tradeoff curve using a general linear model. Area under the curve (AUC) provides a measure of the efficiency of inhibition. Higher values of AUC suggest that less strategic slowdown is necessary to increase stopping accuracy.

Results

Overall accuracy on the primary response task (left/right discrimination) was high (M = 94%, SD = 5.0%). Mean response time on the speed block was 264.6 ms (SD = 33.3 ms). Independent-samples t-tests revealed that block order did not influence SGT for each Motivational Context (all p > 0.1). In the 3 (Motivational Context) × 2 (Task Version) analysis, there was a significant main effect of Motivational Context on SGT ($F_{(2,38)}$ = 70.99, $p < 0.001$, $h_p^2 = 0.79$), RR ($F_{(2,38)}$ = 55.91, $p < 0.001$, $h_p^2 = 0.75$), Go RT slowdown ($F_{(2,38)}$ = 18.81, $p < 0.001$, $h_p^2 = 0.50$), and SSRT ($F_{(2,38)}$ = 4.7, $p = 0.024$, $h_p^2 = 0.20$). As rewards and penalties increasingly favored correct stopping over fast responding (Go bias block > No bias block > Stop bias block), SGT values increased, RR decreased, RTs increased, and critically, SSRT decreased (see Figure 3). Main effects of Motivational Context were also significant on all outcome variables for each task version independently (see Table 2).

There were significant interactions between Task Version and Motivational Context on SGT ($F_{(2,38)}$ = 10.4, $p < 0.001$, $h_p^2 = 0.35$), RR ($F_{(2,38)}$ = 8.13 $p = 0.001$. $h_p^2 = 0.3$), and Go RT slowdown ($F_{(2,38)}$ = 8.42, p =0.002, $h_p^2 = 0.31$). As predicted, larger changes in SGT, RR, and Go RT slowdown were observed across Motivational Contexts for the 50% task version than for the 25% task version. However, the interaction between Task Version and Motivational Context on SSRT was not significant ($F_{(2,38)}$ = 1.8, $p = 0.19$, $h_p^2 = 0.09$), suggesting that motivational effects on SSRT were roughly equivalent across 25% and 50% stop-trial versions.

Compared to the 50% stop-signal task, the 25% stop-signal task produced higher overall RRs ($F_{(1,19)}$ = 6.58, $p = 0.010$, $h_p^2 = 0.26$), less Go RT slowdown ($F_{(1,19)}$ = 19.4, $p < 0.001$, $h_p^2 = 0.51$), and longer SSRTs ($F_{(1,19)}$ = 13.4, $p = 0.002$, $h_p^2 = 0.41$), across all blocks. The Task Versions did not differ on overall SGT ($F_{(1,19)}$ = 0.036, $p = 0.85$, $h_p^2 = 0.002$).

To successfully estimate a stop-go tradeoff curve, there must be sufficient variability in the modeled data. Individuals who did not substantially shift performance across the different Motivational Contexts showed little to no variability in the timeout rate and/or the correct stopping rate. As a result, curves that best fit the data of these subjects may not accurately portray inhibitory efficiency, as measured by AUC, since performance was not sampled at varying tradeoff points. To ensure that the AUC metric has the same interpretation across subjects, the curves should be fit to data occurring at similar tradeoff points (e.g. 0.3, 0.5, and 0.7) for all subjects (see Figure 4A) Subjects who demonstrated a shift in SGT bias less than 0.20 units between the Go Bias and Stop Bias blocks were excluded from AUC analysis. For the remaining 15 subjects, the mean AUC was 0.45 (SD = 0.18), with values ranging from 0.16–0.72 (Figure 4B). Because participants in the 25% stop-signal condition demonstrated significantly less shift in SGT across blocks, reliable estimates of the stop-go tradeoff curve could be made for relatively few subjects (N = 3) in this condition. As a result, AUC could not be compared across subjects in the 25% and 50% stop-signal tasks.

Discussion

The results of Experiment 3 demonstrate that stop signal task performance and measures of response inhibition are influenced by Motivational Context. Participants responded more accurately on stop trials (lower RR) and responded more slowly overall, as rewards and punishments increasingly favored stop accuracy over speed. The significant change in SGT across blocks suggests the adaptive titration of rewards and penalties was successful in producing the desired performance shifts. Critically, SSRT was greater when a participant demonstrated a bias toward speed and was lower when a participant demonstrated a bias toward stop accuracy. Based on these results, we might conclude that inhibitory control is worse when favoring a speed bias and better when favoring an accuracy bias. Alternately, inhibitory control ability may not actually be changes with motivational shifts, but rather, our ability to measure stop latency does not account for Motivational Context and associated performance shifts.

We also found that the shifts in performance induced by changes in Motivational Context were less extreme when stop-signal probabilities were lower (i.e. in the 25% version). However, there was no significant difference between task versions on the change in SSRT across Motivational Contexts. We had hypothesized that stop-signal performance measures, including SSRT, would show less change across Motivational Contexts in the 25% stop-signal task than in the 50% stop-signal task, because there is less competition for resources, and thus less SGT tradeoff, when the stop-signal probability is relatively low. Furthermore, we expected Motivational Context to have a smaller impact on SSRT in the 25% task relative to the 50% task because response inhibition should be more difficult in the 25% task version, and studies of attentional control have found that extraneous dimensions exert less impact on performance when the task is sufficiently difficult (Lavie, 2005). The significantly higher SSRT scores for the 25% task relative to the 50% task suggests the 25% task was indeed more difficult. Nonetheless, the influence of Motivational Context on SSRT did not vary across the two versions of the task, suggesting that Motivational Context is a relevant predictor of stop-signal performance and SSRT regardless of task difficulty.

