

Dissociating Interference-Control Processes Between Memory and Response

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The ability to mitigate interference is of central importance to cognition. Previous research has provided conflicting accounts about whether operations that resolve interference are singular in character or form a family of functions. Here, the authors examined the relationship between interference-resolution processes acting on working memory representations versus responses. The authors combined multiple forms of interference into a single paradigm by merging a directed-forgetting task, which induces proactive interference, with a stop-signal task, which taps response inhibition processes. The results demonstrated that proactive interference and response inhibition produced distinct behavioral signatures that did not interact. By contrast, combining two different measures of response inhibition by merging a go/no-go task variant and a stop signal produced overadditive behavioral interference, demonstrating that different forms of response inhibition tap the same processes. However, not all forms of response conflict interacted, suggesting that inhibition-related functions acting on response selection are dissociable from those acting on response inhibition. These results suggest that inhibition-related functions for memory and responses are dissociable.

Keywords: inhibition, proactive interference, response selection, stop-signal paradigm, working memory

The concepts of inhibition¹ and control over interference have been topics of intense interest (for reviews, see Dempster, 1995; MacLeod, Dodd, Sheard, Wilson, & Bibi, 2003). This interest stems from the pervasive nature of processes that resolve interference throughout many cognitive activities. For example, changes in putative interference-related functions have been used to explain cognitive development (Diamond & Gilbert, 1989; Ridderinkhof, van der Molen, Band, & Bashore, 1997) as well as age-related cognitive decline (Hasher & Zacks, 1988; McDowd, Oseas-Kreger, & Fillion, 1995). Additionally, deficient interference-control processes have been linked to many disorders, including attention-deficit/hyperactivity disorder (Barkley, 1997; Nigg, 2001), autism (Ciesielski & Harris, 1997), schizophrenia (Nestor & O'Donnell, 1998), obsessive-compulsive disorder (Enright &

Beech, 1993), and depression and anxiety disorders (Muris, Merckelbach, & Horselenberg, 1996; Wegner & Zanakos, 1994). Although central to an understanding of cognition, the mechanisms of interference-control remain poorly understood.

Interference-Control: Common Versus Dissociable Processes

Recently, there has been a movement to understand the relationship among different processes that resolve interference. Some theories propose that all forms of interference resolution depend on a single function, such as inhibition (Hasher & Zacks, 1988; Hasher, Zacks, & May, 1999). For example, Hasher et al. (1999) demonstrated similar age-related declines for perceptual selection, memory, and response production in the face of interference. The proposal is that these declines may be explained by general inhibitory deficits. Other researchers have demonstrated that differences

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¹ Previous work has demonstrated that recruiting the concept of inhibition can often be misleading and unnecessary (MacLeod et al., 2003). However, inhibition has been a historically popular account of how we resolve interference. Moreover, there is now good evidence that inhibition plays a role in restraining responses (Aron, 2007). It is less clear that inhibition plays a role in resistance to proactive interference. Hence, when discussing both of these functions, we use the terms “inhibition-related functions,” “interference-resolution processes,” or “interference-control processes,” reflecting our uncertainty about the precise mechanism underlying resistance to proactive interference. However, we refer to restraining prepotent responses as “prepotent response inhibition,” reflecting our faith that inhibition is the operational mechanism in this case.

in working memory capacity explain variations in several different interference tasks (Heitz & Engle, 2007; Kane, Bleckley, Conway, & Engle, 2001; Kane & Engle, 2000; Rosen & Engle, 1998). Kane et al. (2001) suggested that such differences might reflect differences in controlled attention that serve to maintain relevant information amidst distraction. Neuroimaging studies examining multiple interference tasks have demonstrated similar frontal and parietal recruitment when subjects resolve different forms of interference (Fan, Flombaum, McCandliss, Thomas, & Posner, 2003; Nee & Jonides, 2009; Nee, Wager, & Jonides, 2007; Wager et al., 2005). These studies converge on the idea that inhibition-related functions may be of one sort, regardless of the form of interference.

By contrast, some evidence suggests that inhibition-related functions form a family and cannot be understood as a single unitary construct (Harnishfeger, 1995; Kramer, Humphrey, Larish, & Logan, 1994; Nigg, 2000; Shilling, Chetwynd, & Rabbitt, 2002). For example, behavioral correlations among interference tasks are generally low, often near zero (Fan et al., 2003; Kramer et al., 1994; Shilling et al., 2002; Wager et al., 2005). Moreover, despite common neural recruitment across different interference tasks, regions unique to different tasks are evident as well (Nee & Jonides, 2009; Nee, Wager, & Jonides, 2007; Wager et al., 2005). Therefore, perhaps there are dissociable forms of inhibition-related functions. However, theories remain in conflict regarding the proper taxonomy of inhibition-related functions (Dempster & Corkill, 1999; Friedman & Miyake, 2004; Harnishfeger, 1995; Kornblum, Hasbroucq, & Osman, 1990; Nigg, 2000). Some recent work has begun to shed light on this matter.

Interference Control in Perception, Memory, and Responding

Friedman and Miyake (2004) examined the relationship among three putative inhibitory functions: prepotent response inhibition, resistance to distractor interference, and resistance to proactive interference.² Prepotent response inhibition involves suppressing dominant, automatic tendencies to respond. For example, in the stop-signal task (Logan & Cowan, 1984), subjects must withhold a selected response when a tone is presented. In the go/no-go task, subjects must overcome a prepotency to respond by withholding a response to imperative no-go stimuli (Donders, 1868/1969). In both cases, it is presumed that control operations are elicited to inhibit a response.

