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Dissociating Interference-Control Processes between Memory and Response

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Abstract

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, we examined the relationship between interference-resolution processes acting upon working memory representations versus responses. We combined multiple forms of interference into a single paradigm by merging a directed-forgetting task, which induces proactive interference, with a stop signal task that 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 over-additive 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 upon response selection are dissociable from those acting upon response inhibition. These results suggest that inhibition-related functions for memory and responses are dissociable.

Key Words/Phrases

Inhibition; Proactive Interference; Response Selection; Stop-Signal Paradigm; Working Memory

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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,

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1988;McDowd, Oseas-Kreger, & Filion, 1995). Additionally, deficient interference-control processes have been related 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 and colleagues (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 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 and colleagues (2001) suggested that such differences may 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, Wager, & Jonides, 2007; Nee & Jonides, in press; 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 et al., 2007; Wager et al., 2005; Nee & Jonides, in press). So, 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 interference². 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

¹Previous 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” or “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.

²These functions have been coined by a variety of different terms by other authors. Hasher and colleagues (2007) refer to resistance to distractor interference as “access”, resistance to proactive interference as “deletion”, and prepotent response inhibition as “restraint”.

no-go stimuli (Donders, 1868). 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, requiring 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 (PI) 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 PI include the recent-probes task (Monsell, 1978), the directed-forgetting task (Nee, Jonides, and 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 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 PI. Their analyses demonstrated that resistance to distractor interference and prepotent response inhibition were highly 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 PI.

Using a subset of the tasks studied by Friedman and Miyake (2004), Verbruggen and colleagues have examined the relationship between prepotent response inhibition and resistance to distractor interference by combining interference tasks (Verbruggen, Liefvooghe, & Vandierendonck, 2004; Verbruggen, Liefvooghe, Notebaert, & Vandierendonck, 2005a; Verbruggen, Liefvooghe, & Vandierendonck, 2006). These authors determined that prepotent response inhibition, as measured by the stop-signal paradigm (e.g. Logan and Cowan, 1984), interacted with several other distractor interference tasks that require responding to a target stimulus while filtering out irrelevant perceptual information (Verbruggen et al., 2004; 2005a; 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 tasks (Navon, 1977). 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 PI are distinct, no study has examined this claim in more detail. Notably, the reliabilities of the measures of PI studied by Friedman and Miyake (2004) were very low (0.12 or lower). Furthermore, Friedman and Miyake (2004) modeled resistance to PI 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 PI, providing a

potentially ambiguous construct for comparison with distractor-response inhibition. The lack of relationship between distractor-response inhibition and resistance to PI 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 PI and distractor-response inhibition to see if 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 subjects with multiple conflicting response representations among which one must be selected during response production. Hence, also of interest is whether conflict acting upon different stages of response production is resolved via dissociable processes. Existing studies investigating these processes provide mixed evidence regarding their possible separability. For example, Logan and Irwin (2000) demonstrated that prepotent response inhibition interacted with response conflict in a stimulus-response compatibility (SRC) task, but only for eye movements, not manual responses. Due to the speed with which eye movements are executed and the strong prepotency to produce saccades in the direction of targets, such SRC tasks with eye movements have largely been associated with prepotent response inhibition rather than response selection (Friedman & Miyake, 2004). In other manual response tasks, Kramer et al., (1994) and Ridderinkhof, Band, & Logan (1999) demonstrated interactions between prepotent response inhibition and conflict in the flanker task. Chambers and colleagues (2007) demonstrated with repetitive transcranial magnetic stimulation (rTMS) a reliance on right inferior frontal gyrus (IFG) for combined prepotent response inhibition and flanker conflict. However, Verbruggen and colleagues (2004; 2006) have argued that these interactions may be due to stimulus rather than response conflict present in the flanker task. Finally, Verbruggen, Liefvooghe, and Vandierendonck (2005b) reported no interaction between prepotent response inhibition and the negative priming task (Tipper, 1985) that forces subjects to respond to previously ignored information. Although some argue that the negative priming task induces response conflict during selection (Neill, Valdes, Terry, & Gorfein, 1992), several other accounts exist that do not include a role for response conflict (Tipper, 2001; Nee & Jonides, 2008). Therefore, it remains unclear whether control processes acting upon 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 upon responses and memories, and whether control processes acting upon different stages of response production are also dissociable.