The stop-signal task variant outlined in Experiment 3 has the potential to provide estimates of inhibitory ability, as well as measures of individuals' strategic bias and reward and punishment sensitivity (not examined here). This may serve as an important tool for characterizing clinical disorders, such as ADHD, that have been associated not only with impaired response inhibition (Schachar *et al*., 2000), but also with motivational deficits (Slusarek *et al*, 2001) and altered processing of rewards (Luman, Oosterlaan, & Sergeant, 2005). If SSRT varies with SGT setting, as observed in Experiments 3, then estimates of stop latency confirming inhibitory control deficits in clinical populations may reflect different motivational or strategic concerns rather than differences in inhibitory ability. Experiments should account for these strategic and motivational biases in some way, either by simply measuring bias (e.g. SGT measure), attempting to control it (e.g. via feedback and reinforcement), or both. One advantage of the procedures we employ here is that we control strategies and performance tradeoffs using quantitative manipulations of objective payoffs, rather than relying solely on instructions to participants. Researchers wishing to implement the procedure should manipulate motivational context in a way that, ideally, targets approximate RR values of 30%, 50%, and 70% for each participant. This could be done by manipulating motivational context, or in principle by using adaptive tracking procedures targeting multiple performance accuracies (e.g. by varying SOA), though other methods were not tested here.

By sampling performance at multiple SGT points, it may be possible to establish a measure of inhibition efficiency that accounts for stop-signal performance in various Motivational Contexts. The area under the speed-accuracy tradeoff curve (AUC) is one such measure.

Higher AUC values reflect more efficient inhibitory ability, i.e. the subject requires less slowdown of responses to achieve greater stopping accuracy. An inefficient inhibitory (lower AUC) would require greater response slowdown to achieve the same level of stopping accuracy. To use a metric like the AUC, it is necessary to target similar tradeoff biases across participants. As Figure 4A illustrates, modeling invariant data can result in tradeoff curves that fit the data well, but have unknown predictive validity, and which cannot easily be interpreted. Most of the participants in the 50% stop-signal task achieved the targeted SGT biases, allowing for successful estimation of the speed-accuracy tradeoff curve and AUC. However, most of the participants in the 25% stop-signal task did not reach the targeted tradeoff points, suggesting that the reward titration used was not appropriate for both groups. Enhancement of this procedure would likely improve the ability to target various tradeoff points in a 25% stop-signal task so that summary measures like AUC could be estimated reliably. Using the GLM to find the AUC is only one approach to measuring inhibition under varying Motivational Contexts. Additional research is necessary to determine if other statistical models would provide a better explanation of stop-signal performance.

Experiment 4

Based on the results of Experiment 3, we can conclude that Motivational Context, defined in terms of monetary gains and losses, can shape performance bias, which influences SSRT. However, we cannot determine whether such shifts in performance were the result of explicit strategy, or whether performance was simply shaped by reinforcing feedback. In Experiment 4, we addressed this question by comparing a group of subjects who received instructions to strategically shift behavior in response to reinforcement as in Experiment 3, to a group of subjects who only received instructions to strategically shift behavior without receiving any trial-by-trial feedback or reinforcement. Because the groups differ only by performance feedback, any differences observed between the groups can be attributed to properties of reinforcement.

If explicit strategic control of behavior mediates performance shifts, we would expect to see comparable changes in stop-signal task performance and SSRT as a function of variations in Motivational Context. If variations in stop-signal performance and SSRT were driven by reinforcement learning, rather than by explicit strategic control, we would expect to observe gradual shifts toward the targeted tradeoff bias. We hypothesized that stop-signal performance and SSRT would vary systematically with Motivational Context for both groups, demonstrating that explicit strategic control can influence stop-signal performance and SSRT.

Method

Participants—Thirty-one individuals (12 Males, 19 females) ages 18–35 (median = 23) participated in Experiment 4. Subjects were randomly assigned to the reinforcement group (n=16) or to the strategy-only group (n=15). Participants were informed they could earn bonus money for good performance, but were not given the criteria for earning bonus money. All participants were paid $12 for their participation.

Stimuli—All stimuli are identical to those described in Experiment 1. All trials lasted 1200 ms. For the reinforcement group, feedback was displayed for 500 ms after each trial. No feedback was provided for the strategy-only group. Between trials, the interval was randomly selected from a list of values between 300–500 ms in 50 ms intervals. During this interval, a fixation cross was displayed centrally. On go trials, arrows were presented until a response was made or 1200 ms had elapsed. The fixation cross was displayed for any time remaining (1200-Go RT). On stop trials, stop signals were presented after the subject specific delay (based on values derived from speed block). Both the arrow and the stop signal then remained on screen until 1200 ms had elapsed from the trial start.

Procedure

Speed Block: Participants first completed a speed block of 70 trials. RT cutoff and stop signal onset times were determined from the speed block as in Experiment 3.

Mixed Blocks: Participants were given a practice block of 100 trials (30% stop), on which they were instructed to respond to the arrow as quickly and accurately as possible and to try to inhibit their response if the stop-signal appeared. They were instructed to avoid delaying responses to improve stopping accuracy and that speeded responses and correctly stopping were equally important. Next, subjects completed two strategy blocks, presented in counterbalanced order. Each block had 70 go trials and 30 stop trials randomly intermixed. Before each block, the phrase “Speed Next” or “Accuracy Next” was presented for 3000 ms to indicate which type of performance should be favored in the upcoming trial block. For the Go Bias block, all subjects were instructed to focus 70% of their effort on making fast responses and 30% of their effort on inhibiting responses when the stop-signal occurred. For the Stop Bias block, subjects were instructed to focus 30% of their effort on making fast responses and 70% of their effort on correctly inhibiting responses to the stop-signal.

