

INVESTIGATING A RACE MODEL ACCOUNT OF EXECUTIVE CONTROL IN RATS WITH THE COUNTERMANDING PARADIGM

J. BEUK,^a R. J. BENINGER^{a,b,c} AND M. PARÉ^{a,b,d,*}

^a Centre for Neuroscience Studies, Queen's University, Kingston, Ontario K7L 3N6, Canada

^b Department of Psychology, Queen's University, Kingston, Ontario K7L 3N6, Canada

^c Department of Psychiatry, Queen's University, Kingston, Ontario K7L 3N6, Canada

^d Department of Biomedical & Molecular Sciences, Queen's University, Kingston, Ontario K7L 3N6, Canada

Abstract—The countermanding paradigm investigates the ability to withhold a response when a stop signal is presented occasionally. The race model (Logan and Cowan, 1984) was developed to account for performance in humans and to estimate the stop signal response time (SSRT). This model has yet to be fully validated for countermanding performance in rats. Furthermore, response adjustments observed in human performance of the task have not been examined in rodents. Male Wistar rats were trained to respond to a visual stimulus (go signal) by pressing a lever below that stimulus, but to countermand the lever press (25% of trials) subsequent to an auditory tone (stop signal) presented after a variable delay. We found decreased inhibitory success as stop signal delay (SSD) increased and estimated a SSRT of 157 ms. As expected by the race model, response time (RT) of movements that escaped inhibition: (1) were faster than responses made in the absence of a stop signal; (2) lengthened with increasing SSD; and (3) were predictable by the race model. In addition, responses were slower after stop trial errors, suggestive of error monitoring. Amphetamine (AMPH) (0.25, 0.5 mg/kg) resulted in faster go trial RTs, baseline-dependent changes in SSRT and attenuated response adjustments. These findings demonstrate that the race model of countermanding performance, applied successfully in human and nonhuman primate models, can be employed in the countermanding performance of rodents. This is the first study to reveal response adjustments and AMPH-induced alterations of response adjustments in rodent countermanding. Crown Copyright © 2014 Published by Elsevier Ltd. on behalf of IBRO. All rights reserved.

Key words: behavioral inhibition, stop task, inhibition function, impulsivity, response adjustments, amphetamine.

*Correspondence to: M. Paré, Centre for Neuroscience Studies, Queen's University, Kingston, Ontario K7L 3N6, Canada. Tel: +1-613-533-3107; fax: +1-613-533-6840/6880.

E-mail address: martin.pare@queensu.ca (M. Paré).

Abbreviations: AMPH, amphetamine; ANOVA, analysis of variance; CV, coefficient of variation; FR1, fixed-ratio 1; RT, response time; SD, standard deviation; SEM, standard error of mean; SSD, stop signal delay; SSRT, stop signal response time; ZRFT, Z relative finishing time.

INTRODUCTION

In a dynamically changing environment, executive processes are internally generated acts of control that allow an organism to adapt to changing situations and bring courses of thought and action in line with current goal sets (Logan, 1994). The executive system requires the ability to inhibit thoughts or actions no longer appropriate in light of new goals. Thus, inhibition of action, or countermanding, is one important aspect of behavioral control that can be studied to elucidate executive functions (Logan and Cowan, 1984). Furthermore, impairment of inhibitory control characterizes several human psychopathologies, including attention deficit/hyperactivity disorder, obsessive compulsive disorder, and schizophrenia (Alderson et al., 2007; Chamberlain and Sahakian, 2007; Crosbie et al., 2008; Lipszyc and Schachar, 2010).

The countermanding task, also known as the stop task, was specifically designed to investigate inhibitory control. Subjects are given a primary response to perform at the onset of a go signal. On a small subset of trials a stop signal is presented at a variable stop signal delay (SSD) following the go signal, requiring inhibition of the primary task (Lappin and Eriksen, 1966). Logan and Cowan (1984) developed a horse-race model to account for countermanding performance, positing independent go and stop processes racing toward a finish line. The first process to cross its finish line wins the race and determines the behavioral outcome (Fig. 1A).

To validate the race model for human countermanding task performance, Logan and Cowan (1984) predicted and accordingly demonstrated that inhibiting a response was less probable as SSD lengthened and that non-canceled responses on stop trials were generally faster than go trial responses and approached mean go trial response time (RT) as SSD lengthened. Furthermore, the race model allowed fairly precise estimations of mean non-canceled RT at different SSDs given the observed go trial RTs and probability of responding at that SSD, although predicted non-canceled RTs tended to underestimate the observed ones at shorter SSDs. The power of the race model is that it permits estimation of the time required to cancel a response – the stop signal response time (SSRT) – a variable that is not directly observable (Band et al., 2003). Confirming these specific predictions of task performance is necessary to validate the assumptions underlying the race model (Logan, 1994). The SSRT estimate is only valid if race model predictions of performance are

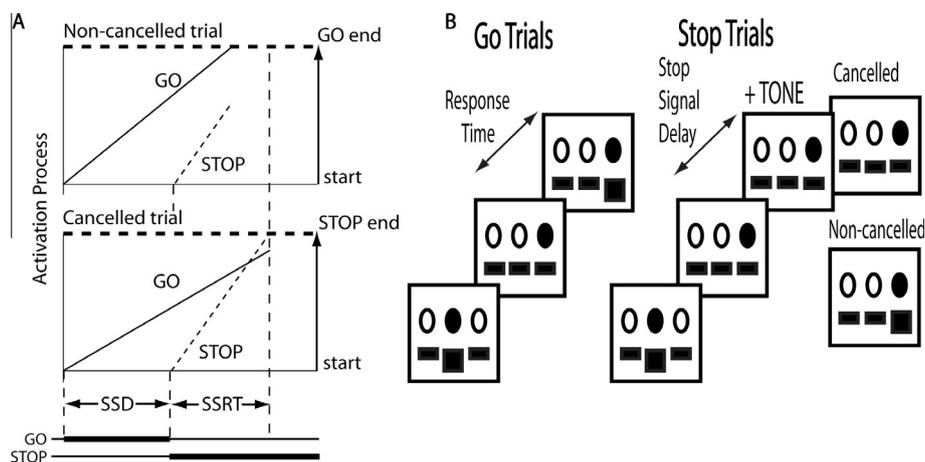


Fig. 1. (A) The race model of countermanding performance proposes that two sets of processes, one initiated by a go signal and one by a stop signal after a variable stop signal delay (SSD), race toward a threshold whereby the winner of the race determines the behavioral outcome. The stop signal RT (SSRT) can be estimated as the time between stop signal onset and the point where the stop process crosses the threshold to countermand the response (adapted from Paré and Hanes, 2003). (B) Before a trial, the center light is illuminated. A center lever press begins a trial and a light is immediately illuminated randomly above the left or right lever (i.e., the go stimulus). On go trials (75%), pressing the lever directly below the illuminated light results in reward. On stop trials (25%) an auditory tone (i.e., the stop stimulus) is presented at varying delays from go stimulus onset (SSD) and canceling the lever press results in reward, whereas a non-cancelled lever press results in a timeout period.

respected. Consequently, these predictions were replicated to account for both human saccade (Hanes and Carpenter, 1999) and macaque monkey (Hanes and Schall, 1995; Hanes et al., 1998; Paré and Hanes, 2003) countermanding task performance.

The application of the countermanding task to investigate inhibitory control with rats has grown rapidly (e.g., Feola et al., 2000; Eagle and Robbins, 2003a,b; Pattij et al., 2007; Eagle et al., 2009; Kirshenbaum et al., 2011). Yet, there has been sparse systematic investigation into the validity of a race model account of rodent stop task performance. Rats have been omitted in previous reports for performing the stop task outside the framework of the race model, namely generating unstable go trial accuracy or non-increasing probabilities of response inhibition as SSD lengthened (Eagle and Robbins, 2003a,b, 2008; Pattij et al., 2007, 2009; Robinson et al., 2008; Bari et al., 2009, 2011; Eagle et al., 2011); however, these data were not explicitly displayed. Additionally, a number of these studies noted that rats included in analysis performed the task according to the assumptions of the race model. This was partially demonstrated with increased probability of non-cancelled responding as SSD increased, although these inhibition functions never spanned the full range from 0% to 100% inhibition. Eagle et al. (2007) reported that mean non-cancelled stop trial RT was faster than mean go trial RT in a group of control rats. To date, this is the only evidence directly confirming the race model predictions of stop task performance outlined by Logan (1994). Thus, it remains to be established whether this crucial prerequisite is fully met in rats.

Rat models allow behavioral and invasive investigations in large samples of animals and, ipso facto, the study of inter-individual variability in the control of behavior. Inter-individual differences in executive control are particularly significant given the

non-linear role of catecholamine systems in this function (Lidow et al., 1998). For example, amphetamine (AMPH) increased or decreased SSRT in rats, dependent on fast or slow baseline performances respectively (Feola et al., 2000; Eagle and Robbins, 2003a). Important inter-individual differences in adaptive response adjustment have also been documented in humans and macaque monkeys performing the countermanding task; slower responses usually following successfully canceled responses (Emeric et al., 2007), but have not been observed in rats. In addition, there exists several rat models of neuropsychiatric symptoms (Nestler and Hyman, 2010; Sontag et al., 2010; Bari and Robbins, 2011) for which the assessment of executive control deficits would benefit from the rigorous testing offered by the countermanding paradigm.