In this study, we examined the relationship between PI and prepotent response inhibition, and the relationship between control processes operating at different stages of response production. In Experiment 1, we combined a directed-forgetting task that induces PI 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) with the stop-signal task to examine whether different measures of prepotent response inhibition interact. In addition, we examined whether inhibition-related functions related to different stages of response production (selection and execution) interact. The results lead to a taxonomy of inhibition-related functions that distinguishes resistance to PI, prepotent response inhibition, and response selection.

Experiment 1

Method

Subjects—Sixteen subjects (11 male, mean age 22) were recruited from the Ann Arbor area and were compensated \$50 plus a performance-based bonus awarded for accuracy and reaction time on stop-signal-absent trials, and 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 two months.

Design and Procedure—As depicted in Figure 1, each trial began with 1s of fixation, followed by a memory set of 4 centrally displayed letters presented for 2s. After a 3s delay, 2 letters of the memory set were re-presented. Subjects were instructed to remove these letters from memory and to retain the 2 letters that had not been re-presented. After a 1s 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 consonants excluding ‘W’ with the restriction that no letter had appeared on the previous two trials. Fifty percent of the probes 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 2 trials (Control probes). PI was measured by differences between Forget probes and Control probes. Although Control probes do require some resolution of PI since letters are repeated throughout the experiment, there should be considerably less PI associated with Control than Forget probes, justifying the Forget-minus-Control probe comparison as a measure of PI (Jonides & Nee, 2006; Nee & Jonides, 2008). Before the experiment, subjects were given written and oral instructions, and were administered 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 1s 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 subject. If a stop signal was presented, the subject 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 subject 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 reaction time (SSRT) value which is 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 50ms, 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 should 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 3 testable probe types, AX, AY, and BY).

We measured SSRT by first calculating the mean stop-signal delay for each subject for each probe type (Forget, Control, and Positive) independently. We then calculated the mean “Go” 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 PI rely on the same processes, we would expect an interaction such that SSRT for Forget probes that require PI-resolution to be greater than SSRT for Control probes that require minimal PI-resolution. This prediction follows the logic of additive factors that posits that two variables that act upon the same process will yield over-additive contributions to processing time (Sternberg, 1969).

Results

Mean reaction times (RT) 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 PI on RT and error rates, but no interaction between resolving PI and response inhibition. Separate repeated measures one-way ANOVAs were computed for RT, SSRT, and error rate for signal-absent trials, using probe-type as a factor. Where sphericity cannot be assumed, the Huynh-Feldt correction was used. These tests revealed a significant effect of probe-type in RT [$F(2,30)=59.1$, $MS_e=496.98$, $p<.001$] and error rate on signal-absent trials [$F(2,30)=8.13$, $MS_e=.001$, $p<.005$]. Planned t-tests revealed that these differences were due to worse performance for Forget probes compared to Control probes (Table 1, $t(15)=8.08$ for RT, $t(15)=3.08$ for error rate). These results establish robust effects of PI.

SSRT did not vary as a function of probe type [$F(2,30)=.546$, $MS_e=458.57$, $p>.5$; Figure 2]. A planned t-test comparing SSRT on Forget probes to SSRT on Control probes revealed no difference ($t(15)=0.089$, $p>0.93$). 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 PI 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 versus Control probes). This analysis yielded a reliability of .319 (adjusted correlation with Spearman-Brown prophecy formula to mirror the procedure used by Friedman & Miyake, 2004: .484), demonstrating that the directed-forgetting task was considerably more reliable than previous measures of resistance to PI.³

Discussion

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

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

To ensure that the lack of an interaction between prepotent response inhibition and resistance to PI 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 upon 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 upon both response selection and response execution (i.e. prepotent response inhibition). The combination of these two tasks also allowed us to examine the separability of different response level processes.