Participants in the reinforcement condition were informed they would receive feedback after every trial to indicate whether they were successful or not. Instructions were virtually identical to those received by participants in Experiment 3. Rather than the reward titration procedure used in Experiment 3, we used fixed rewards and penalties for each block in Experiment 4. On the Go Bias block, responses faster than the RT cutoff received 20 points, and slow responses lost 20 points; successful inhibition resulted in 10 points, and stop-signal responses were penalized 10 points. On the Stop Bias block, fast responses won 10 points and slow responses lost 10 points; successful inhibition resulted in 30 points and stop-signal responses were penalized 30 points. Participants were told to try to earn as many points as possible.

Analyses—Using 2 (between) × 2 (within) ANOVAs, we examined the effects of Feedback Type (reinforcement vs strategy-only) and Motivational Context (Speed bias vs. Accuracy bias) on SGT, stop-signal RR, and Go RT slowdown.

With respect to SSRT, we did not target specific SGT biases as in Experiment 3, and thus we expected that individuals would differ in both the magnitude of shift in SGT and (as a result), shift in SSRT induced by the feedback/strategy manipulation. Thus, we included a Strategic Shift measure as a covariate in the analysis of Feedback and Motivational Context on SSRT. Strategic Shift was operationalized as the difference between mean Go RTs (Accuracy – Speed) divided by difference in stop accuracy (1-RR) across blocks. Thus, strategic shift reflected the overall change in SGT between blocks, as well as the efficiency of trading off between speed and accuracy: lower Shift scores reflect less strategic slowdown per unit increase in stopping accuracy.

To examine the time-course of shifts in performance tradeoff bias, we calculated the RR for every ten stop-signal trials in a motivation block. Within the speed block, and separately within the accuracy block, we examined the RR trajectory across the two subjects groups in a 3-Within (Time: Early, Middle, Late) × 2-Between (Reinforcement vs. Strategy Only) ANOVA. If strategy shifts are achieved through reinforcement learning, stop-signal RR should gradually approach the targeted tradeoff for the reinforcement group. Otherwise, the targeted tradeoff should be achieved in the first ten trials of the block (Early), suggesting the tradeoff bias was induced by adopting an explicit strategy.

Results

Accuracy on the left/right discrimination task was high overall (M = 98.1%, SD = 0.018). Mean response time on the speed block was 324.6 ms (SD = 37.9). Neither accuracy nor speed block RT differed by Feedback Type (all $p > .5$). SGT for Go Bias and Stop Bias blocks did not depend on which block was presented first (all $p > .1$).

The results of Experiment 4 are summarized in Table 3. As in Experiment 3, we observed significant main effects of Motivational Context on SGT ($F_{(1,29)} = 123.7$, $p < 0.001$, $h_p^2 = 0.81$), stop-signal RR ($F_{(1,29)} = 140.3$, $p < 0.001$, $h_p^2 = 0.83$), and Go RT slowdown ($F_{(1,29)} = 64.8$, $p < 0.001$, $h_p^2 = 0.69$). Between subject groups there was a significant main effect of Feedback on SGT ($F_{(1,29)} = 24.0$, $p < 0.001$, $h_p^2 = 0.453$), RR ($F_{(1,29)} = 6.3$, $p = 0.018$, $h_p^2 = 0.18$), and Go RT slowdown ($F_{(1,29)} = 15.2$, $p = 0.001$, $h_p^2 = 0.34$). Relative to the Reinforcement group, the Strategy-only group demonstrated higher average SGT biases, lower average stop-signal RR, and greater strategic slowdown across both Motivational Context blocks. There were no significant interactions between Feedback and Motivational Context (all $p > 0.1$).

Consistent with our expectations, Strategic Shift varied considerably across subjects. After removing an extreme outlier with a shift score of 1389 (IQR = 112 – 287), we found that Strategic Shift was highly correlated with shift in SSRT across blocks ($r = -0.68$, $p < 0.001$), though it did not differ between Feedback groups ($t_{(28)} = -0.48$, $p = 0.64$). Controlling for SGT shift, the main effect of Motivational Context was significant: SSRT was higher for the Go Bias block relative to the Stop Bias block ($F_{(1, 27)} = 4.2$, $p < 0.05$, $h_p^2 = 0.14$). Interestingly, the interaction between Motivational Context and strategic shift was highly significant ($F_{(1,27)} = 24.1$, $p < 0.001$, $h_p^2 = 0.47$). Figure 2 illustrates that participants with the lowest Shift scores had the largest difference in SSRT (Go SSRT > Stop SSRT), and participants with the highest Shift scores had the most negative change in SSRT (Go SSRT < Stop SSRT).

Table 4 displays the RR change over each of the Motivation blocks for the reinforcement and strategy only groups. In the Go Bias block, there was a significant main effect of Group ($F_{(1,29)} = 4.18$, $p = .05$), such that RR were higher overall for the strategy-only group. The main effect of Time on RR was marginally significant ($F_{(2,58)} = 2.79$, $p = 0.07$), and there was a significant interaction between Group and Time on RR ($F_{(2,58)} = 5.43$, $p = .007$). Throughout the speed block, RR was consistent for the reinforcement group but increased over time for the strategy only group. In the Stop Bias block, there was a significant main effect of Group ($F_{(1,29)} = 7.55$, $p = .01$), with RR being higher overall for the strategy-only group. There was also a significant main effect of Time on stop-signal RR ($F_{(2,58)} = 6.21$, $p = .004$). In both subject groups, RR increased over the course of the block. However, the amount of increase was not significantly different between groups ($F_{(2,58)} = 0.562$, $p = .573$).