In other cases, subjects must refrain from encoding salient distractors in the environment, which requires the ability to resist distractor interference. A paradigmatic example comes from the flanker task (Eriksen & Eriksen, 1974) in which subjects must make responses to a centrally presented target stimulus while ignoring irrelevant flanking stimuli. Hence, in this task, control processes act during perception to filter out irrelevant information. Notably, failure to completely filter out distracting flanker items may lead to the activation of competing responses, calling for control processes to select among conflicting responses. Therefore, the flanker task may be considered a task that taxes control acting upon both perception and response selection.

Finally, resistance to proactive interference suppresses memory intrusions from previously relevant but no longer relevant information. Such processes are engaged in item-recognition tasks that

probe information that was once in memory but that is no longer relevant (see Jonides and Nee, 2006, for a review). Examples of tasks that require resistance to proactive interference include the recent-probes task (Monsell, 1978), the directed-forgetting task (Nee, Jonides, & Berman, 2007), and the cued-recall task (Tolan & Tehan, 1999). In these tasks, subjects must retain information in memory and respond to recognition probes. When probed with items that were recently in memory but are not relevant for the current trial, subjects must overcome the lure of responding positively to information familiar in memory and correctly reject recent, but irrelevant memory items.

Using confirmatory factor analysis, Friedman and Miyake (2004) examined the relationship among prepotent response inhibition, resistance to distractor interference, and resistance to proactive interference. Their analyses demonstrated that resistance to distractor interference and prepotent response inhibition were strongly related, suggesting that these inhibition-related functions could be distilled into a single construct (distractor-response inhibition). However, distractor-response inhibition appeared to be distinct from resistance to proactive interference.

Using a subset of the tasks studied by Friedman and Miyake (2004), Verbruggen et al. have examined the relationship between prepotent response inhibition and resistance to distractor interference by combining interference tasks (Verbruggen, Liefvooghe, Notebaert, & Vandierendonck, 2005; Verbruggen, Liefvooghe, & Vandierendonck, 2004; Verbruggen, Liefvooghe, & Vandierendonck, 2006). These authors determined that prepotent response inhibition, as measured by the stop-signal paradigm (e.g. Logan & Cowan, 1984), interacted with several other distractor interference tasks that require responding to a target stimulus while filtering out irrelevant perceptual information (Verbruggen, Liefvooghe, Notebaert, & Vandierendonck, 2005; Verbruggen et al., 2004, 2006), including the flanker (Eriksen & Eriksen, 1974), Simon (Simon, 1990; Lu & Proctor, 1995), spatial Stroop (Lu & Proctor, 1995), color-word Stroop (Stroop, 1935), and global-local (Navon, 1977) tasks. These interactions remained even in the absence of response conflict, demonstrating that the relationship between prepotent response inhibition and resistance to distractor interference is not caused by common motor demands (Verbruggen et al., 2004, 2006). This pattern of results confirms that prepotent response inhibition and resistance to distractor interference are closely related.

Although Friedman and Miyake (2004) suggested that distractor-response inhibition and resistance to proactive interference are distinct, no study has examined this claim in more detail. Notably, the reliabilities of the measures of proactive interference studied by Friedman and Miyake (2004) were very low (.12 or lower). Furthermore, Friedman and Miyake (2004) modeled resistance to proactive interference as residual variance not captured by pure recall. Hence, it is possible that much of their construct was due to measurement error, rather than actually reflecting the ability to resist proactive interference, providing a potentially ambiguous construct for comparison with distractor-response inhibition. The

² These functions have been coined by a variety of different terms by other authors. Hasher, Lustig, and Zacks (2007) referred to *resistance to distractor interference* as "access," *resistance to proactive interference* as "deletion," and *prepotent response inhibition* as "restraint."

lack of relationship between distractor-response inhibition and resistance to proactive interference may be due to these differences in measuring each function. Therefore, of interest for models of interference control is further examination of the constructs of resistance to proactive interference and distractor-response inhibition to determine whether these functions truly are independent or whether they interact.

Multiple Processes of Response Control?

Models of cognition recognize that responding can be divided into multiple stages, one of which corresponds to selecting a response (response selection) and another of which corresponds to executing a selected response (response execution; Meyer & Kieras, 1997). Prepotent response inhibition, as measured by the stop-signal task, is thought to load primarily on control processes acting during the execution phase of responding. In addition, several tasks present respondents with multiple conflicting response representations among which the respondent must select during response production. Hence, also of interest is whether conflict acting on different stages of response production is resolved via dissociable processes. Existing studies investigating these processes provide mixed evidence regarding their possible dissociation. For example, Logan and Irwin (2000) demonstrated that prepotent response inhibition interacted with response conflict in a stimulus-response compatibility task, but only for eye movements, not for manual responses. Because of the speed with which eye movements are executed and the strong prepotency to produce saccades in the direction of targets, such stimulus-response compatibility tasks with eye movements have largely been associated with prepotent response inhibition rather than with response selection (Friedman & Miyake, 2004). In other manual response tasks, Kramer et al. (1994) and Ridderinkhof, Band, and Logan (1999) demonstrated interactions between prepotent response inhibition and conflict in the flanker task. Using repetitive transcranial magnetic stimulation, Chambers et al. (2007) demonstrated a reliance on right inferior frontal gyrus for combined prepotent response inhibition and flanker conflict. However, Verbruggen et al. (2004, 2006) argued that these interactions might be due to stimulus, rather than response, conflict present in the flanker task. Finally, Verbruggen, Liefvooghe, and Vandierendonck (2005) reported no interaction between prepotent response inhibition and the negative priming task (Tipper, 1985), which requires subjects to respond to previously ignored information. Although some have argued that the negative priming task induces response conflict during selection (Neill, Valdes, Terry, & Gorfein, 1992), several other accounts do not include a role for response conflict (Nee & Jonides, 2008; Tipper, 2001). Therefore, it remains unclear whether control processes acting on response selection are dissociable from those that underlie prepotent response inhibition.