Experiment 2

In addition to the stop-signal task, prepotent response inhibition is often measured using the go/no-go task that requires subjects to respond to a stream of stimuli but withhold a response to a particular target stimulus (Donders, 1868). 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 to 1) affirm that different measures of prepotent response inhibition interact and 2) 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 & Logan (in press) reveal that when subjects prepare to stop 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 to a stop signal. So, this work 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 upon different stages of response production, or whether they have been due to the known interaction between stimulus conflict and prepotent 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 (5 male, mean age 21) were recruited from the Ann Arbor area and were compensated \$50 plus a performance bonus awarded for accuracy and reaction time on AY, BY, and BX signal-absent trials, and accurately 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 two months. One subject 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 0.5s, followed by a delay that varied between 0.5s and 1.5s (equally distributed among discrete values of .5s, 1s, and 1.5s). Thereafter, subjects were presented with a target letter for 1s. 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 pseudo-randomized such that 40% of trials were AX trials, 20% were A followed by any non-X (AY trials), 20% were non-A followed by X (BX trials), and 20% were non-A followed by non-X (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-CPT paradigm (Barch et al., 1997; Cohen, Braver, & O’Reilly, 1996) uses RT as the main dependent measure, allowing 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 subject. The staircase procedure for varying stop-signal delay and the calculation of SSRTs proceeded in the same manner as Experiment 1, except that the stop-signal delay was initially set to 250ms recognizing 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 had 20 practice trials under supervision by 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, since 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 must respond, despite the fact that an “X” often indicates a non-response 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 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

Mean reaction times were computed only for correct signal-absent trials. 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, and error rate on signal-present trials, with trial-type as a factor. Where sphericity cannot be assumed, the Huynh-Feldt correction was used. 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 [$F(2,30)=20.66$, $MS_e=978.07$, $p<.001$] and error rate on signal-absent trials [$F(2,30)=6.15$, $MS_e=.0002$, $p<.01$]. Planned t-tests demonstrated that subjects were significantly slower on AY trials compared to BY trials ($t(15)=5.73$, $p<0.001$), revealing a robust effect of prepotent response inhibition. These trials did not differ in error rate ($t(15)=0.78$, $p>0.4$). To determine the reliability of our 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 and more error prone on BX trials compared to BY trials ($t(15)=6.43$, $p<0.001$ for RT, $t(15)=3.59$, $p<0.005$ 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 [$F(2,30)=12.08$, $MS_e=1582.77$, $p<.001$]. A planned t-test revealed that SSRT on AY trials was longer than SSRT on BY trials ($t(15)=3.91$, $p<0.005$), 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 ($t(15)=1.18, p>0.25$), suggesting independence between control processes acting upon 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 separability of control processes acting upon different levels of response production. As expected, we demonstrated a strong interaction between different measures of prepotent response inhibition, validating that the lack of interaction between PI 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 to 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 PI, prepotent response inhibition, and response selection are dissociable. Whereas different measures of response inhibition interacted, prepotent response inhibition did not interact with PI, suggesting that prepotent response inhibition and resistance to PI 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 PI is dissociable from other forms of interference control. Using confirmatory factor analysis, Friedman and Miyake (2004) demonstrated that prepotent response inhibition and resistance to PI are distinct inhibitory functions. Using event-related fMRI, Nelson, Reuter-Lorenz, Sylvester, Jonides, & Smith, (2003) examined the neural correlates of PI and response conflict. These authors discovered that whereas the left inferior frontal gyrus was involved in the resolution of PI, the anterior cingulate was uniquely involved in response conflict. Nee and Jonides (in press) 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 PI (the recent probes task and 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 non-specific buildup of PI (Postle & Brush, 2004), as well as PI in the AB-AC-AD paradigm (Henson, Shallice, Josephs, & Dolan, 2001). Therefore, whereas a variety of different tasks and forms of PI share a close relation, resistance to PI 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 their separability. 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 and colleagues (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 dissociable process from prepotent response inhibition.