Discussion

Experiment 4 replicated the results of Experiment 3 with respect to the influence of Motivational Context on stop-signal performance. Moreover, those subjects who only received instructions to shift strategy demonstrated similar shifts in performance bias as those who were given trial-by-trial feedback and reinforcement for performance. The lack of significant interactions between Motivational Context and Feedback indicate that the observed changes in stop-signal performance in both experiments is likely due to conscious shifts in strategy rather than more automatic processes that could have occurred in the course of reinforcement learning.

However, it is possible that both explicit strategy and reinforcement learning could produce the same pattern of results independently. In the present study, we did not include a group of subjects who received trial-based reinforcement but no strategy instructions. The Feedback groups both received strategy instructions and only differed in the receipt of reinforcement feedback after every trial. However, we implemented the strategic control training used in Experiment 3, and adapted in Experiment 4, because subjects in earlier pilot studies who received only reinforcement and no explicit instruction in strategy shifting, showed little to no change in SGT across Motivational Contexts. Although reinforcement may contribute somewhat to performance shifts, it seems that explicit strategic control is necessary to achieve shifts in performance across multiple SGT settings.

The results of the time-course analysis of RR changes over the course of each Motivational block are consistent with the hypothesis that explicit strategy drives performance shifts. If reinforcement learning significantly contributed to performance shifts, we would expect the reinforcement group to demonstrate gradual shift toward the targeted stop-signal RR. Interestingly, participants in the reinforcement group consistently responded to the stop-signal at the same rate across the Go Bias block, while participants in the strategy-only group steadily decreased in response rate over the course of the block. This suggests that subjects in both groups initially adopted the appropriate strategy, but without the benefit of performance feedback, subjects in the strategy-only group increasingly strayed away from the target over the course of the block. Both groups demonstrated a gradual decrease in RR over the course of the Stop Bias Block. Again, the shift in RR for the strategy-only group can be explained by lack of constraints on performance. On the other hand, the gradual change observed in the reinforcement group likely reflects the gradual shift toward a strategy favoring stop accuracy, which is at odds with the prepotent response to the go stimulus, since the go response is reinforced more frequently than performance on stop trials.

Our interpretations of performance shift within each Motivation block are consistent with the observation of main effects of Feedback group on overall SGT, stop-signal RR, and Go RT slowdown across Motivation blocks. Greater SGT values, lower stop-signal RR, and greater Go RT slowdown observed in the strategy-only group suggest greater inherent bias favoring accuracy over speed in our population. The observed differences in overall strategy between groups may have implications for the design of future experiments. Without the benefit of feedback following each trial, subjects in the strategy-only group ended up being slower overall, which increases likelihood of stopping correctly on stop trials. This demonstrates the importance of using some kind of performance feedback on the stop-signal task to adequately constrain subjects' behavior, which can influence performance bias and our estimation of SSRT.

Another implication for future studies is that it is important to control the strategy setting adopted by participants (e.g., the relative importance of stop- and go-trial performance as measured by SGT). Because we used fixed rewards and penalties (reinforcement group) or no feedback at all (strategy-only group) in Experiment 4, rather than the adaptive titration procedure used in Experiment 3, we observed much variability between subjects in the amount of strategic shift between the two Motivational Contexts. It is important to measure this variability and account for it when both comparing SSRT values across participants (or patient groups) and measuring strategy-induced SSRT changes within-participants. Another, approach is to experimentally control stop/go tradeoff using adaptive payoffs, as in Experiment 3, or other manipulations that impact stopping accuracy and Go RT slowdown. This approach is recommended, if it can be employed, because it ensures that all participants adopt similar strategy settings and obviates the need to include SGT changes as a covariate.

Interestingly, Figure 5 illustrates that those individuals with the largest strategic shift scores actually demonstrated higher SSRT scores on the Stop Bias block than the Go Bias block. This was inconsistent with our hypotheses as well as with the results from Experiment 3 that showed that SSRT was higher for the Go Bias block relative to the Stop Bias block. As the shift scores reflect the ratio of the change in Go RT slowdown to the change in stopping accuracy, higher strategic shift scores indicate that subjects slowed down considerably, but did not substantially increase inhibition accuracy. This pattern may suggest a nonlinear tradeoff between speed and accuracy, or it could be the result of poor decision-making on a limited number of trials for subjects who may have found the strategy instructions confusing or difficult, though no measures of perceived difficulty were obtained. Either way, the pattern of performance associated with higher strategic shift scores brings to light another way that strategic bias can influence SSRT estimates. Because the stop-signal onset time relative to the go-signal onset time was fixed across Motivational Contexts, a dramatic slowdown in Go RT on the Stop Bias block resulted in a lengthened SSRT. Certain participants may show this type of pattern in the absence of any explicit strategy instructions, and thus our findings have implications for the interpretation of SSRT in more commonly used variants of the stop-signal task.

General Discussion

The stop-signal task and associated SSRT measure (Logan, Cowan & Davis, 1984) provide a simple and reliable probe of response inhibition ability. In this paper, we address the central role of motivational influences on stop-signal performance and measurements of inhibitory ability. Although strategic bias has been acknowledged as a potential nuisance factor since the stop-signal paradigm's inception (Logan & Cowan, 1984), the overwhelming majority of research using the stop-signal task does not consider motivational influences when interpreting the results of SSRT differences across individuals or groups, in part because there has been no empirical demonstration of motivational effects on SSRT.