Here, we demonstrate that the race model does account for performance of rats in a countermanding task closely resembling tasks used in humans and monkeys. Rats adjusted their responses in this task, primarily by slowing responses following non-cancelled stop trial responses. Administration of AMPH attenuated these response adjustments.

EXPERIMENTAL PROCEDURES

Animals

Behavioral data were collected from two cohorts of male albino Wistar rats. The first cohort ($n = 8$) was used to test race model predictions, while the second cohort ($n = 16$) was added to test the effects of AMPH. All animal care and experimental protocols were approved by the Queen's University Animal Care Committee and were in accordance with the guidelines of the Canadian Council on Animal Care and the Animals for Research Act. Rats bred by Charles River Laboratories

(St. Constant, Quebec, Canada) were housed in pairs in clear plastic cages (50.0 × 40.0 × 20.0 cm high) with woodchip bedding (Beta Chip; Northeastern Products Corp., Warrensburg, NY, USA) in an environmentally controlled colony room with a reversed 12-h light–dark cycle, where dark began at 0700 h. Rats were given free access to water, with food (LabDiet 5001, PMI Nutrition Intl, Brentwood, MO, USA) freely available or restricted (see procedure).

Apparatus

Data were collected from four identical operant chambers (30.5 × 24.1 × 21.0 cm high) with a clear polycarbonate door, rear wall and roof (ENV-008, Med Associated Inc., St. Albans, VT, USA). The floor consisted of 0.5-cm-diameter parallel stainless-steel rods 1.0 cm apart. On both side walls, four aluminum posts separated the walls into three panels. On one wall, the far panel contained a 2.8-watt incandescent house light, 1.0 cm from the roof and 5.0 cm above a tone generator. The tone generator emitted a single tone with a frequency that differed in each box, ranging from 2400 Hz to 3400 Hz at an intensity of 75 dB. On the same wall, the middle panel contained a food pellet receptacle (5.1 × 5.1 × 2 cm deep) that was 3.0 cm above the grid floor. Dustless precision food pellets (45 mg) from Bio-Serv (Frenchtown, NJ, USA; product number: F0021) were dispensed from a pedestal mounted pellet dispenser located outside of the chamber. On the opposite wall, each of the three panels was outfitted with a 2.5-cm-diameter LED stimulus light that was 4.5 cm below the ceiling and 5.0 cm above a retractable response lever (4.8 × 1.7 × 1.3 cm thick). Each chamber was isolated in a sound-attenuating case. Programming and data analysis were controlled by MED-PC[®] IV software (Med Associated Inc.).

Training procedures

Rats were initially housed in pairs and had food and water available *ad libitum*. From day 3 until 7 of colony room habituation, rats were handled in pairs approximately 5 min/day. Food access was restricted on the 7th day to 1 h free-feeding/day for the majority of training. Food access was increased to 2 h/day later in the study to maintain weight growth.

First, animals were trained to lever press for food reward. The center light was illuminated and a lever was extended directly below it. The house light was always illuminated except during timeout periods (see below). Sucrose pellets were dispensed as rats progressed toward making a lever press until they successfully pressed the extended lever to dispense food pellets on a fixed-ratio 1 (FR1) schedule. An animal was considered trained (1–3 sessions) when it pressed the lever at least 30 times during a 30-min FR1 schedule session.

Second, a stimulus light was randomly illuminated directly above either the left or right extended levers for light discrimination training. Pressing the lever directly below the illuminated light was considered a correct

response. All correct responses during training resulted in sucrose pellet reward and all lights above levers turning off for a 5-s intertrial interval preceding the next trial. Pressing the lever below the non-illuminated light was considered an incorrect response. All incorrect responses during training resulted in no sucrose pellet reward and all lights, including the house light, turning off for a 10-s timeout period. The timeout period was followed by a 5-s intertrial interval where only the house light was illuminated preceding the next trial. Lever press omission after a 60-s time limit was considered incorrect. Light discrimination training was considered acquired when a rat met criterion (3–5 sessions). Criterion for training sessions was correct responding on ≥80% of the last 100 trials in a session.

Third, all three levers were extended for the duration of 60-min go trial training sessions. Before trial initiation, the center light was illuminated, requiring a center lever press. For the remainder of training, if the rat did not make a center lever response within a 60-s time limit, or pressed a different lever, the response was considered incorrect. If the rat pressed the center lever to initiate a trial, the center light turned off. Immediately, the left or right stimulus light illuminated randomly (acting as the go signal) signifying the lever below the illuminated stimulus as the target lever. Pressing the target lever was considered a correct response. The amount of time from go signal onset until target lever press was recorded as the go trial RT. Pressing a lever other than the target lever was considered an incorrect response. Once criterion was met, the time limit for pressing the target lever was limited in the next session such that the target lever was only active for an amount of time that approximately eliminated the slowest 10% of the distribution of go trial RTs from the previous session. This shortening of the time limit continued until rats met criterion with a time limit between 1.0 and 1.6 s (4–7 sessions).

Fourth, rats were given one 30-min tone habituation session. All levers were retracted. Only the house light was presented. A short acoustic burst (1 s) was presented on a variable-time 30-s schedule. Immediately after auditory stimulus presentation a sucrose pellet was delivered to associate the tone with reward in the absence of lever pressing.

Fifth, rats received stop trial training. All three levers were made available for the duration of the 60-min sessions. The center light was illuminated and if the center lever was pressed to initiate a trial, the stimulus light was randomly illuminated immediately above the left or right lever; however a 1-s auditory stimulus was presented concurrently (acting as the stop signal). If lever press responding was withheld for the entire 1-s time limit, the response was considered correct. If a lever press was made during the trial, the response was considered incorrect. As soon criterion was met, the time limit was increased by 0.5 s in the next session until criterion was met with a time limit of 2-s (4–7 sessions).

Sixth, rats were given a 30-min go trial session using the time limit previously established in go trial training immediately followed by a 30-min stop trial session using a 2-s time limit. Go and stop trial sessions were

tested consecutively each day until rats met criterion in both sessions on the same day (3–6 days).

Seventh, countermanding task training consisted of 75% go trials and 25% stop trials presented randomly throughout the session. The target lever was active for the time limit previously established in go trial training. The time limit varied for each rat between 1.0 and 1.6 s during countermanding task training until an appropriate time limit was found that eliminated approximately the slowest 10% of the go trial RT distribution. After a number of countermanding task training sessions (4–7), animals met criterion and were ready to be tested in the countermanding task (approximately 20–36 training sessions in total).

Countermanding task

Immediately prior to each countermanding session, rats completed training blocks of 10 go trials followed by 10 stop trials with a trial time limit of 1.5 s. Countermanding sessions (60 min) consisted of 75% go trials and 25% stop trials presented randomly (Fig. 1B). The house light was always illuminated except during timeout periods. Initially the light above the center lever was illuminated requiring a center lever press to initiate a trial. Immediately after a center lever press, the target light (acting as the go signal) was randomly illuminated above either the left or right lever, signifying the lever below the illuminated light as the target lever. The target lever was active for a time limit previously established in countermanding task training for each rat (1.0–1.6 s). For go trials, rats were required to press the target lever before the end of the time limit to be rewarded. If the target lever was not pressed before the end of the time limit, or a different lever was pressed, the response was considered incorrect. In stop trials, a center lever press resulted in go signal presentation. An acoustic burst (white noise; 75 dB), acting as the stop signal, was presented for the length of the time limit plus an additional 300 ms and instructed the rat to inhibit a lever press to be rewarded. Any lever press was considered an incorrect response. All correct responses dispensed a food pellet. Incorrect responses resulted in a 10-s timeout period, whereby all lights in the chamber, including the house light, were turned off. A 5-s intertrial interval, where only the house light was illuminated, preceded the onset of the next trial in either case. Using a staircase procedure with a 100-ms step, countermanding task sessions began with an initial SSD of 100 ms. The SSD increased by one step if a lever press was correctly countermanded or decreased by one step if a non-canceled lever press was made. Finally, if a lever press on a stop trial occurred before stop signal presentation, the trial was recorded as a non-canceled response; however the rat was given a sucrose pellet and a 5-s intertrial interval (i.e., it appeared as a go trial to the rat). In these instances the SSD was decreased by one step.

Data analysis

Race model analysis sessions were omitted if they contained less than 200 total trials (this would include less than 50 stop trials). If SSD increased by more than two consecutive steps later in a 1-h countermanding task session and did not return back toward the mean SSD for that session, all trials from the point where the SSD increased were excluded from analysis. Increased SSD later in sessions was generally associated with slower responses, indicating a decrease in motivated, attentive behavior. Models of RT slowing later in stop task sessions revealed significant SSRT misestimation (Verbruggen et al., 2013). Because these data were generally unstable and variable, their omission from analysis was required.

Each rat was tested over a number of sessions (11–33 sessions). We pooled data from multiple sessions into one data set for each rat to ensure a full range of response inhibition probabilities with enough stop trials at each SSD to confidently test race model predictions. For each rat, RT distributions on go trials were compared to other sessions using independent Kolmogorov–Smirnov tests (KS-test). Five sessions found to not differ statistically were pooled into one data set for each animal. The number of non-canceled responses made at a particular SSD was compared to the total number of stop trials of that delay to calculate the proportion of non-canceled responses at each SSD (i.e., the inhibition function). Inhibition functions from selected individual sessions for each rat were examined to confirm that they shared a similar form. Furthermore, SSDs for individual sessions displayed comparable ranges for each rat (less than a 1-step difference for the minimum SSD and 3-steps or less for the maximum SSD). Independent Chi-square tests were conducted on probability contingencies of the full inhibition functions to determine if the proportion of non-canceled responses varied across SSDs.