Neural work has also suggested that prepotent response inhibition and response selection conflict may have somewhat distinct neural loci. Rubia and colleagues (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 et al., 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 non-target stimuli (flankers), but orient to other non-target 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 are differentiable 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, Merckelbach, & Horselenberg, 1996; Wegner & Zanakos, 1994), and successful suppression of intrusive, unwanted thoughts requires resistance to PI. In addition, children with ADHD, but not anxious children, show impaired response inhibition (Oosterlaan, Logan, & Sergeant, 1998). The separability between resistance to PI 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 targeted narrowly at 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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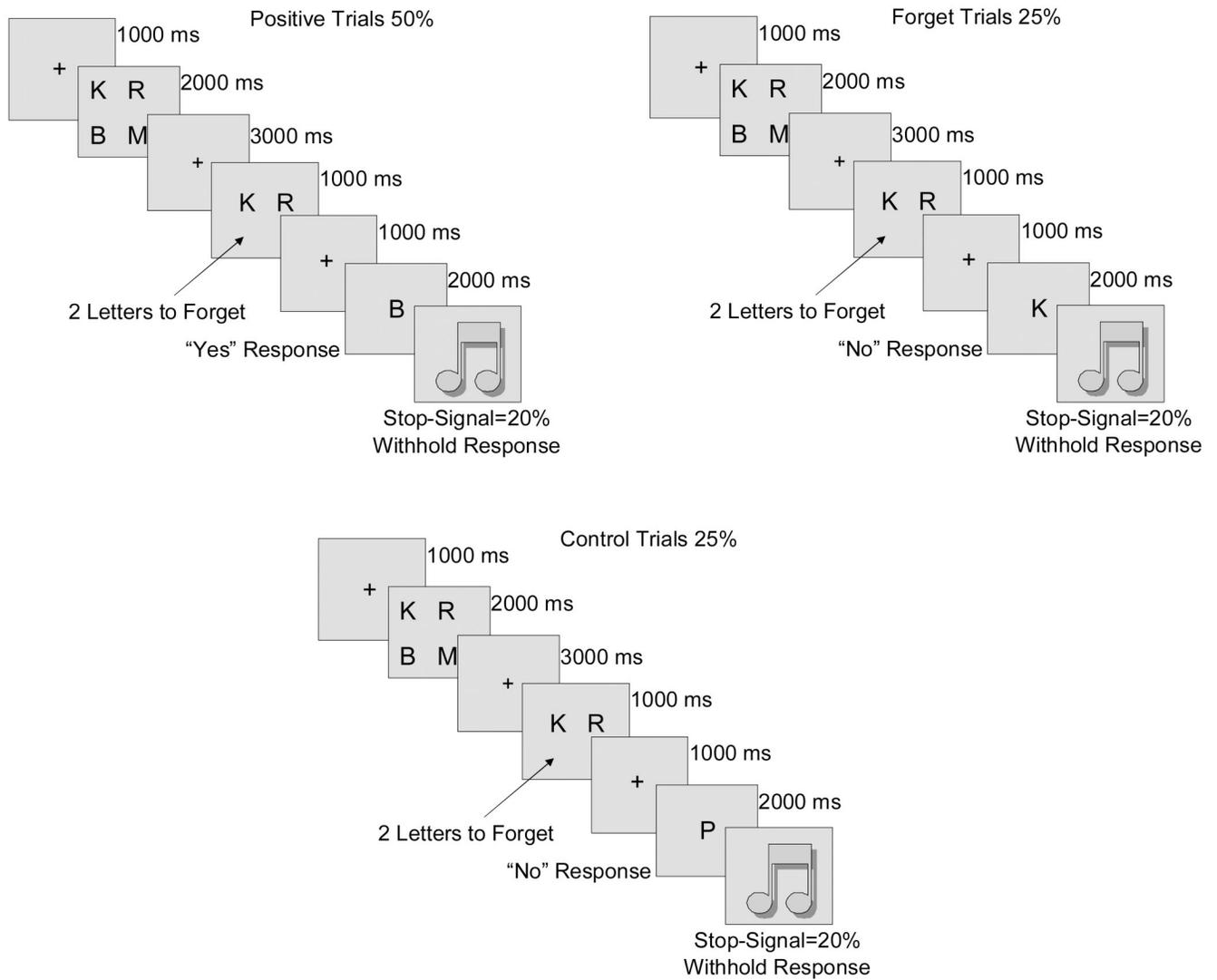


Figure 1. Schematic of the 3 probe-types in Experiment 1. Presentation duration is in the upper-right corner of each slide in milliseconds.