In the present study, however, we demonstrate that performance on the stop-signal task is indeed susceptible to changes in motivational context. Behavior—in particular the tradeoff between correct response withholding on stop trials and fast responding on go trials—was influenced by experimentally manipulating the payoffs associated with fast responses or with accurate inhibition. As a result, SSRT estimates of stop-latency systematically varied, suggesting that the SSRT measure, as typically implemented, is not insensitive to motivational and strategic influence. The change in SSRT observed in Experiment 3 is comparable to the difference in SSRT reported between individuals with ADHD and healthy controls in several studies (Aron, *et al.*, 2003; Epstein, *et al.*, 2001; Manassis, Tannock & Barbosa, 2000). If motivational bias or strategy shifts can affect SSRT estimates *within* individuals, then inherent motivational biases may be driving much of the difference observed in SSRT estimates *between* individuals.

Motivational context may produce systematic variations in SSRT for two major reasons: (1) Inhibitory ability is independent of motivational context, but our *measures* of inhibitory ability (e.g. SSRT) depend on processes influenced by motivational context. Violation of the major assumptions of the SSRT measurement model (Logan & Cowan, 1984) may lead to biased estimates of stop latency (Band *et al.*, 2003; De Jong *et al.*, 1990). One way to address this issue would be to obtain summary measures of inhibitory ability, which account for variations in performance across multiple contexts, such as the AUC measure used in Experiment 3. Alternately, (2) inhibitory ability may not be a fixed trait ability, but may be mutable, so that stopping correctly becomes more or less difficult for an individual depending on the primary motivational focus toward speed or accuracy. A plausible mechanism might be that putative go and stop pathways in the brain (Frank, Seeberger, &

O'Reilly, 2004) can be differentially potentiated by mental preparation, and that shifts in motivation to go fast or stop correctly may change the relative potentiation of the pathways. Future studies designed to test these alternative hypotheses would make significant contributions to our understanding of inhibitory control and how it is modulated by motivational context.

Motivational influences on stop-signal performance can be understood in terms of a simple Bayesian decision framework. In this framework, information about a trial increases sequentially over time, and a response is made (either activation of response or cancellation of response) once sufficient information is acquired to reach the decision threshold. On a given trial in the stop-signal task, information about the trial type (stop vs. go) is accumulated. Over time, the probability that a stop-signal will occur decreases and the probability that a go-response should be made increases. However, decision thresholds may depend on prior expectancies of stop-signal probability. We hypothesize that Motivational Context influences the prior expectation of stop-signal probability, resulting in shifts in performance tradeoffs and differences in SSRT.

Figure 6 outlines a theoretical model for explaining motivational influences on performance on the stop-signal task. On a given trial, a subject must calculate the probability that a stop-signal will occur, while simultaneously accumulating information about the go stimulus (respond left or right). Perceptual information is accumulated until the criterion is met for one of three responses (left, right, or inhibit). As the probability of a stop-signal trial increases, task performance could be affected in several ways: (1) a lower threshold for the inhibit response could result in early cancellation of all motor output; (2) an increased threshold for both go responses (left and right) would require greater information accumulation before initiating a go response; or (3) go response thresholds remain unchanged, but calculation of the joint probabilities delays the accumulation of information to reach a response threshold. All of these mechanisms would result in the same outcome: longer and more variable go responses, decreased probability of responding on a stop-signal trial, and shorter SSRTs.

Motivational Context likely contributes to prior probability expectancies at several different levels, explaining multiple phenomena observed in the stop-signal task. The expected probability of a stop-signal may be influenced by experience (e.g. overall frequency or history of trials). Consider performance in the context of the "speed" block, where no stop-signals are presented. The probability of a stop-trial is zero in this block, and responses depend merely on the accumulation of information to reach either the left or right response threshold. However, when stop-signal trials are introduced, the probability of a stop trial becomes greater than zero, and invariably, subjects demonstrate slowdown of go responses. Furthermore, greater frequency of stop-signals (50% vs. 25%) increase the expected probability of stop-signals, and consequently may contribute to the lengthening of go responses and shortening of SSRT estimates observed in Experiment 3 and by others (Ramautar et al., 2006). Additionally, prior probabilities of stop-trials may depend on the recent history of trials experienced by a subject. If a stop-signal does not occur for several trials, the probability that the next trial will be a stop trial increases and the probability that a go response will be necessary decreases. As a result, decision criteria are adjusted, go response latencies increase, and successful inhibition becomes more probable.

Prior probabilities may also depend on the subjective cost of responding on a stop-signal trial. Actual probabilities may be subjectively weighted for several reasons, including (1) individual differences in the interpretation of task goals and what it means to be successful on the stop-signal task, explaining differences in performance and in SSRT in subjects from Experiments 1 and 2; (2) variations in explicit reward and penalties for performance on stop (and go) trials, as in Experiment 3, as well as sensitivity to those rewards and penalties (Yechiam *et al*, 2006) and (3) informational value imposed by instructions to adopt a specific strategic tradeoff, as in Experiment 4.

We present the model outlined in Figure 6 as a preliminary theoretical explanation of motivational influences on response inhibition in the stop-signal task. Though formal testing of the model is beyond the scope of the present paper, we believe that this framework is an appropriate starting point for explaining the observed phenomena. The proposed model is consistent both with signal detection theory and with error-driven learning models, and many researchers have applied similar decision models to explain response times, decisions, and speed-accuracy tradeoffs in cognitive tasks (Busemeyer & Townsend, 1993; Ratcliff, 1985, 1988; Ratcliff & Smith, 2004; Smith & Vickers, 1988; Usher & McClelland, 2001). Across the four experiments presented here, we demonstrate various sources of motivational and strategic bias that influence stop-signal performance and measures of inhibitory ability. Ultimately, each of the motivational effects we observed, as well as some effects commonly observed in other research (e.g. frequency and history effects), can be effectively explained by the proposed conceptual framework.