Summary and Lead-in to the Present Study

Previous work has convincingly demonstrated a strong relationship between control processes that resist perceptual distraction and those that inhibit prepotent responses. However, a full taxonomy of control processes remains incomplete. Of interest is further examination of the relationship between control processes acting on responses and memories and the question of whether control

processes acting on different stages of response production are also dissociable.

In this study, we examined the relationship between proactive interference and prepotent response inhibition as well as the relationship between control processes operating at different stages of response production. In Experiment 1, we combined a directed-forgetting task that induces proactive interference in working memory with a stop-signal task that requires prepotent response inhibition. In Experiment 2, we combined a variant of the go/no-go task (Donders, 1868/1969) with the stop-signal task to examine whether different measures of prepotent response inhibition interact. In addition, we examined whether inhibition-related functions associated with different stages of response production (selection and execution) interact. Taken together, the results of these experiments lead to a taxonomy of inhibition-related functions that distinguishes resistance to proactive interference, prepotent response inhibition, and response selection.

Experiment 1

Method

Subjects

Sixteen subjects (of whom 11 were male and 5 were female; mean age = 22 years) were recruited from the Ann Arbor, Michigan area. Subjects were compensated \$50 plus a performance-based bonus awarded for accuracy and reaction time (RT) on stop-signal-absent trials as well as for stop-signal accuracy on signal-present trials. All subjects were right-handed native English speakers who had not completed any similar experiments during the past 2 months.

Design and Procedure

As depicted in Figure 1, each trial began with 1 s of fixation, followed by a memory set of four centrally displayed letters presented for 2 s. After a 3-s delay, two letters of the memory set were presented again. Subjects were instructed to remove these letters from memory and to retain the two letters that had not been presented twice. After a 1-s delay, subjects responded to a probe letter affirmatively (by pressing '1' on a standard keyboard), if the probe letter was one of the to-be-remembered letters, or negatively (by pressing '0'), if it was not.

Each memory set was chosen randomly from the set of capital letter consonants, excluding 'W,' with the restriction that no letter had appeared on the previous two trials. Of the probes, 50% were members of the target set (positive probes), 25% were letters that subjects were instructed to forget and hence had to reject (forget probes), and 25% were letters that had not been presented on the previous two trials (control probes). Proactive interference was measured by differences between forget probes and control probes. Although control probes do require some resolution of proactive interference, as letters are repeated throughout the experiment, there should be considerably less proactive interference associated with control than with forget probes, justifying the forget-control probe comparison as a measure of proactive interference (Jonides & Nee, 2006; Nee & Jonides, 2008). Before the experiment, subjects were given written and oral instructions and were admin-

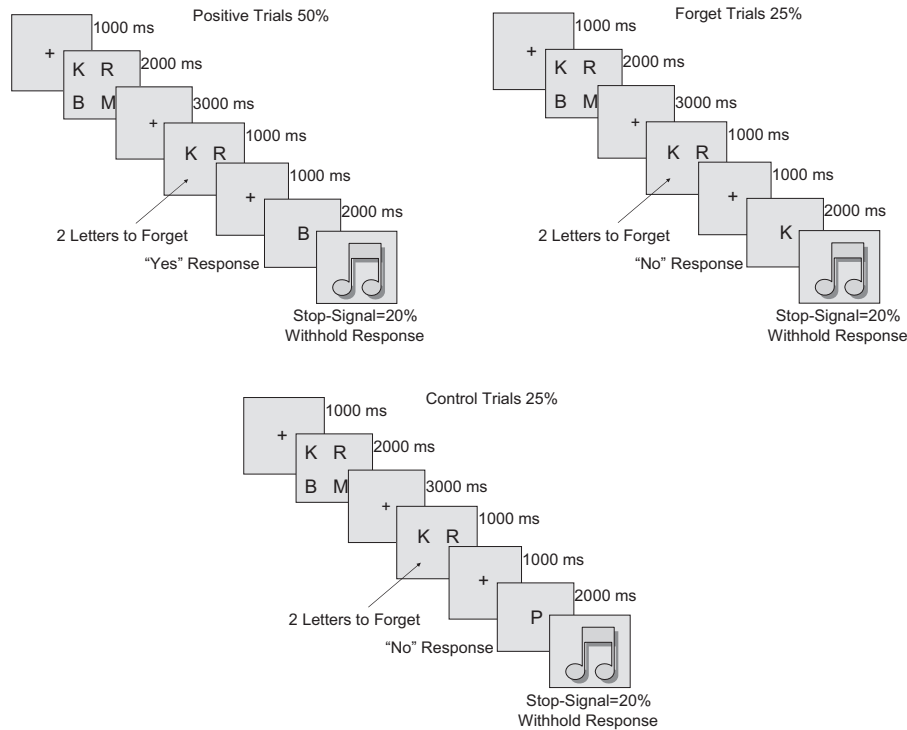


Figure 1. Schematic of the three probe types in Experiment 1. Presentation duration is indicated at the upper right corner of each slide.

istered 16 practice trials under experimenter supervision. The experiment consisted of 16 runs of 60 trials each.