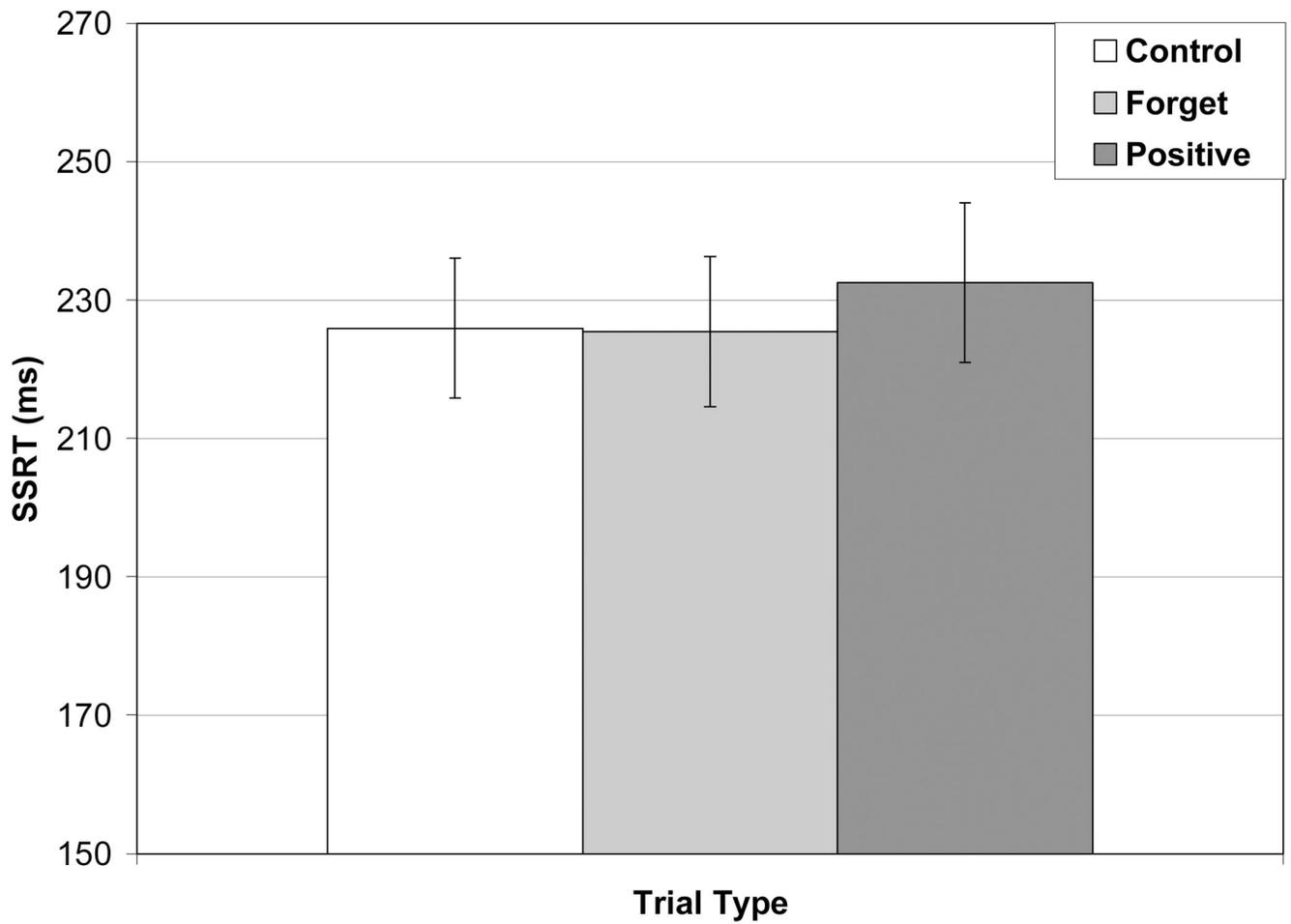


Figure 2. Stop-signal reaction times for 3 probe-types in Experiment 1. Error bars denote one standard error of the mean.