It is important to address the influence of motivation on inhibitory control, since these inhibitory control processes are thought to play principal roles in other basic cognitive processes such as attention (Neill, 2007; Rafal & Henik, 1994) and memory (Anderson & Green, 2001; Hasher & Zacks, 1988), as well as in complex regulatory behaviors related to emotion processing and social interaction (Kunda & Spencer, 2003). However, many researchers have questioned the reliability and validity of response inhibition measures as indices of inhibitory control, largely because zero-order correlations between different measures of inhibitory control tend to be very low (Friedman & Miyake, 2004; Kramer et al, 1994; Shilling et al, 2002). However, small correlations do not necessarily imply that the measures are unrelated. Friedman & Miyake (2004) suggested that low zero-order correlation could be explained by the impurity of the inhibition measures, due to idiosyncratic differences in stimuli and task demands. Here, we have made a similar point with respect to the stop-signal paradigm, arguing that slight differences in task instructions, stimuli, and experimental parameters can alter performance and associated inhibition measures substantially. Hopefully, the present study will encourage researchers to take these considerations into account when designing future studies, ultimately contributing to a unified goal of developing an improved taxonomy of inhibitory control.

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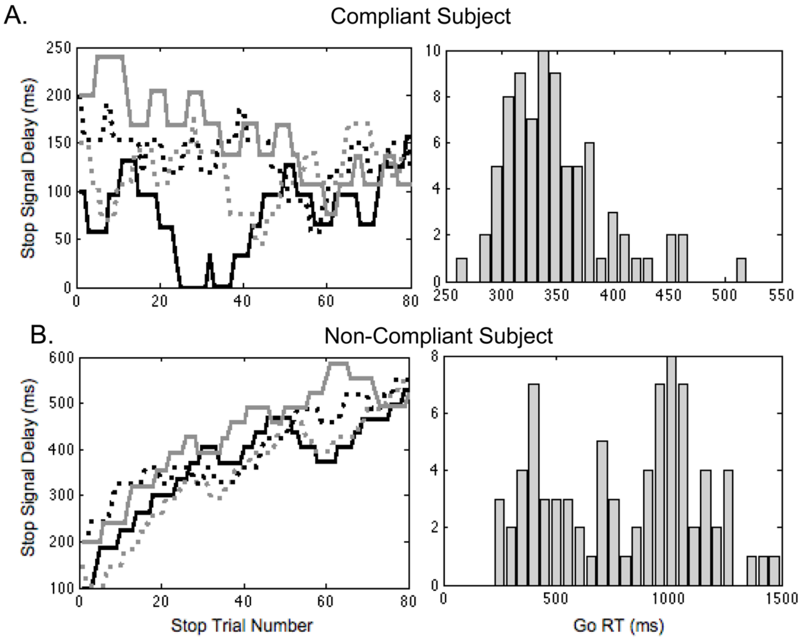

Figure 1.

Interpretations of performance differ for compliant (A) and non-compliant (B) subjects on the SSD tracking procedure (Experiment 1). On the left, we display the stop-signal delay (SSD) values as a function of stop trial number. Each line represents one of four staircases with different starting values. On a given stop-signal trial, the SSD is chosen from one of the four staircases. If inhibition is successful, the SSD for that staircase will be increased by 50ms and if inhibition is unsuccessful and a response is made, the SSD will be decreased by 50ms. Ideally, the four staircases will converge on the SSD value that results in 50% stopping accuracy. On the right, we display the go RT distributions from the tracking block. (A) The compliant subject consistently responded fast throughout the experiment, resulting in a typical choice RT distribution that is unimodal and slightly positively skewed (right). The four staircases (left) converge and oscillate around SSD = 125ms. (B) In contrast, the staircases for the noncompliant subject (left) steadily increase throughout the tracking block, suggesting the subject increasingly slowed responses in order to avoid responding on stop trials. The bimodal distribution of dramatically lengthened RTs (right) confirms this hypothesis and demonstrates a type of noncompliant behavior that can compromise the utility of an SSD tracking procedure.

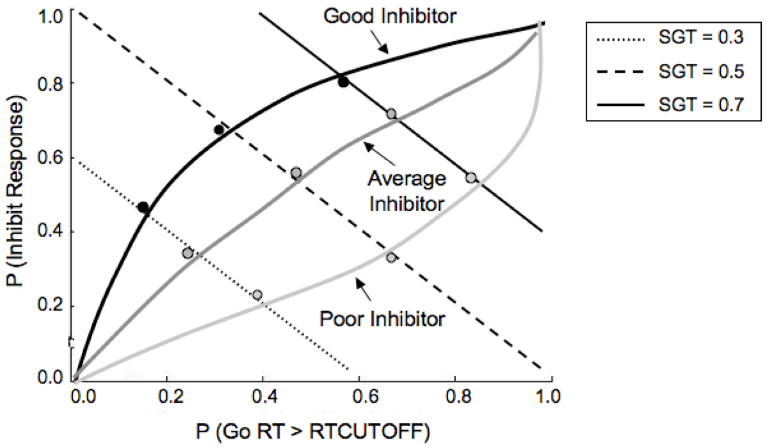

Figure 2.