On 20% of trials in each trial type, an auditory stop signal (a 1-s tone) was presented shortly after the probe. This resulted in 48 signal-present trials for the forget and control conditions and 96 signal-present trials for the positive condition for each participant. If a stop signal was presented, the participant was instructed to refrain from responding. Subjects were also instructed not to adopt the strategy of simply waiting for stop signals before deciding whether to respond because this would decrease their monetary bonus.

A horse-race model has been proposed to explain stop-signal results (Logan & Cowan, 1984). It is assumed that there are two processes whose finishing times are independent: a “go” process and a “stop” process. If the go process finishes first, the participant will respond, and if the stop process finishes first, a response will be successfully inhibited. A staircase procedure for varying when the stop signal is presented yields a stop-signal RT (SSRT) value, which represents the amount of time necessary after the stop-signal delay for the stop process to finish at the same time as the go process. We varied the delay between presentation of the probe and the stop signal (the stop-signal delay) in a staircase fashion, with the initial stop signal set at 350 ms after probe onset (Logan, Cowan, & Davis, 1984). After successfully stopping, the stop-signal delay increased by 50 ms, which handicaps the stop process on the next stop-signal trial. After unsuccessful stopping, the stop-signal delay decreases, handicapping the go process on the next stop-signal trial. This calculation is necessary because there is no overt response recorded during a successful stop-signal trial.

This value is expected to yield 50% accuracy on signal-present trials in each experiment across all probe types, and our experiments reveal this result (Experiment 1, 50% accuracy; Experiment 2, 50% accuracy on three testable probe types, AX, AY, and BY, described below).

We measured SSRT by first calculating the mean stop-signal delay for each participant for each probe type (forget, control, and positive) independently. We then calculated the mean go reaction time (RT) for each probe type on signal-absent trials. Each mean stop-signal delay was subtracted from the respective mean go RT for our SSRT measure (Logan, Schachar, & Tannock, 1997). SSRT provides a presumed latency to stop.

Of interest is whether SSRT varied as a function of probe type (control, forget, or positive probe). If prepotent response inhibition and resistance to proactive interference rely on the same processes, we would expect an interaction such that SSRT for forget probes that require proactive interference resolution would be greater than SSRT for control probes, which require minimal proactive interference resolution. This prediction follows the logic of additive factors, which posits that two variables that act on the same process will yield overadditive contributions to processing time (Sternberg, 1969).

Results

Mean RTs were computed only for correct trials where no stop signal was present (signal absent). Results are summarized in Table 1. The results demonstrate significant effects of proactive interference on RT and error rates but no interaction between

Table 1
Experiment 1 Data

Measure	Control <i>M</i>	Forget <i>M</i>	Positive <i>M</i>	Forget vs. control	
				<i>t</i> (15)	<i>p</i>
RT (ms)	541.76	577.90	503.35	8.08	<.001
Error rate	2.1%	5.8%	5.1%	3.08	<.01
SSRT (ms)	225.92	225.39	232.49	0.09	>.90

Note. RT = reaction time; SSRT = stop-signal reaction time. Control, forget, and positive represent probe types.

resolving proactive interference and response inhibition. We computed separate repeated-measures one-way analyses of variance (ANOVAs) for RT, SSRT, and error rate for signal-absent trials, using probe-type as a factor. Where sphericity could not be assumed, we used the Huynh-Feldt correction. These tests revealed a significant effect of probe type in RT, $F(2, 30) = 59.1$, $MSE = 496.98$, $p < .001$, and error rate on signal-absent trials, $F(2, 30) = 8.13$, $MSE = .001$, $p < .005$. Planned *t* tests revealed that these differences were due to worse performance for forget probes compared with control probes (see Table 1; $t(15) = 8.08$ for RT, and $t(15) = 3.08$ for error rate). These results establish robust effects of proactive interference.

SSRT did not vary as a function of probe type, $F(2, 30) = 0.55$, $MSE = 458.57$, $p > .50$ (see Figure 2). A planned *t* test comparing SSRT on forget probes with SSRT on control probes revealed no difference, $t(15) = 0.09$, $p > .93$. To determine the reliability of our SSRT measure across all probe types, we calculated reliability with split-half (odd–even) correlations. This analysis yielded a reliability of .879 (adjusted correlation with Spearman–Brown prophecy formula: .936), demonstrating the high reliability of our SSRT measure.