The integration method was used to estimate SSRT (Logan and Cowan, 1984). The average of the peaks and valleys of each SSD run and midpoint of every second SSD run were estimated and averaged to approximate the SSD at which the probability of making a non-canceled response was 0.5 (Levitt, 1971). Assuming SSRT is a constant, the integration method estimates the time at which the stop process ends – given the SSD where the probability of making a non-canceled response is 0.5 – by integrating the distribution of go trial RTs until the integral equals the RT at which the probability of making a non-canceled response is 0.5. SSRT equals this time (i.e., the instant when the stop process ends) minus the SSD where the probability of making a non-canceled response is 0.5 (i.e., the instant when the stop process is initiated).

Rats did not make a response on a small proportion of go trials. The possibility exists that a correctly inhibited stop trial was in fact a failed go response. For rats 1–8, the proportion of omission errors on go trials (0.14, 0.10, 0.07, 0.08, 0.08, 0.08, 0.16, and 0.06 respectively) was accounted for in SSRT estimation. To account for omission errors, the inhibition probability data were

corrected using a procedure modified from [Tannock et al. \(1989\)](#): $Y = (X - O)/(N - O)$, where Y is the corrected proportion of non-canceled stop trials at a specific SSD, X is the observed number of non-canceled stop trials at that SSD, O is the correction for the number of omission errors calculated as the proportion of omissions that occurred in go trials and N is the total number of stop trials at that SSD.

Paired samples t -tests were conducted to evaluate race model predictions of stop task performance. Data from SSDs were excluded from analysis if there were less than 10 trials. We further examined RT adjustments by identifying blocks of three consecutive trials where a correct go trial occurred prior to and following a correct go trial response, a non-canceled stop trial response or a canceled stop trial response. An analysis of variance (ANOVA) was conducted to analyze adaptive RT adjustments. Follow up paired samples t -tests compared the average RTs of the go trial before and following each interleaved trial type. Partial eta squared (η_p^2) and Cohen's d were used to estimate effect sizes ([Cohen, 1988](#)). For within-subject tests, the effect size was corrected for dependence among means ([Morris and DeShon, 2002](#); Eq. (8)). All analyses were conducted using a significance level of 0.05.

AMPH treatment

Following race model testing, rats from the first cohort were divided into two groups and randomly administered d-amphetamine sulfate (AMPH, 0.5 mg/kg, i.p.; Sigma, Oakville, Ontario, Canada) or saline immediately before testing in the countermanding task. Two no-treatment days were conducted between administrations.

Rats were excluded from analysis if any administration session did not contain sufficient data (<50 total trials) or contained either >30% omissions on go trials or a non-varying inhibition function that yielded an SSRT estimate <50 ms; both of which indicate improper task performance (e.g., [Ghahremani et al., 2012](#)). We further omitted cases where there was not at least an increase of 0.5 between the minimum and maximum values of the IF as SSD increased, which is an additional indicator of proper task performance (cf. [Kapoor and Murthy, 2008](#)). Two rats from the first cohort were excluded because they showed non-varying inhibition functions: one after saline treatment and one after AMPH treatment. Six animals from the first cohort thus yielded data for this experiment.

An additional 16 male albino Wistar rats (Charles River Laboratories) were trained to perform the countermanding task following the same protocol as above. One subject was excluded due to health complications and two others were excluded for not meeting performance criteria regularly (i.e. <50 trials). This left 13 rats for subsequent AMPH testing from the second cohort.

Rats were randomly assigned to three groups of three subjects and one group of four subjects following task training. Groups were randomly administered AMPH (0, 0.25, 0.5, 0.75 mg/kg; i.p.) immediately prior to testing in the countermanding task with two no-treatment days

between administrations. After an 11-day washout period, rats were reassigned into two groups of 4 and one group of 5 for a second round of AMPH administrations of each dose, with the exception of 0.75 mg/kg. This dose was omitted from testing and analysis due to increased (>30%) omissions on go trials and poorer overall task performance; there was no statistical difference in omission rate between saline and the lower AMPH doses (paired t -tests, $p > 0.05$). Two no-treatment days were conducted between treatment sessions. Administration sessions were excluded if the above performance criteria were not met. Go trial RT and SSRT were calculated for each session as described above. We also quantified the variability in go trial RT with the coefficient of variation (CV) given by the ratio of the standard deviation (SD) and the mean of the RT distribution ([Bellgrove et al., 2004](#)). If both sessions at a particular dose of AMPH were valid for a given rat, mean go trial RT, CV, and SSRT were averaged from both sessions.

Because only rats in the 2nd cohort were administered 0.25 mg/kg AMPH, doses of AMPH were compared to vehicle separately. For the 0.25 mg/kg AMPH comparison, 13 rats from the 2nd cohort met criteria and were analyzed for SSRT. For the 0.5 mg/kg AMPH analysis, five rats were omitted for displaying >30% omissions and/or <50 trials, while one rat was omitted for producing flat IFs in AMPH sessions. This left seven rats from the 2nd cohort to be combined with the six rats from the 1st cohort for analysis. Following [Kapoor and Murthy \(2008\)](#), the minimum and maximum probability values of the inhibition functions obtained from these animals in all sessions included in the analyses spanned at least 0.5: mean (\pm SD) = 0.88 ± 0.15 (0.25 mg/kg AMPH; $n = 22$), 0.89 ± 0.14 (0.5 mg/kg AMPH; $n = 18$); 0.91 ± 0.13 (vehicle; $n = 27$).

Paired samples t -tests were conducted to evaluate the difference in go trial RT and SSRT after AMPH and saline administration. Percent change was calculated for SSRT after AMPH administration based on SSRT after saline administration for each rat. Pearson correlations were conducted to examine percent change in SSRT after AMPH treatment compared to vehicle SSRT.

The inhibition functions obtained following AMPH and vehicle sessions were compared after converting the data obtained from each animals into the standardized relative finishing time (ZRFT) described by [Logan and Cowan \(1984\)](#): $ZRFT = [\text{goRT}(\text{mean}) - \text{SSD} - \text{SSRT}] / \text{goRT}(\text{SD})$, where $\text{goRT}(\text{mean})$ and $\text{goRT}(\text{SD})$ are the mean and SD of the RT in go trials. The standardized inhibition function, which relates the probability of canceled trials to ZRFT scores across animals, was fit with a Weibull function: $W_{(ZRFT)} = \gamma - (\gamma - \delta) \cdot \exp[-(ZRFT/\alpha)^\beta]$, where α is the threshold (i.e., the ZRFT value at which the function reaches 64% of its full growth), β is the slope and γ and δ are, respectively, the maximum and minimum values of the function ([Weibull, 1951](#)).

Adaptive RT adjustments were analyzed as described above. In instances where both sessions for a particular

dose of AMPH were valid for a given rat, the 3-trial blocks from each session were combined to calculate overall mean go trial RTs. Rats were excluded from analysis at a particular dose of AMPH if <5 instances of any interleaved trial type were observed. This left eight rats from the 2nd cohort for adaptive RT adjustment analysis following administration of 0.25 mg/kg AMPH and five rats from the 1st cohort as well as three rats from the 2nd cohort for analysis following administration of 0.5 mg/kg AMPH. Because these dose groups contained different rats, 0.25 mg/kg and 0.5 mg/kg AMPH were compared to vehicle separately. All analysis was conducted using a significance level of 0.05.

RESULTS

Race model analysis

The mean total number of trials in pooled data sets was 1362 ± 70 . Thus, each data set contained approximately 340 stop trials and each individual

session contained approximately 272 trials. Fig. 2 shows each rat's distribution of go trial RTs in each of the five sessions considered for race model analyses. All RTs from each animal were pooled into a single distribution, and the mean (\pm standard error of mean (SEM)) go trial RT for each animal is given in Fig. 3A. Across rats, mean go trial RT averaged 570 ± 17 ms. From these pooled sessions, we generated each rat's inhibition function from the corrected proportions of non-canceled responses on stop trials (Fig. 3B). These proportions spanned the whole range and increased significantly with increasing SSD for all rats (χ^2 test, $p < 0.01$). The nearly perfect monotonicity of the inhibition functions demonstrates that rats were sensitive to the stop signal, a prerequisite for the application of the race model.