Stop-signal task performance was sampled at multiple stop-go tradeoff (SGT) settings to obtain an inhibitory control measure that is orthogonal to SGT bias. In Experiment 3, rewards and penalties for performance were titrated to target each of three SGT settings (diagonal lines) for the Go Bias, No Bias, and Stop Bias blocks, respectively. For example, if a participant adopts a strategy that favors fast responding over accurate inhibition, performance would lie somewhere along the diagonal where SGT = 0.3. A measure of inhibitory ability can be estimated by estimating the speed-accuracy tradeoff curve that best explains performance across the three SGT points. SGT should be independent of the curve because the same SGT setting is possible anywhere along its diagonal, as demonstrated with three sample subjects of varying inhibitory ability: a relatively good inhibitor (concave curve), an average inhibitor (middle gray curve), and a relatively poor inhibitor (convex curve).

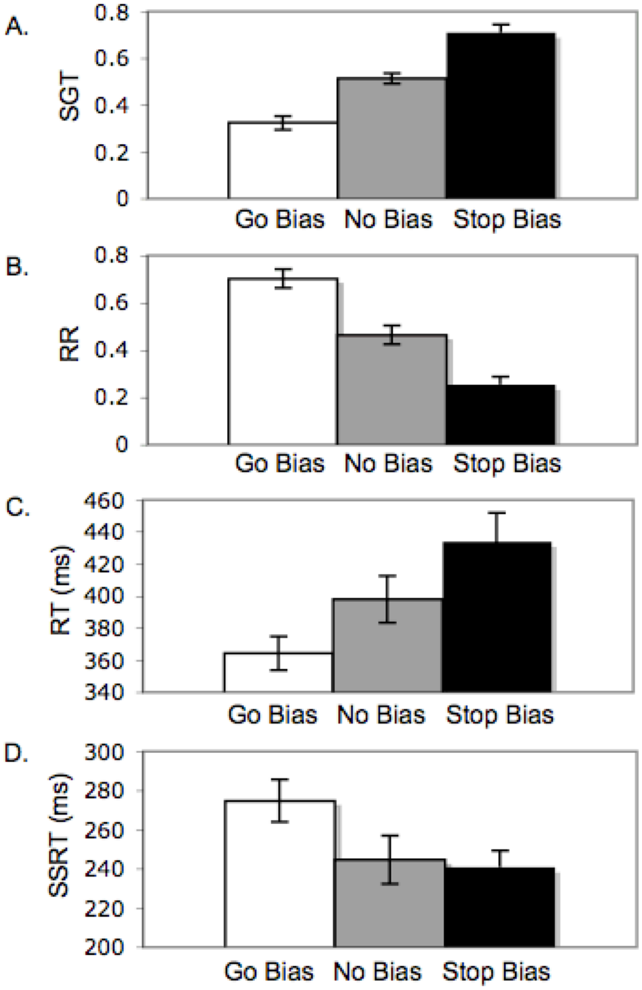

Figure 3.

Variations in rewards and punishments result in strategic changes in stop signal performance in Experiment 3. The figures display, respectively, that as payoffs increasingly favor stop accuracy over speed, (A) SGT values increase (B) stop-signal RR decreases (C) "go" response times increase, and (D) SSRT estimates decrease.

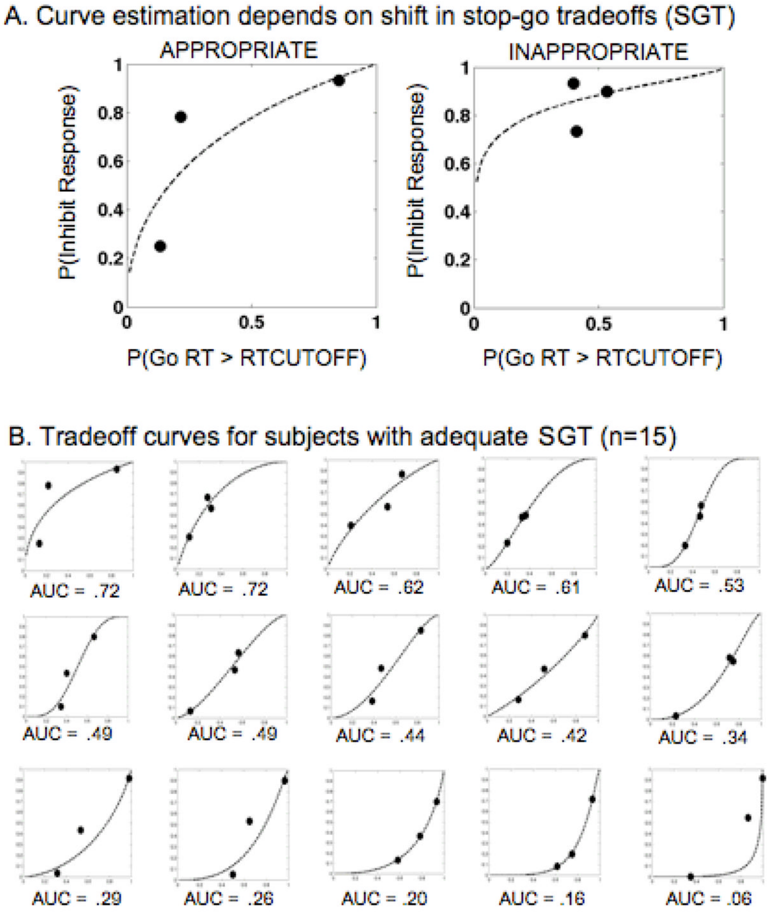

Figure 4.

(A) Example SGT curves based on data from two Experiment 3 subjects. Successful estimation of the speed-accuracy tradeoff curve depends on appropriate variability in the SGT settings sampled. The subject on the left shifted SGT adequately (AUC = 0.72), whereas the subject on the right did not shift SGT settings at all (AUC = 0.85). As a result, the curve that best explains the data on the right does not have very good predictive validity at other SGT settings, and so accuracy of the curve and of the resulting AUC measure are questionable. (B) Tradeoff curves for the 15 subjects with appropriate shifts in SGT across Motivational Contexts.