As mentioned earlier, a critique of previous work that demonstrated a lack of interaction between prepotent response inhibition and resistance to proactive interference (Friedman & Miyake, 2004) was that measures of proactive interference suffered from low reliability (.12 or less). To determine whether the directed-forgetting task used here also suffered from such reliability concerns, we calculated reliability with split-half (odd–even) correlations (forget vs. control probes). This analysis yielded a reliability of .319 (with an adjusted correlation obtained with the Spearman–Brown prophecy formula, mirroring the procedure used by Friedman & Miyake, 2004, of .484). This demonstrated that the directed-forgetting task was considerably more reliable than previous measures of resistance to proactive interference.³

Discussion

Experiment 1 examined the relationship between resistance to proactive interference and prepotent response inhibition by combining a directed-forgetting task with the stop-signal task. Despite robust effects of proactive interference, we were unable to find an interaction between resistance to proactive interference and prepotent response inhibition. These results support the idea that resistance to proactive interference and prepotent response inhibition are separable inhibition-related functions (Friedman & Miyake, 2004).

To ensure that the lack of an interaction between prepotent response inhibition and resistance to proactive interference was not due to insufficient power, we aimed to demonstrate that a significant interaction in SSRT would be present if two tasks that tap the same inhibition-related function were combined. Moreover, we were interested in examining whether control processes operating on different levels of response production could be dissociated. Hence, Experiment 2 combined the stop-signal task with a variant of the go/no-go task requiring control processes operating on both response selection and response execution (i.e., prepotent response inhibition). The combination of these two tasks also allowed us to examine the relationship between different response-level processes.

Experiment 2

In addition to the stop-signal task, prepotent response inhibition is often measured with the go/no-go task, which requires subjects to respond to a stream of stimuli but to withhold a response to a particular target stimulus (Donders, 1868/1969). In the variant used here, we examined prepotent response inhibition, as well as conflict during response selection. Combining this task with the stop-signal task afforded us the ability (a) to affirm that different measures of prepotent response inhibition interact and (b) to determine whether interference effects at different stages of response production interact or are separable. There is some evidence that different measures of prepotent response inhibition interact. Verbruggen and Logan (in press) revealed that when subjects prepare to stop in response to a stop signal, they increase their go task response threshold, which interacts with prepotent response inhibition (van den Wildenberg, van der Molen, & Logan, 2002). Increasing response threshold by preparing to stop may involve tonic response inhibition that is similar in kind to the phasic response inhibition associated with reactively stopping in response to a stop signal. This work therefore suggests an interaction between different measures of response inhibition. Conversely, it is less clear whether different stages of response production rely on common or independent control processes. When interactions have been found (Kramer et al., 1994), it has been unclear whether they have been the result of interacting control processes acting on different stages of response production or whether they have been due to the known interaction between stimulus conflict and pre-

³ Note, of course, that this value is bound to be somewhat low because it is a measure of the reliability of a difference score.

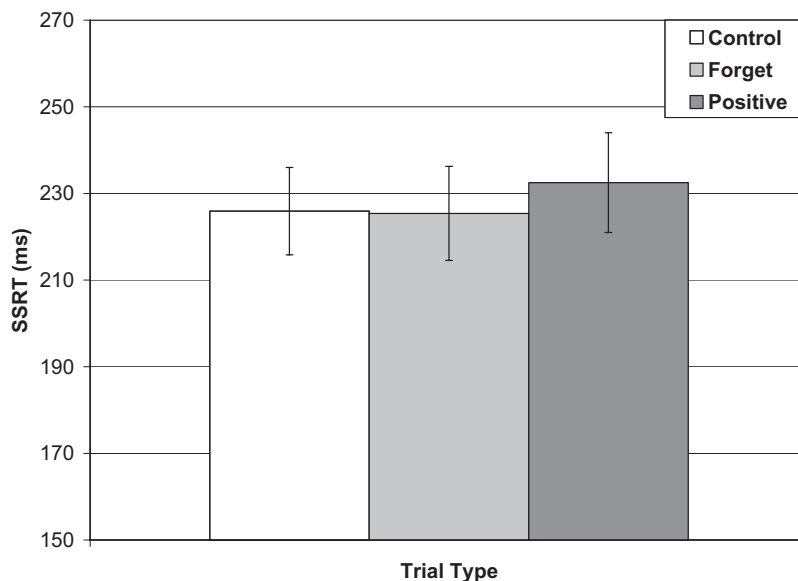


Figure 2. Stop-signal reaction time (SSRT) values for the three probe types in Experiment 1. Error bars denote one standard error of the mean.

potent response inhibition (Verbruggen et al., 2004, 2006). In the present experiment, we included no stimulus conflict, allowing for a unique assessment of response conflict. Our design thus gave us the ability to separably examine conflict during response selection and prepotent response inhibition.

Method

Subjects

Sixteen subjects (of whom 5 were male and 11 were female; mean age = 21 years) were recruited from the Ann Arbor, Michigan area. None of the subjects from Experiment 1 participated in Experiment 2. Subjects were compensated \$50 plus a performance bonus awarded for accuracy and RT on AY, BY, and BX signal-absent trials as well as for accurate stopping on AX and signal-present trials (trial types described below). All subjects were right-handed native English speakers who had not completed any similar experiments during the past 2 months. One participant was eliminated because of a computer error during the experiment.

Design and Procedure

As displayed in Figure 3, on each trial subjects saw a prime letter for 0.5 s, followed by a delay that varied between 0.5 s and 1.5 s (equally distributed among discrete values of 0.5 s, 1 s, and 1.5 s). Thereafter, subjects were presented with a target letter for 1 s. Subjects were instructed to respond via keypress to the second letter unless the second letter was an 'X' preceded by an 'A' (AX trials). The letters were pseudorandomized such that 40% of trials were AX trials, 20% consisted of 'A' followed by any non-'X' letter (AY trials), 20% consisted of a non-'A' letter followed by an 'X' (BX trials), and 20% contained a non-'A' letter followed by a non-'X' letter (BY trials). Non-'A' and non-'X' letters were randomly chosen from all consonants except for 'A,' 'X,' and 'W.'