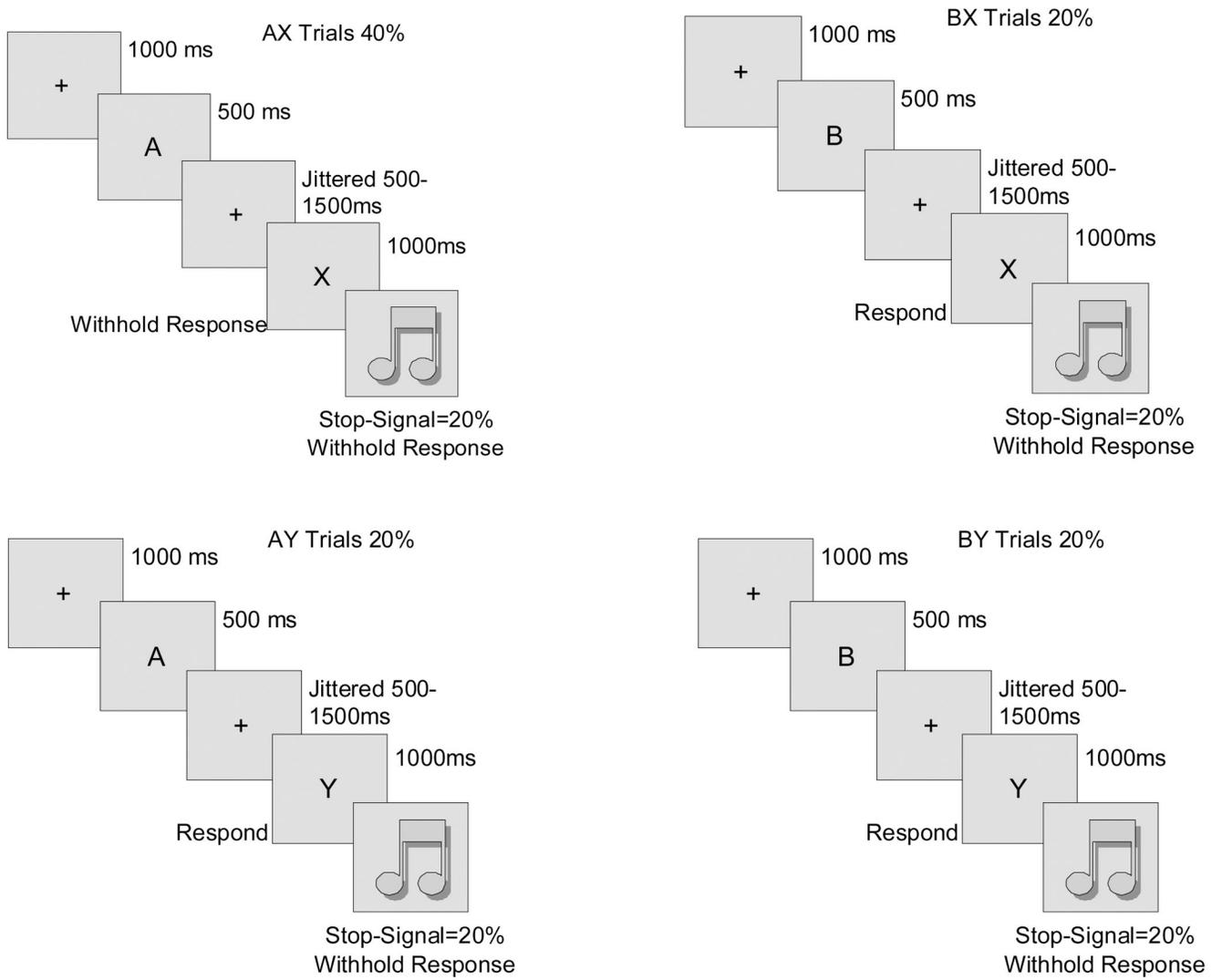


Figure 3. Schematic of the 4 trial-types within Experiment 2. B denotes a non-A first letter, and Y denotes a non-X second letter. Presentation duration is in the upper-right corner of each slide in milliseconds.