The staircase procedure for SSD was analyzed to estimate the SSD at which the probability of making a non-canceled response was 0.5 for each subject. The peaks and valleys average of SSD for subjects ranged

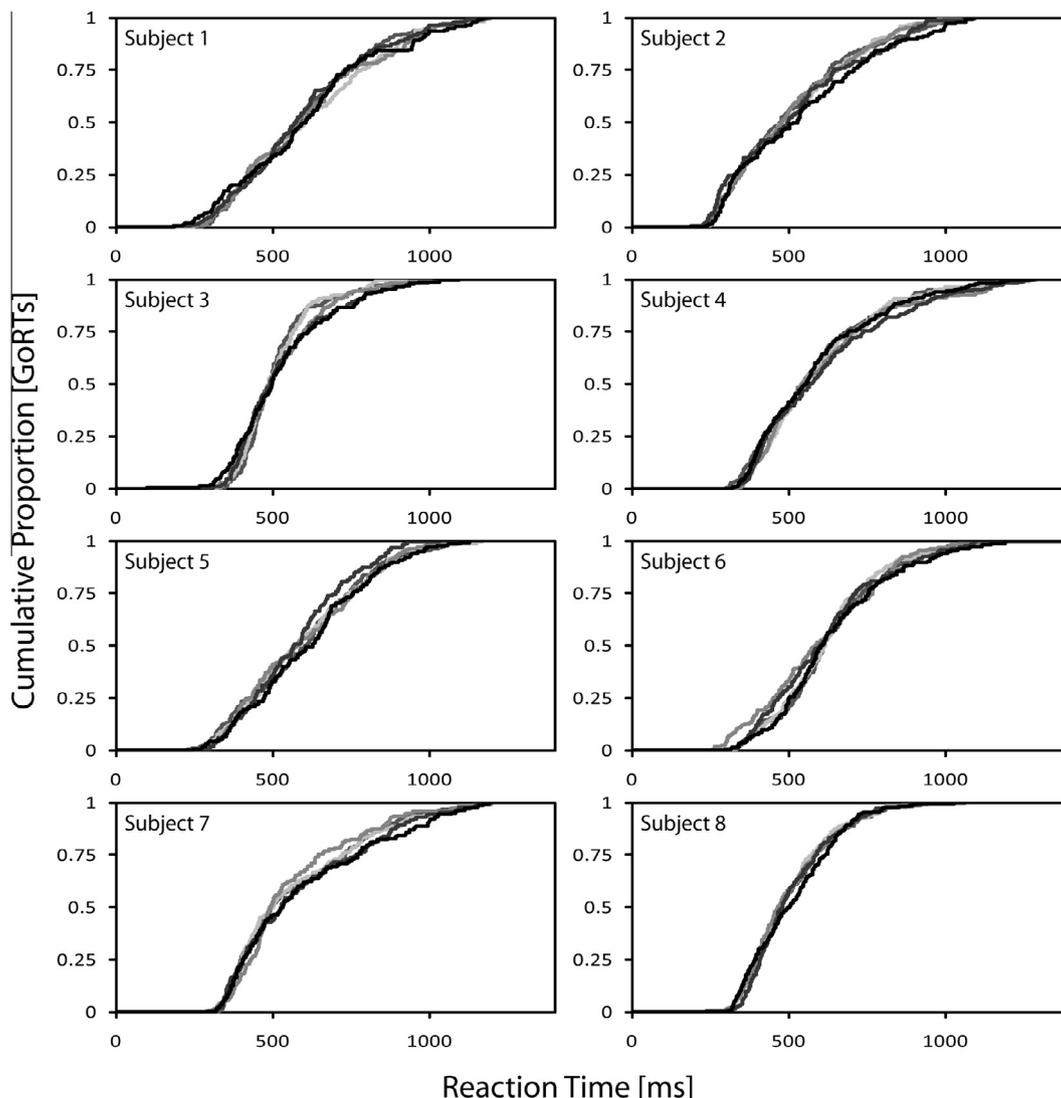


Fig. 2. Cumulative go trial RT [GoRT] distributions of all five sessions for each individual subject in experiment 1. The five sessions were combined into one data set for each subject as none of the GoRT distributions were found to differ significantly.

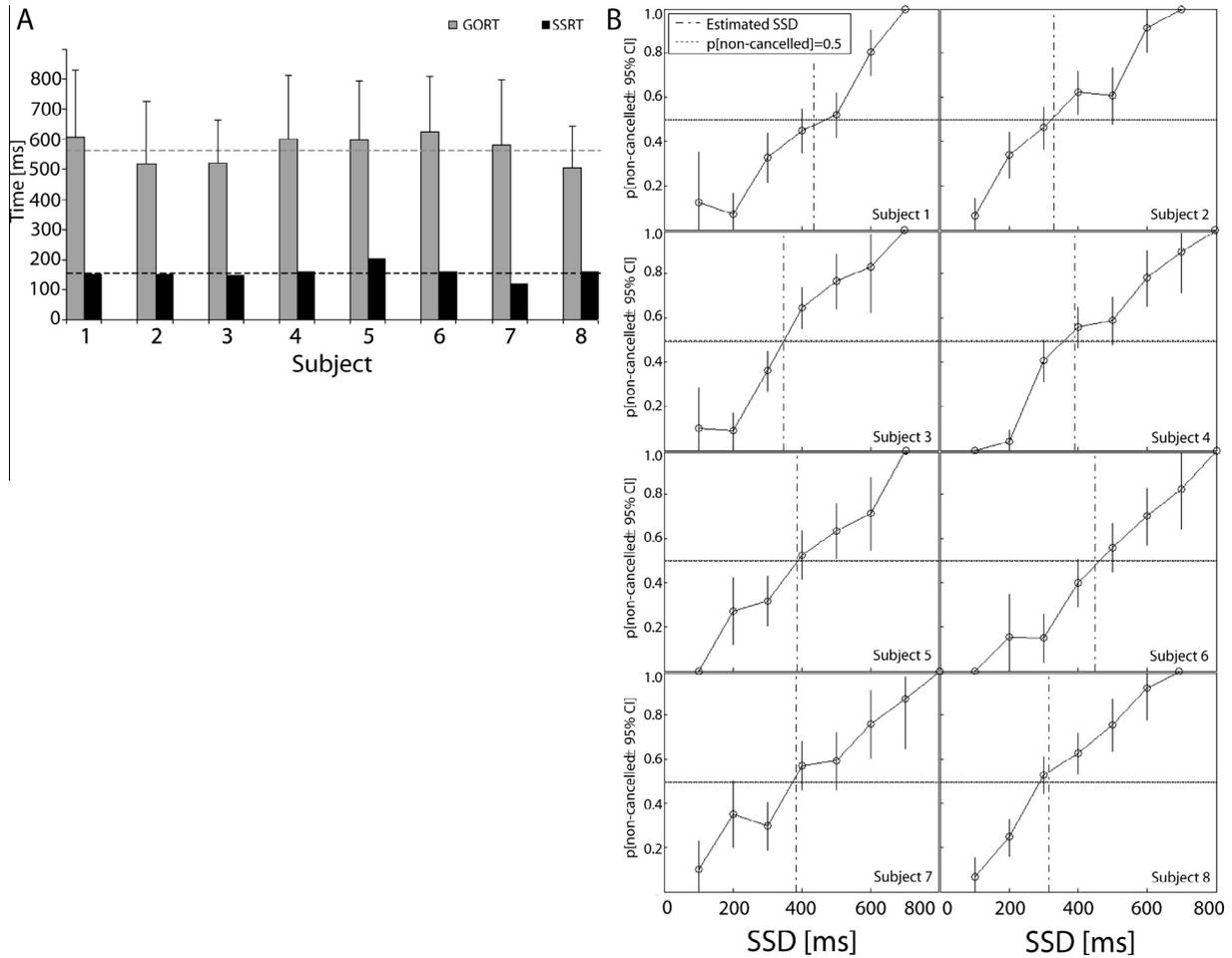


Fig. 3. (A) Mean (\pm SEM) go (GoRT; gray) and stop signal RT (SSRT; black) for each rat. Dashed horizontal lines represent overall means. (B) The probability of making a non-cancelled response (\pm 95% confidence interval) increased as the stop signal delay (SSD) lengthened for all eight subjects. The horizontal dashed line represents the point at which the probability of making a non-cancelled response was 0.5. The vertical dashed line represents the staircase procedure estimation of the SSD at which the probability of making a non-cancelled response was 0.5.

from 315 ms to 448 ms while the midpoint of each second run average of SSD for subjects ranged from 316 ms to 448 ms (Table 1). The average of these two estimations approximated the SSD at which the probability of making a non-cancelled response was 0.5 for each subject. The go trial RT distribution was then integrated until the proportion of RTs was equal to 0.5. The

corresponding RT at which this proportion was reached ranged from 475 ms to 609 ms across subjects. SSRT was calculated by taking the RT at which the probability of making a non-cancelled response was 0.5 for each subject, and subtracting the SSD where the probability of making a non-cancelled response was 0.5. The estimated mean SSRT was 157 ± 8 ms (Fig. 3A).

Table 1. Stop signal response time estimation. Peaks & Valleys and Second Run analysis is the stop signal delay (SSD) derived from the staircase procedure at which $P[\text{non-cancelled}] = 0.5$. SSD is the average of these two analyses. Response time [RT] is the point from the go RT distribution in which the integrated proportion of RTs is 0.5 (i.e., the median RT). Stop signal RT (SSRT) = RT – SSD

Rat	Peaks & Valleys	Second Run	SSD	RT	SSRT
1	435	435	435	585	150
2	331	330	330	484	154
3	346	346	346	491	145
4	391	391	391	552	161
5	385	385	385	589	204
6	448	448	448	609	161
7	382	385	384	505	121
8	315	316	316	475	159

Race model predictions. The race model makes three main predictions of countermanding task performance (Logan, 1994). First, the model predicts that the mean non-cancelled RTs should be shorter than the mean go trial RTs, because the stop signal should truncate the RT distribution when presented (Fig. 4A). Second, the model’s assumptions predict that non-cancelled RTs should lengthen with increasing SSD, because gradually more responses can escape inhibition as the stop signal is delayed (Fig. 4B). Finally, to fully account for the rat’s performance, the model should predict the observed non-cancelled RTs (Fig. 4C). We tested these predictions with data from SSDs having at least 10 trials (on average, 34 trials).