This version of the AX-continuous performance task (CPT) paradigm (Barch et al., 1997; Cohen, Braver, & O'Reilly, 1996) uses RT as the main dependent measure. Use of this measure thus allowed us to embed stop signals on critical trials of interest. Similar to Experiment 1, an auditory stop signal was presented on 20% of trials for each trial type, indicating that a response should be withheld, regardless of prior instructions. This resulted in 80 signal-present trials for the AY, BX, and BY conditions and 160 signal-present trials for the AX condition for each participant. The staircase procedure for varying stop-signal delay as well as the calculation of SSRTs proceeded in the same manner as in Experiment 1, except that the stop-signal delay was initially set to 250 ms, with the recognition that the average responses were faster for this task. Subjects performed 80 runs of 25 trials each. Before the experiment, subjects were given written and verbal instructions and completed 20 practice trials under the supervision of an experimenter.

We posited that when an 'A' was presented as a prime letter, subjects would establish a prepotency to withhold a response. On AY trials, this prepotency would have to be overcome in order to respond correctly. Hence, responses to AY trials examine the ability to overcome prepotent response inhibition. Of particular interest is SSRT on AY trials, as stop-signal trials require subjects to first overcome their initial prepotent response inhibition (i.e., respond to the 'Y') and then re-establish inhibition of a prepotent response (i.e., withhold a response to the stop signal). In addition, on BX trials, subjects were instructed to respond, despite the fact that an 'X' often indicates a nonresponse cue. We hypothesized that BX trials induce conflict while subjects select a response (response selection). Although conflict during response selection is often considered a co-activation of two different responses (e.g., right vs. left), it can be similarly characterized as a competition between a go and a stop response. In fact, modeling go/no-go tasks in this manner produces close fits to behavioral data, justifying this

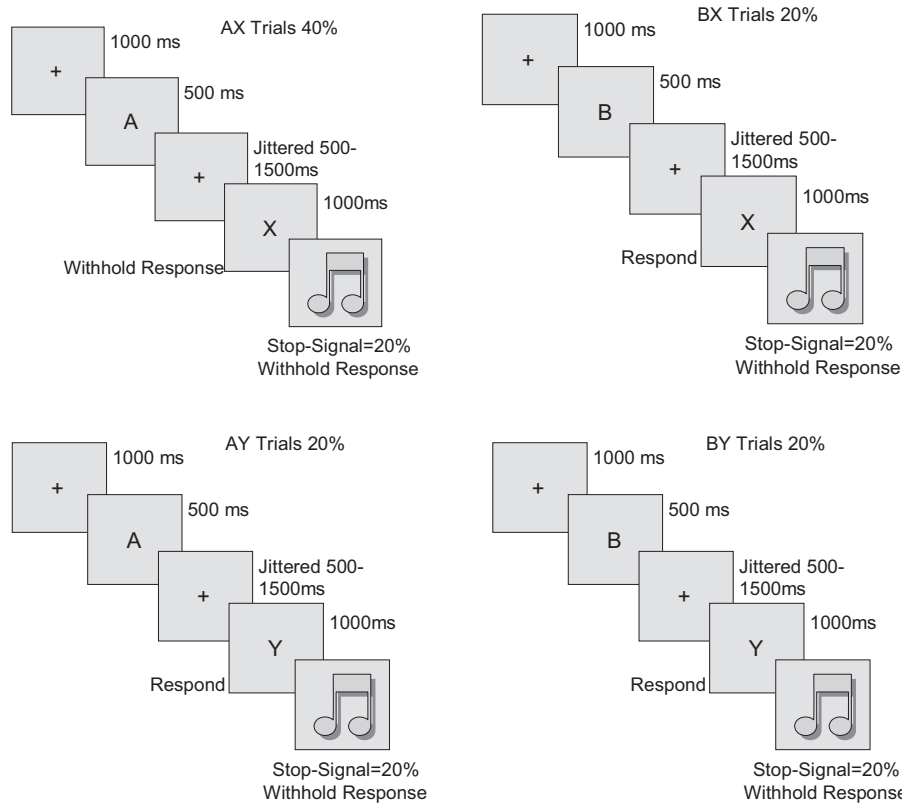


Figure 3. Schematic of the four trial types within Experiment 2. B denotes a non-‘A’ first letter, and Y denotes a non-‘X’ second letter. Presentation duration is indicated at the upper right corner of each slide.

conceptualization (Jones, Cho, Nystrom, Cohen, & Braver, 2002). Hence, it is also of interest to examine whether this form of response-selection conflict interacts with the prepotent response inhibition due to the stop signal.

Results

We computed mean RTs for correct signal-absent trials only. Results are summarized in Table 2. Separate one-way ANOVAs were computed on AY, BY, and BX trials for RT, SSRT, and error rate on signal-absent trials, with trial type as a factor. Where sphericity could not be assumed, we used the Huynh-Feldt correction. The results demonstrated significant effects of prepotent response inhibition and response-selection conflict in the AX-CPT task. Prepotent response inhibition robustly interacted with SSRT

(see Figure 4). Conflict during response selection did not interact with SSRT.