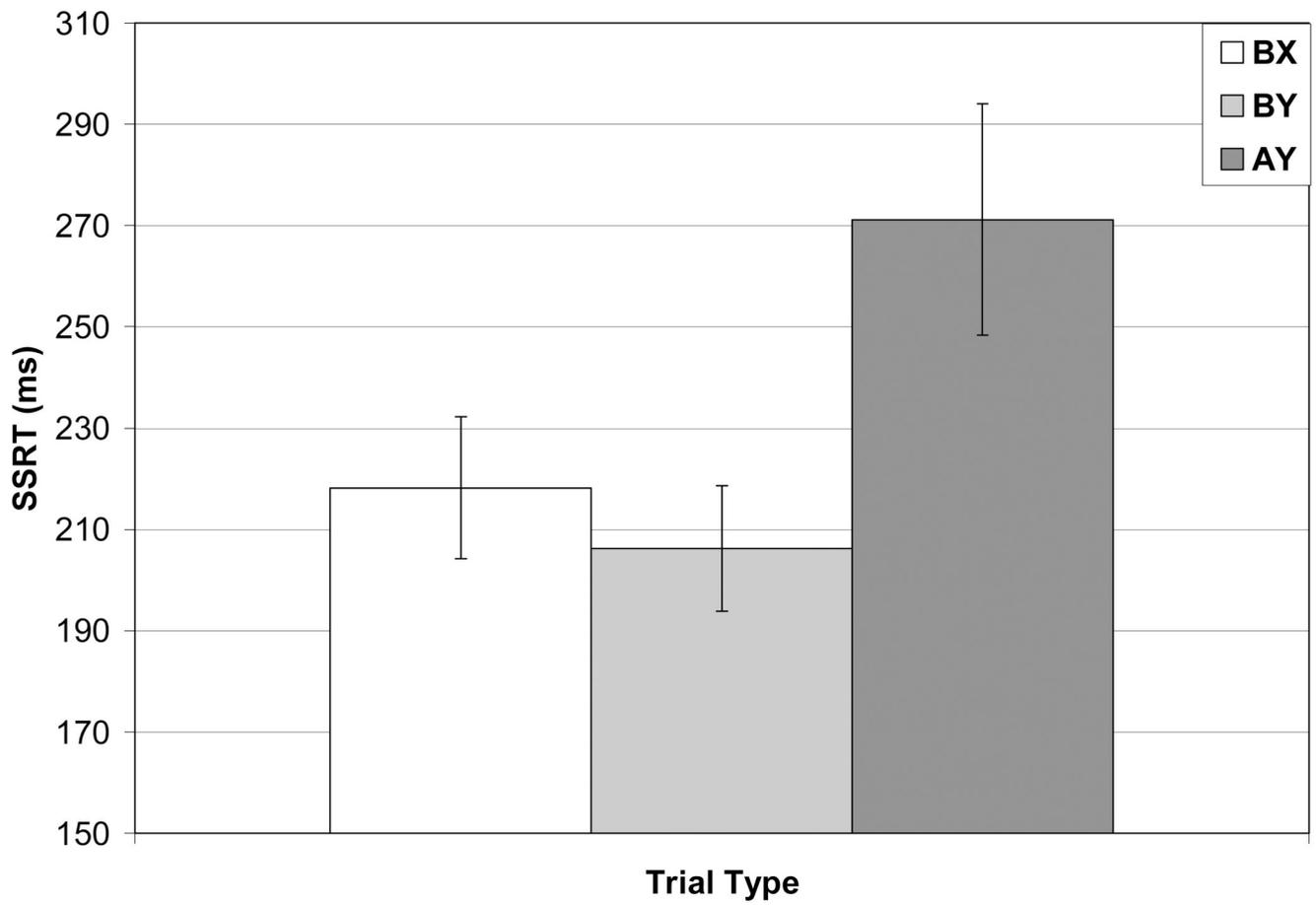


Figure 4. Stop-signal reaction times for the 3 overt response conditions in Experiment 2. Error bars denote one standard error of the mean.

Table 1

Experiment 1 Data

Control Measure	Control		Forget		Positive		Forget vs.	
	Mean	Mean	Mean	Mean	t-statistic	p-value	t-statistic	p-value
RT	541.76	577.90	503.35	8.08		p<.001		
Error Rate	2.12%	5.75%	5.12%	3.08		p<.01		
SSRT	225.92	225.39	232.49	0.089		p>.9		

Note. RT = reaction time, SSRT = stop-signal reaction time

Table 2

Experiment 2 Data

Measure	AX		AY		BX		BY		AY vs BY		BX vs BY	
	Mean	p-value	Mean	p-value	Mean	p-value	Mean	p-value	t-statistic	p-value	t-statistic	p-value
RT	N/A		585.36		559.86		524.74		5.73		6.43	
p<.001												
Error Rate	3.6%		3.1%		8.2%		2.6%		0.78		5.13	
p<.001												
SSRT	N/A		271.22		218.22		206.27		3.911		1.18	
p>.25												

Note. RT = reaction time, SSRT = stop-signal reaction time