Figure 5.

Change in SSRT across Motivational Contexts is inversely related to shift in strategic tradeoff in Experiment 4. On the y-axis, positive SSRT change scores reflect that SSRT Speed block > SSRT Accuracy block, whereas negative change scores reflect SSRT Speed < SSRT Accuracy. Strategic shift is a measure of the slowdown in Go RT divided by the increase in stop accuracy when comparing performance on the Stop Bias block relative to the Go Bias block. Thus, strategic shift reflects the overall change in SGT between blocks, as well as the efficiency of trading off between speed and accuracy: higher strategic shift scores were observed for participants who slowed considerably when shifting strategies but did not improve stopping accuracy. As a result, these subjects demonstrated a negative change in SSRT, reflecting a larger SSRT for the Stop Bias block relative to the Go Bias block, whereas participants with lower Strategic Shift scores demonstrated more positive change in SSRT, reflecting a larger SSRT for the Go Bias block relative to the Stop Bias block.

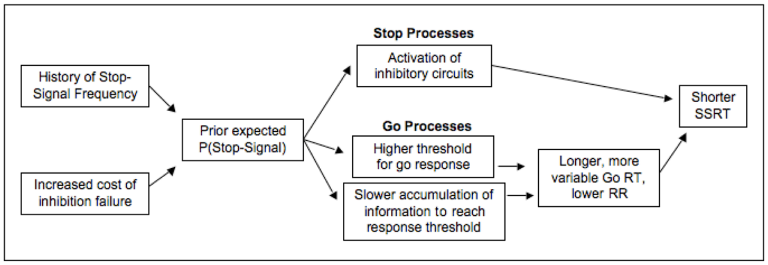

Figure 6.

Theoretical Model for Explaining Motivational Influences on Response Inhibition. Motivational context influences the expected probability the stop-signal will occur, either directly by changing the frequency of stop trials, or indirectly, by changing the subjective weighting of probabilities due to internally generated value of stopping or externally imposed rewards and penalties for performance. Increase in P(stop-signal) may alter inhibitory control either directly by affecting stop-processes and engaging inhibitory circuits, or indirectly, by changing the decision threshold (or latency to reach the decision threshold) for go responses. In either case, we would expect to observe lengthened go responses and shortened SSRT values.

Table 1

RT Slowdown, RR, and SSRT in Experiment 1

	Mean (*SE*)				
	Speed RT (ms)	**Tracking RT (ms)**		**RR**	**SSRT (ms)**
		Early	***Late***		
Compliant (N=25)	343 (23)	438 (92)	438 (90)	0.49(.05)	202 (40)
Noncompliant (N=9)	347 (39)	566 (123)	698 (142)	0.31(.07)	94 (59)

Subjects were defined as non-compliant if they responded to stop-signals less than 40% of the time. Targeted stop-signal RR was 50%.

Table 2

Variation in SGT, RR, RTs and SSRT Across Motivational Contexts in Experiment 3

		Mean (*SE*)				
Measure		**Go Bias**	**No Bias**	**Stop Bias**	***F***	***p* <**
SGT						
	25%	0.42 (.04)	0.53 (.04)	0.63 (.05)	16.6	0.001
	50%	0.29 (.04)	0.53 (.03)	0.79 (.04)	62.4	0.001
RR						
	25%	0.49 (.05)	0.35 (.06)	0.26(.05)	9.28	0.005
	50%	0.79 (.05)	0.50 (.05)	0.24 (.04)	59.9	0.001
RT Δ (ms)						
	25%	−15 (13)	−3 (20.)	8 (25)	3.75	0.05
	50%	47 (12)	105 (18)	171 (23)	20.8	0.001
SSRT (ms)						
	25%	294 (21)	268 (23)	264 (14)	16.2	0.005
	50%	257 (19)	214 (20)	209 (13)	19.3	0.005

Statistics are from separate repeated measures ANOVAs for each task version (25% vs. 50% stop-signal trials). Outcomes: stop-go tradeoff (SGT), stop-signal response rate (RR), slowdown of mean Go RT relative to speed block RT (RT Δ), and stop-signal reaction time (SSRT).

Table 3

Variation in SGT, RR, RTs and SSRT Across Motivational Contexts in Experiment 4

	Mean (*SE*)			
	SGT	**RR**	**RT Δ (ms)**	**SSRT (ms)**
Go Bias Block				
Reinforcement	.33 (.03)	.75 (.04)	15 (10)	220 (8)
Strategy-Only	.50 (.04)	.65 (.04)	65 (10)	206 (9)
Stop Bias Block				
Reinforcement	.65 (.03)	.37 (.04)	82 (15)	211 (8)
Strategy-Only	.84 (.03)	.23 (.04)	153 (16)	192 (8)

For SSRT, means reported are adjusted for model including Strategy Shift as a covariate.

Table 4

Stop-Signal Response Rate Changes Within Go Bias and Stop Bias Blocks

	Go Bias			Stop Bias		
	Early	**Middle**	**Late**	**Early**	**Middle**	**Late**
Reinforcement	.27 (.20)	.26 (.23)	.22 (.20)	.56 (.20)	.63 (.22)	.71 (.23)
Strategy-Only	.25 (.16)	.42 (.20)	.44 (.22)	.73 (.14)	.79 (.16)	.82 (.13)

Stop-signal response rates were averaged over the first ten stop trials (Early), the second ten stop trials (Middle), and the last ten stop trials (Late) for each Motivation block. Standard deviations are in parentheses.