There was a significant effect of trial type on RT, $F(2, 30) = 20.66$, $MSE = 978.07$, $p < .001$, and error rate on signal-absent trials, $F(2, 30) = 6.15$, $MSE = .0002$, $p < .01$. Planned t tests demonstrated that subjects were significantly slower on AY trials compared with BY trials, $t(15) = 5.73$, $p < .001$, revealing a robust effect of prepotent response inhibition. These trials did not differ in error rate, $t(15) = 0.78$, $p > .45$. To determine the reliability of the obtained AY–BY RT difference, we calculated reliability with split-half (odd–even) correlations. This analysis yielded a reliability of .952 (adjusted correlation with Spearman–Brown prophecy formula: .975), demonstrating the high reliability of this measure. Additionally, subjects were significantly slower

Table 2
Experiment 2 Data

Measure	AX <i>M</i>	AY <i>M</i>	BX <i>M</i>	BY <i>M</i>	AY vs. BY		BX vs. BY	
					$t(15)$	p	$t(15)$	p
RT (ms)		585.36	559.86	524.74	5.73	<.001	6.43	<.001
Error rate	3.6%	3.1%	8.2%	2.6%	0.78	>.45	5.13	<.001
SSRT (ms)		271.22	218.22	206.27	3.91	<.005	1.18	>.25

Note. RT = reaction time; SSRT = stop-signal reaction time. AX, AY, BX, and BY represent trial types. “Y” denotes a non-X second letter. “B” denotes a non-A first letter.

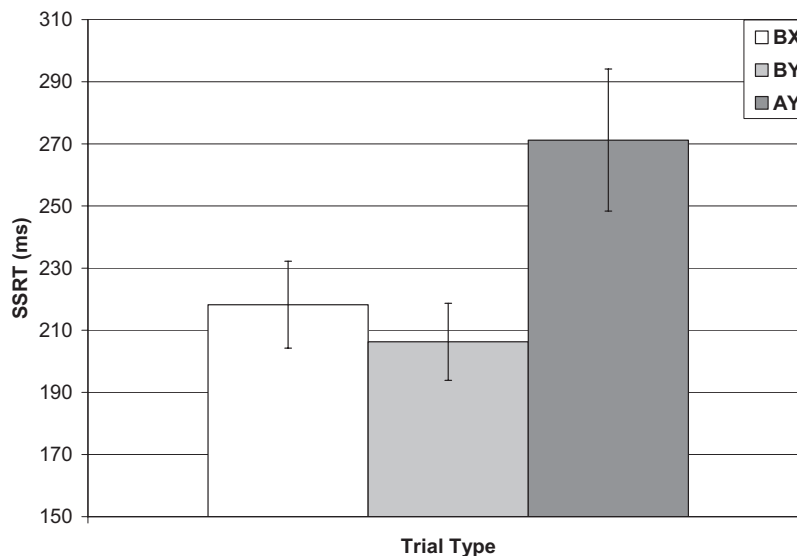


Figure 4. Stop-signal reaction times for the three overt response conditions in Experiment 2: BX, BY, and AY (see Figure 3 and the *Design and Procedure* section of Experiment 2 for a description of the conditions). SSRT = stop-signal reaction time. Error bars denote one standard error of the mean.

and more error prone on BX trials compared with BY trials, $t(15) = 6.43$, $p < .001$, for RT and $t(15) = 3.59$, $p < .005$, for error rate, demonstrating an effect of control over response selection. This difference yielded a reliability of .534 (adjusted correlation with Spearman–Brown prophecy formula: .696), demonstrating the reliability of this measure. These results demonstrate the expected interference effects in the AX-CPT task.

There was a significant effect of trial type on SSRT, $F(2, 30) = 12.08$, $MSE = 1,582.77$, $p < .001$. A planned t test revealed that SSRT on AY trials was longer than SSRT on BY trials, $t(15) = 3.91$, $p < .005$, demonstrating the expected interactive effect of different forms of prepotent response inhibition. Mean SSRT on BX trials did not differ from mean SSRT on BY trials, $t(15) = 1.18$, $p > .25$, suggesting independence between control processes acting on response selection and response execution. To determine the reliability of our SSRT measure across all probe types (BX, BY, and AY), we calculated reliability with split-half (odd–even) correlations. This analysis yielded a reliability of .978 (adjusted correlation with Spearman–Brown prophecy formula: .989), demonstrating the high reliability of our SSRT measure.

Discussion

Experiment 2 examined the relationship between two independent measures of prepotent response inhibition, as well as the degree to which control processes acting on different levels of response production are separable. As expected, we demonstrated a strong interaction between different measures of prepotent response inhibition, validating that the lack of interaction between proactive interference and prepotent response inhibition in Experiment 1 was not due to SSRT having insufficient sensitivity to yield an interaction. Moreover, the interaction that we found in Experiment 2 demonstrates that prepotent response inhibition is a consistent measure across different paradigms. By contrast, interference control during response selection and prepotent response

inhibition did not interact with each other. Compared with BY trials, BX trials demonstrated a consistently significant interference effect in RT, indicating a demand on control processes acting upon response selection. However, BX and BY trials did not differ in SSRT, suggesting that the control involved in response selection on BX trials did not interact with the prepotent response inhibition required by stop signals. It appears, then, that inhibition-related functions acting upon response selection are dissociable from those acting upon response inhibition.