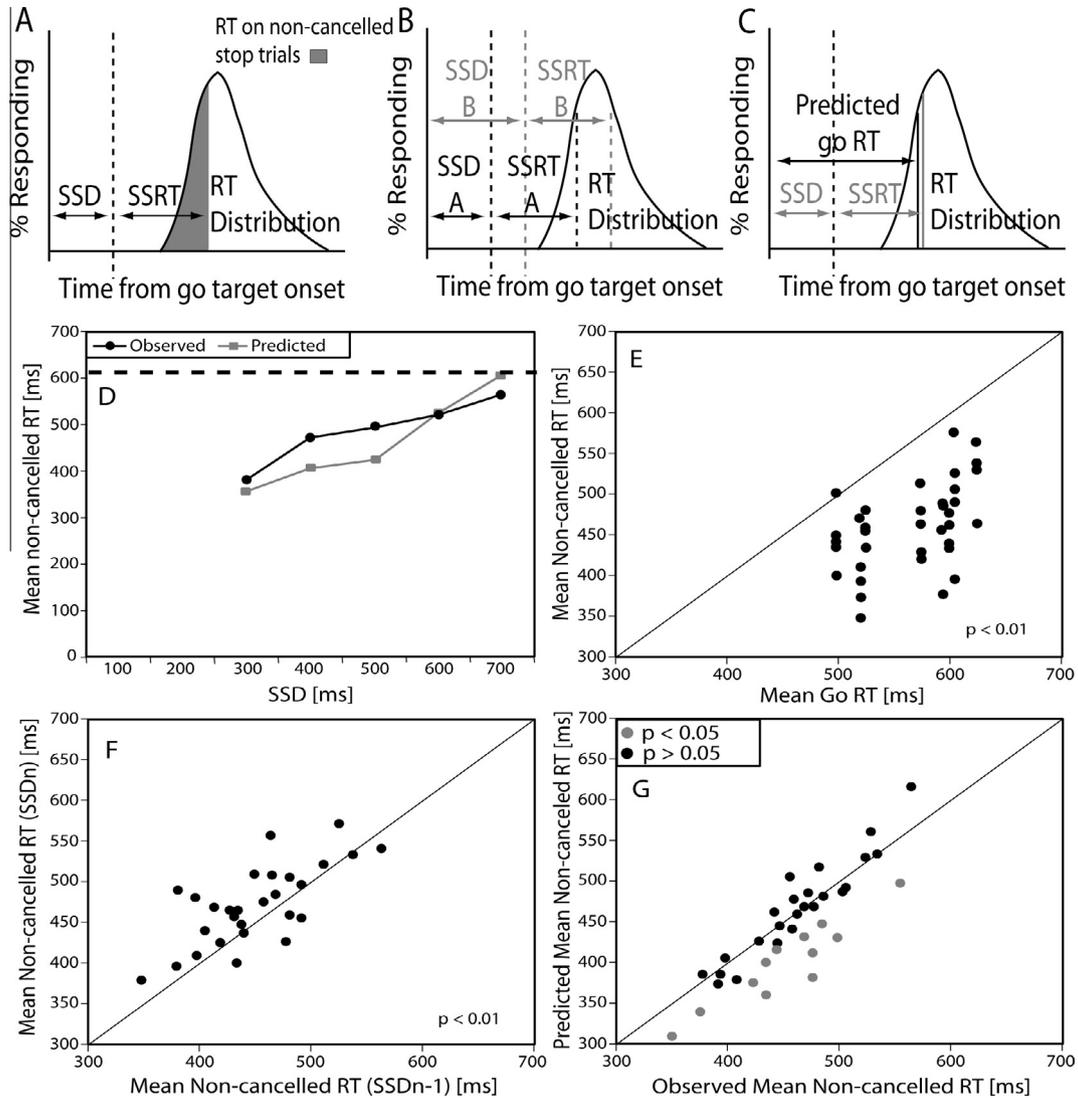


Fig. 4. The race model predicts: (A) mean non-cancelled RT (RT) should be shorter than mean go RT because only fast go RTs escape inhibition. (B) Mean non-cancelled RT increases as the stop signal delay (SSD) increases because more of the distribution of go RT escapes inhibition. (C) If stop signal RT (SSRT) is constant, mean non-cancelled RT at a specific SSD is predictable. (D) Race model predictions for one individual subject (Subject 1) showing mean observed non-cancelled RTs increased as SSD increased, were generally predictable and were shorter than mean go RT (dashed line). (E) Mean non-cancelled RT was shorter than mean go trial RT for all eight subjects in support of the first prediction ($p < 0.01$ indicates a significant difference by paired-samples t -test). (F) Mean non-cancelled RT for a subject at a particular SSD (SSD_n) tended to be longer than mean non-cancelled RT at the SSD that was 100 ms shorter (SSD_{n-1}), in support of the second prediction ($p < 0.01$ indicates a significant difference by paired-samples t -test). (G) Observed mean non-cancelled RT was longer than predicted. Most (24 of 36) observed mean non-cancelled RTs were not significantly different than predicted at specific SSDs by paired-samples t -test (black dots). Instances that were significantly different (Gray dots) tended to occur at shorter SSDs ($p < 0.05$).

To determine whether the first prediction was respected, the mean non-cancelled RT of a particular SSD in each rat was compared to overall mean go trial RT for that rat ($N = 36$ comparisons). All mean non-cancelled RTs were found to be shorter than their corresponding mean go trial RTs, as displayed in Fig. 4E. The mean of these RT differences (-112.1 ± 8.2 ms) was significantly different from 0 (t -test, $t(35) = 13.74$, $p < 0.001$; Cohen's $d = 2.30$).

To test the second prediction, we compared in each rat the mean non-cancelled RT at a particular SSD (SSD_n) with the mean non-cancelled RT observed at the immediately shorter SSD (SSD_{n-1}) ($N = 28$ comparisons). We found that the mean non-cancelled

RTs at the longer SSD were longer in 75% (21/28) of the comparisons, as displayed in Fig. 4F. The mean of these RT differences (21.8 ± 7.4 ms) was significantly different from 0 (t -test, $t(27) = 2.96$, $p < 0.01$; Cohen's $d = 0.56$).

We first tested the third prediction by comparing the average non-cancelled RT observed across each rat's SSDs to the average RT predicted by the race model. Because the number of trials varied across SSDs, we weighted the means for each SSD by the frequency of occurrence. The overall weighted mean non-cancelled RT predicted by the race model (mean \pm SEM = 458 ± 14 ms) did not differ significantly from the overall weighted mean observed non-cancelled RT

(mean \pm SEM = 456 \pm 13 ms; paired *t*-test, $t(7) = 0.65$, $p = 0.54$; Cohen's $d = 0.23$). We next analyzed observed mean non-canceled RT at each SSD for each animal ($N = 36$ comparisons) to the mean RT that would be predicted for that SSD by the race model (Fig. 4D). In general, the observed non-canceled RT at individual SSDs were not significantly different than predicted, but significant differences were found in 33% (12 of 36) of the comparisons (paired *t*-tests, $ps < 0.05$; Fig. 4G); the observed non-canceled RTs being significantly longer. It appeared that the race model underestimates the non-canceled RT at short SSDs. The SSDs at which we found significantly different comparisons were statistically shorter than those of the non-significant ones (*t*-test, $t(24) = 2.44$, $p < 0.05$). Unduly long non-canceled RTs have been observed on short-SSD stop trials previously in humans and interpreted as delayed responses following successful cancelation (e.g., Hanes and Carpenter, 1999; Boucher et al., 2007). If this were to account for our observations, we would predict the non-canceled RT distributions of the significant 12 comparisons to be highly skewed. Indeed, their skewness, quantified with the Fisher-Pearson standardized moment coefficient, was more than double that of the other comparisons ($G = 2.39 \pm 0.92$ vs. 1.08 ± 1.0 ; *t*-test, $t(24) = 3.62$, $p < 0.001$; Cohen's $d = 1.41$). To further determine the contribution of the long tail in the distribution of non-canceled RTs to our observations, we eliminated the 90th percentile of non-canceled RTs from each animal's data set. Of the 12 comparisons that were originally statistically different, eight became non-significant after this correction.

Altogether, the race model accounted suitably well for rat performance in our countermanding task.

Response adjustment

Humans and macaque monkeys adjust their RT adaptively in the countermanding task, responding faster after consecutive go trials and slower after canceled stop trials. We examined whether rats also adapt their responses to trial and/or performance history by comparing RTs in correct go trials that began (go1RT) and ended (go2RT) a sequence of three consecutive trials, when the interleaved trial was: (1) a correct go trial; (2) a canceled stop trial; or (3) a non-canceled stop trial. Fig. 5A shows the mean (\pm SEM) RT for each animal, along with the average RT across animals.

A two-way ANOVA, with go trial and interleaved-trial type as factors, revealed no main effects but a significant interaction ($F(2, 14) = 5.17$, $p < 0.05$, $\eta_p^2 = 0.43$). This interaction appears to arise from the significant increase in RT that was limited to when the interleaved trial was a non-canceled stop trial (paired *t*-test, $t(7) = 2.31$, $p < 0.05$, Cohen's $d = -1.16$). An increase in RT was also found to be significant in two individual rats. The shortening in RT across three consecutive go trials nearly reached statistical significance ($t(7) = 2.23$, $p = 0.056$, Cohen's $d = 1.06$), and the RT in go trials interleaved with a canceled stop

trial was not statistically different ($t(7) = 1.74$, $p = 0.12$, Cohen's $d = 0.64$). Because the distribution in RT was broad and varied substantially among animals, we also standardized the change in RT in each individual trial sequence by computing a Z-score:

$$Z = [\text{go2RT}(\text{trial}) - \text{go1RT}(\text{mean})] / \text{go1RT}(\text{SD})$$

Fig. 5B shows the mean Z-score for each animal, along with the average across animals. Statistics were sensibly the same. The 4% shortening in RT across three consecutive go trials was significantly different from 0 (one-sample *t*-test, $t(7) = -2.38$, $p < 0.05$, Cohen's $d = -0.84$). The 15% lengthening in RT following a non-canceled stop trial just failed to reach statistical significance ($t(7) = 2.13$, $p = 0.07$, Cohen's $d = 0.75$). The change in RT in go trials interleaved with a canceled stop trial was not statistically different ($t(7) = -1.71$, $p = 0.13$, Cohen's $d = -0.61$).