General Discussion

Two experiments investigated whether inhibitory processes of proactive interference, prepotent response inhibition, and response selection are dissociable. Whereas different measures of response inhibition interacted, prepotent response inhibition did not interact with proactive interference, suggesting that prepotent response inhibition and resistance to proactive interference are dissociable control functions. However, not all forms of response conflict interacted, suggesting that inhibition-related functions acting upon response selection are dissociable from those acting upon response inhibition. These results suggest a taxonomy that distinguishes control over memories, control over selecting responses, and control over inhibition of prepotent responses.

Previous work has suggested that resistance to proactive interference is dissociable from other forms of interference control. Using confirmatory factor analysis, Friedman and Miyake (2004) demonstrated that prepotent response inhibition and resistance to proactive interference are distinct inhibitory functions. Using event-related functional magnetic resonance imaging, Nelson, Reuter-Lorenz, Sylvester, Jonides, and Smith (2003) examined the neural correlates of proactive interference and response conflict. These authors discovered that whereas the left inferior frontal gyrus was involved in the resolution of proactive interference, the anterior cingulate was uniquely involved in response conflict. Nee

and Jonides (2009) replicated the relationship between the left inferior frontal gyrus and resistance to proactive interference and demonstrated that this region was unrelated to resistance to distraction. However, different tasks requiring resistance to proactive interference (the recent probes task and the directed-forgetting task) demonstrate overlapping activations in the left inferior frontal gyrus in the same subjects (Nee, Jonides, & Berman, 2007). Moreover, this region is involved in item nonspecific buildup of proactive interference (Postle & Brush, 2004) as well as proactive interference in the AB-AC-AD paradigm (Henson, Shallice, Josephs, & Dolan, 2002). Therefore, whereas a variety of different tasks and forms of proactive interference share a close relation, resistance to proactive interference is distinct from other inhibitory processes.

Prior behavioral studies investigating the relationship of conflict during response selection and prepotent response inhibition provided mixed evidence regarding the degree to which they are separable. Some research has shown that SSRTs are slowed in the presence of response competition in a flanker task, suggesting common control processes underlying the flanker and stop-signal tasks (Kramer et al., 1994; Ridderinkhof et al., 1999). However, the flanker task combines two forms of conflict: stimulus conflict when the flanker stimuli do not match the target stimulus in form and response conflict when the flanker stimuli are associated with a competing response. Verbruggen et al. (2004, 2006) examined whether stimulus conflict, response conflict, or both interacted with SSRT. In two flanker tasks, these authors found that stimulus, but not response, conflict interacted with prepotent response inhibition. Our results provide evidence that resolving conflict during response selection is a process that is dissociable from prepotent response inhibition.

Neural work has also suggested that prepotent response inhibition and response selection conflict may have somewhat distinct neural loci. Rubia et al. (2001) examined the neural correlates of the go/no-go and stop-signal tasks. These authors found common activation for both tasks in the right inferior frontal gyrus, suggesting that this region may be involved in prepotent response inhibition (see also Aron, 2007). However, the go/no-go task showed unique recruitment of more dorsal regions of frontal cortex as well as parietal cortex. The authors reasoned that these regions may be involved in response selection, a function that they proposed is absent in the stop-signal task. A meta-analysis of inhibition-related tasks was consistent with these patterns, with more inferior regions of right frontal cortex associated with response execution and more dorsal regions more strongly associated with response selection (Nee, Wager, & Jonides, 2007). Our converging results suggest that prepotent response inhibition and conflict during response selection involve different brain areas.

It is interesting that resistance to distractor interference and prepotent response inhibition show a strong relation despite the fact that these functions appear to operate at opposite ends of the information processing stream. That these functions appear to be distinct from resistance to proactive interference and response selection provides important constraints for considering how the functions are related. One possibility for the apparent relation between resistance to distractor interference and prepotent response inhibition may be due to the tasks used to investigate their interaction. For example, successful performance on the flanker task requires focusing in on the target stimulus while mitigating distraction from

other stimuli. However, the stop-signal task requires one to orient to a stimulus external to the main task in order to cease a response. When these tasks are combined, subjects must try not to orient to some nontarget stimuli (flankers) but to orient to other nontarget stimuli (stop signals). The need to selectively filter some stimuli and not others may produce conflict that causes interactive effects on control. Future work to test this idea may combine the flanker task with other forms of prepotent response inhibition that do not rely on stimuli that can be differentiated from the target (e.g., a flanker/AX-CPT combination task).

The results of the current study have implications that extend beyond cognitive psychology. Specifically, depression and anxiety disorders have been linked to an inability to suppress unwanted thoughts (Muris et al., 1996; Wegner & Zanakos, 1994), and successful suppression of intrusive, unwanted thoughts requires resistance to proactive interference. In addition, children with attention deficit hyperactivity disorder, but not anxious children, show impaired response inhibition (Oosterlaan, Logan, & Sergeant, 1998). The separable nature of resistance to proactive interference and response inhibition demonstrated in this study can help orient future research on these disorders. For instance, effective characterization and isolation of the specific inhibition-related functions underlying these different disorders allows efforts at rehabilitation to be narrowly targeted toward these processes. This could prove especially important for drug interventions for which there may be interest in rehabilitating a single process while leaving other processes undisturbed (Jonides & Nee, 2005).

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