To further examine response adjustments, we compared RT in correct go trials that began and ended a sequence of three consecutive trials when the interleaved trial was an incorrect go trial response. We observed that the RT of the last go trial of this sequence was significantly longer than that of the first trial (612 ± 19 vs. 582 ± 16 ms; paired *t*-test, $t(7) = 2.62$, $p < 0.05$, Cohen's $d = -0.96$). Altogether, these results reveal large variability in response adjustment of rats performing the countermanding task, but nonetheless suggest that their responses are slower following unrewarded, incorrect responses in both go and stop trials.

AMPH treatment

Previous rodent studies have shown that AMPH administration is associated with both a shortening of go trial RT and a change in SSRT that depends on the animal's original SSRT (Feola et al., 2000; Eagle and Robbins, 2003b). Fig. 6A shows that rats in our study similarly demonstrated shorter go trial RT following AMPH compared to vehicle. Paired-samples *t*-tests revealed that this response speeding was statistically significant following 0.5 mg/kg AMPH ($t(12) = 3.56$, $p < 0.05$, Cohen's $d = 1.34$), but just failed to reach significance following 0.25 mg/kg AMPH ($t(12) = 2.11$, $p = 0.057$, Cohen's $d = 0.58$); percent change in RT amounted to 11.4% and 4.7% shortening, respectively. In addition, the variance of go trial RT was found to increase near-significantly following 0.5 mg/kg AMPH (mean CV = 0.33) compared to saline (mean CV = 0.29; $t(12) = -2.16$, $p = 0.051$, Cohen's $d = -0.63$). No significant difference was observed following 0.25 mg/kg AMPH (CV 0.30) compared to saline (CV = 0.28; $t(12) = 1.42$, $p = 0.18$, Cohen's $d = -0.52$). The mean (\pm SEM) number of trials completed in AMPH sessions was not significantly higher following 0.5 mg/kg (199 ± 16.91) compared to saline (166.54 ± 23.96 ; $t(12) = -1.46$, $p = 0.17$, Cohen's $d = -0.36$) but was significantly higher following 0.25 mg/kg (176.46 ± 14.60) compared to saline (126.46 ± 10.99 ; $t(12) = -3.72$, $p < 0.01$, Cohen's $d = -1.06$).

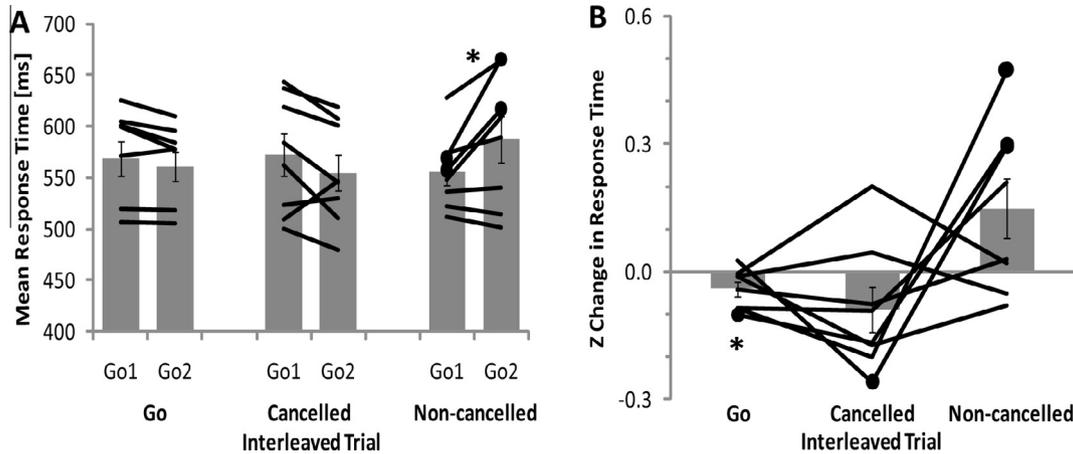


Fig. 5. Response time adjustments. (A) Bars show mean \pm SEM go trial response time [RT] for the 1st (Go1) and 3rd (Go2) trials from sequences of three consecutive trials where the interleaved trial was either a go trial, or a canceled or non-canceled stop trial for each rat (*significant difference in group means with *t*-test, $p < 0.05$; Black lines show individual animal mean RTs and circle markers indicate significant difference in individual animal's means with *t*-test, $p < 0.05$). (B) Bars show mean \pm SEM Z change in RT on Go2 where the interleaved trial was either a go trial, or a canceled or non-canceled stop trial for each rat, where $Z = [\text{Go2RT}(\text{trial}) - \text{Go1RT}(\text{mean})]/\text{Go1RT}(\text{SD})$ (*significant difference of Z score from 0 with *t*-test, $p < 0.05$; Black lines display mean Z scores of each individual rat and circle markers indicate significant difference of an individual animal's Z score from 0 with *t*-test, $p < 0.05$).

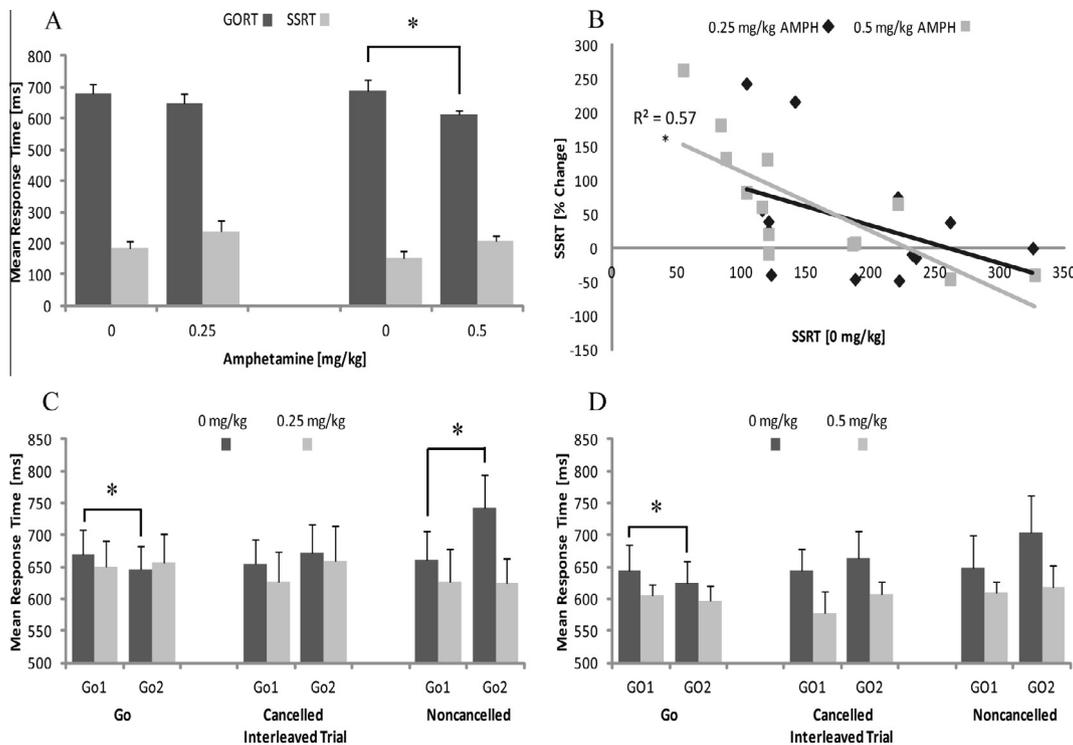


Fig. 6. Amphetamine effects. (A) Mean \pm SEM go trial response time [RT] and stop signal response time [SSRT] for rats performing the countermanding task immediately after injection of saline (dark gray bars) or amphetamine (light gray bars; $N = 13$ for 0.25 mg/kg group, $N = 13$ for 0.5 mg/kg group, i.p.) (*significant difference in group means with paired-samples *t*-test, $p < 0.05$); (B) percent change in SSRT for individual rats after 0.25 mg/kg (dark gray diamonds; $N = 13$) or 0.5 mg/kg (light gray squares; $N = 13$) amphetamine (i.p.) compared to SSRT after saline administration (*significant correlation, $p < 0.05$). (C) Mean go trial response time \pm SEM; ($N = 8$) for the 1st (Go1) and 3rd (Go2) trials in sequences of three consecutive trials where the interleaved trial was either a go trial, a canceled stop trial, or a non-canceled stop trial, after administration of either saline (dark gray bars) or amphetamine (0.25 mg/kg, i.p., light gray bars) (*significant difference in group means with *t*-test, $p < 0.05$). (D) Mean go trial response time \pm SEM; ($N = 8$) for the 1st (Go1) and 3rd (Go2) trials in sequences of three consecutive trials where the interleaved trial was either a go trial, a canceled stop trial, or a non-canceled stop trial, after administration of either saline (dark gray bars) or amphetamine (0.5 mg/kg, i.p., light gray bars) (*significant difference in group means with *t*-test, $p < 0.05$).

We found no significant difference in SSRT when we compared either the 0.25 mg/kg AMPH group ($t(12) = -1.50$, $p = 0.16$, Cohen's $d = -0.44$) or the 0.5 mg/kg AMPH group ($t(12) = -1.92$, $p = 0.07$, Cohen's $d = -0.58$) with vehicle. We examined baseline-dependent effects of AMPH on SSRT by regressing the percent change in SSRT after AMPH administration against vehicle SSRT. Fig. 6B shows that rats with short vehicle SSRT tended to display longer SSRT after AMPH, while rats with longer SSRT were more likely to display shorter SSRT. This relation was significant for the 0.5 mg/kg AMPH group ($R^2 = 0.40$, $p = 0.02$), but only a trend for the 0.25 mg/kg AMPH group ($R^2 = 0.18$, $p = 0.15$). In contrast, no significant correlation was observed between percent change in RT after AMPH administration and vehicle SSRT ($R^2 = 0.02$ and 0.06).

We further investigated the effects of AMPH on inhibitory control by examining changes in the inhibition function. Fig. 7A, B shows the standardized inhibition function (see methods) obtained after each of the AMPH doses along with the associated vehicle. We first modeled each inhibition function with a best-fit Weibull curve, and then used the Weibull model of the vehicle inhibition function to account for the inhibition function obtained from the AMPH sessions. With the exception of slightly shallower slopes following AMPH, the best-fit curves were similar (see equation parameters in Fig. 7 caption). Moreover, the model of the vehicle inhibition function accounted for the data as well as that calculated from the AMPH data. The coefficient of determination (R^2) for the model fitting the 0.25 mg/kg AMPH data was 0.57, while that of the vehicle model

was 0.55 for the same data; the R^2 of the fit to the vehicle data was 0.64. For the 0.5 mg/kg AMPH data, these figures were 0.70 and 0.68; 0.73 for the fit to the vehicle data. These results thus suggest that the inhibitory control displayed by these groups of rats did not change significantly following AMPH administration. We also converted the inhibition function data into cumulative probability distributions to test whether these were statistically different. Two-sample Kolmogorov–Smirnov tests confirmed that the differences between vehicle and AMPH data were not significant (0.25 mg/kg AMPH: $D = 0.125$, $p = 0.53$; 0.5 mg/kg AMPH: $D = 0.063$, $p = 0.99$).

To examine the effects of AMPH on adaptive RT adjustments, a mixed design ANOVA with treatment (AMPH, vehicle), trial (go1RT, go2RT) and interleaved trial type (go, canceled, non-canceled) as within-subject factors was conducted for both AMPH groups separately. For the 0.25 mg/kg AMPH group ($N = 8$), an ANOVA revealed a significant main effect of treatment, ($F(1,7) = 5.96$, $p < 0.05$, $\eta_p^2 = 0.46$) and trial ($F(1,7) = 5.75$, $p < 0.05$, $\eta_p^2 = 0.45$) as well as a significant interaction of all three factors ($F(2,14) = 5.14$, $p < 0.05$, $\eta_p^2 = 0.42$). There was also a significant interaction of interleaved trial type and trial ($F(2,14) = 5.75$, $p < 0.05$, $\eta_p^2 = 0.45$). Planned paired-samples t-tests compared RT before and after each interleaved trial type for both AMPH and vehicle administration. As shown in Fig. 6C, rats displayed significantly shorter RT after interleaved go trials ($t(7) = 3.73$, $p < 0.01$, Cohen's $d = 1.43$) as well as significantly longer RT following non-canceled stop trials ($t(7) = -4.44$, $p < 0.01$, Cohen's $d = -1.70$) in the

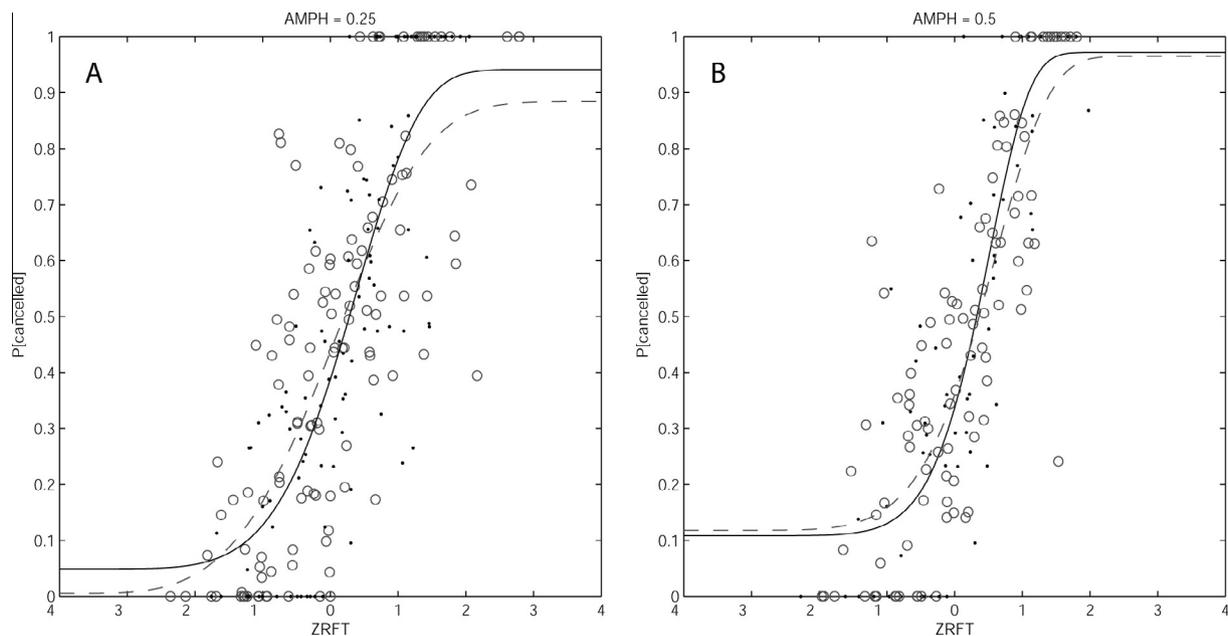


Fig. 7. Standardized inhibition functions. Probability of successfully canceled stop trials as a function of standardized relative finishing time [$ZRFT = (\text{GoRT}(\text{mean}) - \text{SSD} - \text{SSRT})/\text{GoRT}(\text{SD})$] following 0.25 mg/kg (A) and 0.5 mg/kg (B) AMPH (\circ , —) as well as vehicle (\bullet , - -). Parameters of the best-fit Weibull curves were: $\alpha = 0.40$, $\beta = 4.12$, $\gamma = 0.88$, $\delta = 0.005$ (0.25 mg/kg AMPH); $\alpha = 0.55$, $\beta = 5.72$, $\gamma = 0.94$, $\delta = 0.05$ (0.25 mg/kg vehicle); $\alpha = 0.71$, $\beta = 6.71$, $\gamma = 0.97$, $\delta = 0.12$ (0.5 mg/kg AMPH); $\alpha = 0.59$, $\beta = 8.67$, $\gamma = 0.97$, $\delta = 0.11$ (0.5 mg/kg vehicle).

saline condition, replicating the no-treatment results from our first cohort of rats. No significant difference in RT was found in the saline condition for interleaved canceled stop trials ($t(7) = -0.81$, $p = 0.44$, Cohen's $d = -0.32$). There was no RT adjustment following treatment with 0.25 mg/kg AMPH regardless of the interleaved trial: go ($t(7) = -0.68$, $p = 0.52$, Cohen's $d = -0.26$), canceled stop ($t(7) = -1.70$, $p = 0.13$, Cohen's $d = -0.64$) and non-canceled stop trial ($t(7) = 0.13$, $p = 0.90$, Cohen's $d = -0.06$).

A mixed design ANOVA for the 0.5 mg/kg AMPH group ($N = 8$) revealed no significant effects; the main effect of treatment ($F(1,7) = 4.74$, $p = 0.07$, $\eta_p^2 = 0.40$) and trial ($F(1,7) = 4.44$, $p = 0.07$, $\eta_p^2 = 0.39$) failed to reach significance. It was expected that rats would display adaptive RT adjustments after saline treatment. Paired-samples t -tests were therefore conducted to compare RT before and after each interleaved trial type for both drug and saline administration. As displayed in Fig. 6D, rats had significantly shorter RT following interleaved go trials in the saline condition ($t(7) = 3.24$, $p < 0.05$, Cohen's $d = 1.77$). Their RTs were also 10% longer following non-canceled stop trials – a change observed in seven of eight animals and comparable to that observed in the 0.25-mg/kg saline and no-treatment data – but this lengthening was not statistically significant ($t(7) = 1.48$, $p = 0.18$, Cohen's $d = -0.53$). In contrast, the change in RT for the AMPH condition amounted to about 1%. None of the remaining comparisons for the saline or 0.5 mg/kg AMPH treatments were significant.

DISCUSSION

We have demonstrated in a countermanding task closely resembling human and monkey paradigms that the ability of rats to inhibit a motor response was thoroughly accounted for by a race model first developed for human countermanding performance (Logan and Cowan, 1984) and extended to the macaque monkey (Hanes and Schall, 1995). These results validate the race model in rodent stop tasks, an essential step in confidently estimating the amount of time required for rat response cancellation. Our observed go trial RT speeding and baseline-dependent change in SSRT following AMPH treatment supports the generality of rodent stop tasks. Further evidence for executive control in rats was revealed through RT adjustments following primarily unrewarded, non-canceled stop trials, which was impaired with AMPH treatment.

As the duration of time lengthened before stop signal presentation, rats were gradually less able to inhibit responses. Similar inhibition functions are observed in human and nonhuman primate countermanding (Logan and Cowan, 1984; Hanes and Schall, 1995; Hanes and Carpenter, 1999; Band et al., 2003). The monotonic characteristic of the inhibition function is a prerequisite for a race model account of countermanding performance (Logan, 1994). We pooled data from multiple sessions in order to demonstrate the first full inhibition functions in rats spanning the SSD range from

0% to 100% inhibition, aiding in the demonstration that our rat countermanding task is highly analogous to human and nonhuman primate tasks.

The race model accurately predicts response latencies at different SSDs where response inhibition fails in humans (Logan and Cowan, 1984). Moreover, saccade latencies in non-canceled stop trials are shorter compared to go trials for most subjects and increase as SSD increases (e.g., Hanes and Carpenter, 1999). In some cases, mean non-canceled RTs have not differed from mean go RT due primarily to prolonged non-canceled responses at the shortest SSDs (Colonius et al., 2001; Akerfelt et al., 2006). Unduly long non-canceled RTs have been observed on short-SSD stop trials previously in humans and interpreted as delayed responses following successful cancellation (Boucher et al., 2007). Pooling data to obtain many stop trials at each SSD allowed us to make similar observations in rats, supporting the hypothesis that rodent behavior in this task can be generally accounted for by the race model and is highly comparable to humans, even at short SSDs where the race model does not fully account for the behavior.

It is possible that longer than predicted non-canceled RTs at short SSDs observed in rats may be related to differences in neural circuitry between primates and rodents. Human studies have suggested that countermanding ability rests on the integrity of a neural network that includes the dorso-medial and ventro-lateral aspects of prefrontal cortex as well as the basal ganglia direct and hyper-direct pathways (see for review Verbruggen and Logan, 2008; Verbruggen et al., 2010; Jahfari et al., 2011). Work in nonhuman primates has focused on dorso-medial prefrontal cortex, showing that microstimulation within the supplementary eye field while monkeys perform an eye-movement countermanding task improved stopping by increasing RT (Stuphorn and Schall, 2006). In addition, neuronal activity in pre-supplementary and supplementary motor areas of monkeys performing an arm-movement countermanding task has been suggested to contribute to inhibitory control (Scangos and Stuphorn, 2010; see also Chen et al., 2010 as well as Stuphorn et al., 2010).

Evidence for a similar circuit in rodents is equivocal. Inhibitory control has been reported not to be impaired following excitotoxic lesions to the prelimbic and infralimbic areas (Eagle and Robbins, 2003b; Eagle et al., 2008), but reversible inactivation of the dorsal part of the prelimbic area has been shown to significantly lengthen SSRT (Bari et al., 2011). Conversely, excitotoxic lesion to the orbitofrontal cortex was shown to produce longer SSRT (Eagle et al., 2008), but reversible inactivation was not (Bari et al., 2011). Within the basal ganglia, excitotoxic lesions to either the medial striatum (Eagle and Robbins, 2003a) or subthalamic nucleus (Eagle et al., 2008) have been reported to flatten inhibition functions, largely because of poorer performance at short SSDs. The long non-canceled RTs that we observed at short SSDs may be diagnostic of a weaker inhibitory control in rodents compared to primates. This discrepancy warrants further

investigation regarding the role of these brain regions in response countermanding, including in the nonhuman primate model where these areas have yet to be investigated neurophysiologically.

Differences in neural correlates of behavior between primate and rodent stop tasks may be related to subtle differences in task design. Human and non-human primate saccade countermanding tasks clearly require the cancelation of a response before a movement is made (see Hanes and Schall, 1995; Hanes and Carpenter, 1999; Colonius et al., 2001; Stuphorn and Schall, 2006), whereas it is less clear if cancelation occurs before or after movement onset for finger or hand responses (see Logan and Cowan, 1984; Li et al., 2008; Liu et al., 2009). Rodent stop tasks require countermanding an ongoing elongated whole body movement (see Eagle and Robbins, 2003a; Pattij et al., 2007). To date, no distinction has been made between reaction time (i.e., the time required to react to the target lever) and movement time (e.g., the time required to move to the target lever) in the rodent stop task. RT variability can be produced by inconstant movement time between tasks. SSRT estimates arise from the distribution of RTs; therefore, incorporating a longer movement may artificially alter SSRT. A challenge for future experiments will be to evaluate and compare reaction and movement times within overall RT.

Several variances exist between the countermanding task employed in the present study and other rodent stop tasks. Go responses in the single target stimulus task of Eagle and Robbins (2003a) may have become automated with extensive training, thus limiting the investigation of voluntary control of behavior usually afforded by the countermanding paradigm. Longer SSRTs in the Eagle and Robbins task may have resulted from estimations using partial rather than full inhibition functions. Pattij et al. (2007) may have also derived longer SSRTs due to the use of primarily short SSDs that did not examine full inhibition functions. Longer SSRTs may have also been estimated by virtue of a brief stop signal duration (50 ms), which may lead to a reduction in stop accuracy. Importantly, the race model, which is necessary to estimate SSRT, had not previously been systematically confirmed as a valid model for rodent task performance. We have taken the necessary step of rigorously validating a race model account in our version of the countermanding task in rats.

Both humans and nonhuman primates display faster responses after consecutive go trials and slower responses following stop trials (Rieger and Gauggel, 1999; Kornyló et al., 2003; Li et al., 2006, 2008; Emeric et al., 2007; Verbruggen and Logan, 2008; Liu et al., 2009; Chen et al., 2010; Nelson et al., 2010; Thakkar et al., 2011). We are the first to identify response speeding after consecutive go trials as well as post-error slowing, evidenced by longer go trial RTs following both non-canceled stop trials and go trial errors in a rat countermanding task. Response speeding after consecutive go trials did not likely result from trial history, as we observed longer RT if errors were made during interleaved go trials. Response speeding was

also not likely directly attributable to response history, as consecutive lever presses resulted in longer RT following non-canceled stop trials. While these behavioral trends did not always meet statistical significance in our rats, likely owing to small sample sizes (see Button et al., 2013), we generally observed the same RT adjustments in the vehicle-only treatment sessions of our AMPH study, providing strong support for our findings.

Consistent with observations from a delayed response task in rats (Narayanan and Laubach, 2008), error monitoring may best account for the response adjustments we observed. Our findings are not consistent with Emeric et al. (2007), who reported slower responses after canceled stop trials in both humans and nonhuman primates. It is possible that the comparatively long time-out period (10-s) in our study made errors more salient for monitoring. The effect of time-out duration on response adjustments should be examined in the future. Inter-individual variability in error monitoring was evident in these studies (see also Chen et al., 2010). This inter-individual and interspecies variability in the control of skeletomotor and oculomotor responses requires more detailed investigation.

Our replication of go trial RT shortening and baseline-dependent change in SSRT with AMPH, as reported by Feola et al. (2000; see also Eagle and Robbins, 2003a), supports the generality of the stop task. However, Feola and colleagues reported improved stopping in slow stoppers following AMPH and no change in fast stoppers, whereas we observed little change in our slow stoppers and impaired stopping in our fast stoppers. It appears that our animals were generally faster stoppers. Our study may have therefore spanned a different range of baseline performance.

Adaptive response adjustments in rats were additionally impaired with AMPH treatment. The substantial AMPH-induced increase in RT variability we observed may have contributed to reduced response adjustments, as RT variability is putatively associated with reduced ability to regulate behavior (MacDonald et al., 2006; Tamm et al., 2012). We observed a considerable impairment in responding on go trials with 0.75 mg/kg of AMPH and excluded many 0.5 mg/kg AMPH treatment sessions for not meeting performance criteria requirements. These findings mimic observations made by Eagle and Robbins (2003a) following administration of 1 mg/kg AMPH in rats, indicating that these doses of AMPH may be at the high end of an effective dose–response range for behavioral control and may in fact impair regulatory behavior in rats. General AMPH-induced shortening of go RTs were likely a factor in impaired response adjusting as well. Enhanced striatal dopamine following AMPH increases striatal firing and is associated with increased locomotor activity in rats (Salamone et al., 1982; Haracz et al., 1993). We observed faster overall responding with AMPH, which may have produced a floor effect that prevented response adjustments. Increased locomotor activity following AMPH likely mediated our observed increase in total trials as well. Overall, AMPH led to

baseline-dependent effects on stopping and impaired RT adjustments. These results suggest dissociable measures of executive function for rats in the countermanding task.

A limitation of the present study is that go trial only sessions were not conducted. Faster RTs have been observed in sessions with only go trials compared to stop task sessions (e.g., Ozyurt et al., 2003; Akerfelt et al., 2006). It would be of interest to examine whether the introduction of stop trials has a substantial effect on rat RTs as potential evidence for the interaction of go and stop processes in rat brains. It is also uncertain whether rodent stopping in this task reflects inhibition of a small subset of muscles involved in lever pressing, or if the entire motor system receives inhibitory signals when the stop process is activated. Local versus global inhibition is a growing field of investigation (see for review Brunamonti et al., 2012). Future rodent behavioral inhibition studies should attempt to specify motor control modifications resulting from stop signal presentation and identify why variability exists in task performance with individual subjects and different versions of the task. These experiments will extend the exploration of brain mechanisms involved in behavioral inhibition and allow the examination of executive control deficits in animal models of neurological disease and impulsivity.

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