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Examining the costs and benefits of inhibition in memory retrieval

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ABSTRACT

Inhibitory control is thought to serve an adaptive function in controlling behavior, with individual differences predicting variation in numerous cognitive functions. However, inhibition is more properly construed as inducing both benefits and costs to performance. Benefits arise at the point when inhibition prevents expression of an unwanted or contextually inappropriate response; costs arise later, when access to the inhibited representation is required by other processes. Here we illustrate how failure to consider both the costs and benefits of inhibition has generated confusion in the literature on individual differences in cognitive control. Using retrieval-induced forgetting as a model case, we illustrate this by showing that changing the way that retrieval-induced forgetting is measured to allow greater expression of the benefits of inhibition together with the costs can reduce and even reverse the theoretically predicted correlation between motor and memory inhibition. Specifically, we show that when the final test in a retrieval-induced forgetting procedure employs item-specific cues (i.e., category-plus-stem cued recall and item-recognition) that better isolate the lingering costs of inhibition, better motor response inhibition (faster stop-signal reaction times) predicts greater retrieval-induced forgetting. In striking contrast, when the final test is less well controlled, allowing both the costs and benefits of inhibition to contribute, motor response inhibition has the opposite relationship with retrieval-induced forgetting. These findings underscore the importance of considering the correlated costs and benefits problem when studying individual differences in inhibitory control. More generally, they suggest that a shared inhibition mechanism may underlie people's ability to control memories and actions.

1. Introduction

Inhibitory processes are widely considered to be important in the goal-directed control of thought and behavior (e.g., Anderson, 2003; Aron, Robbins, & Poldrack, 2004; Bjork, 1989; Dempster & Brainerd, 1995; Diamond, Balvin, & Diamond, 1963; Friedman & Miyake, 2004; Logan & Cowan, 1984; Munakata et al., 2011; Ridderinkhof, van der Wildenberg, Segalowitz, & Carter, 2004; Smith, 1992). Broadly, the ability to stop unwanted processes via inhibitory control is thought to enable people to suppress reflexive actions, and to behave, think, and remember in a more flexible and context-appropriate manner. Indeed, inhibitory control is viewed as a basic process contributing to general intelligence (e.g., Dempster, 1991). In contrast, individuals with putative inhibition deficits are prone to problems with attention, impulsivity,

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substance abuse, anxiety, and depression (e.g., Disner, Beevers, Haigh, & Beck, 2011; Groman, James, & Jentsch, 2009; Jentsch & Taylor, 1999; Li & Sinha, 2008; Nigg, 2001; Young et al., 2009). Given the range of populations thought to be affected by inhibition deficits, and the broad array of contexts in which inhibition is thought to operate, it is critical to have cognitive measures of this theoretical construct that allow us to properly test theoretical models. In this article, we examine a general problem in the measurement of inhibitory control—the correlated costs and benefits problem (Anderson & Levy, 2007)—and illustrate how failure to address this problem holds the potential to create theoretical confusion in testing predictions about the role of inhibitory control deficits in a given cognitive function. We illustrate this problem in the context of long-term memory retrieval, though the lessons learned apply more broadly.

Research on long-term memory retrieval suggests that the inhibition process underlying behavioral control may also underlie the control of memory (Anderson, 2003; Levy & Anderson, 2008). According to this proposal, retrieval often requires that people override pre-potent memories in much the same way that they stop overt responses, a process thought to be supported by inhibition suppressing the accessibility of competing memory traces. To isolate this process, research on retrieval-induced forgetting employs variations of the retrieval-practice paradigm (Anderson, Bjork, & Bjork, 1994) in which participants are exposed to category-exemplar pairs (e.g., metal-iron; tree-birch; metal-copper) and then receive retrieval practice for half of the exemplars from half of the categories (e.g. metal-ir for iron; but neither copper nor birch would be practiced). This procedure creates three types of items: Items receiving retrieval practice (i.e., Rp+ items; iron), items associated to the same cues as practiced items but not practiced themselves (i.e., Rp− items; copper), and unrelated baseline items (i.e., Nrp items; birch). On a later test given after retrieval practice, participants typically recall Rp+ items best and Rp− items worst. Retrieval-induced forgetting is observed as reduced recall of Rp− items compared to Nrp items, and has proven to be a remarkably robust and general phenomenon (for reviews, see Anderson, 2003; Storm & Levy, 2012; Verde, 2012).

The impaired recall of Rp− items on the final test of the retrieval-practice paradigm is consistent with the involvement of an inhibitory process acting during retrieval practice (e.g., Anderson, 2003; Bäuml, Pastötter, & Hanslmayr, 2010; Román, Soriano, Gómez-Ariza, & Bajo, 2009; Storm & Levy, 2012). By this view, cues presented during retrieval practice activate both target and non-target exemplars, and to facilitate selective access to the target items, the non-target competitors must be inhibited. The persisting aftereffects of inhibition are thought to render competitors less recallable on the final test. Alternatively, impaired recall of Rp− items may reflect increased interference from strengthened Rp+ items occurring at the time of final test (Anderson & Spellman, 1995; Anderson et al., 1994; Raaijmakers & Jakab, 2013; Verde, 2012). Although this form of blocking, caused by increased competition, likely contributes to retrieval-induced forgetting in certain circumstances (for a review, see Anderson, 2003), a large body of cognitive and neural evidence supports a central role for inhibitory control (e.g., Anderson, Bjork, & Bjork, 2000; Anderson, Green, & McCulloch, 2000; Anderson & Spellman, 1995; Aslan & Bäuml, 2011; Bäuml, 2002; Ciranni & Shimamura, 1999; Hellerstedt & Johansson, 2013; Kuhl, Dudukovic, Kahn, & Wagner, 2007; Levy, McVeigh, Marful, & Anderson, 2007; Román et al., 2009; Staudigl, Hanslmayr, & Bäuml, 2010; Storm & Angello, 2010; Storm, Bjork, & Bjork, 2007; Storm, Bjork, Bjork, & Nestojko, 2006; Waldhauser, Johansson, & Hanslmayr, 2012; Wimber et al., 2011; for a recent progress report on the inhibitory account, see Storm & Levy, 2012).

1.1. The costs and benefits of inhibitory control

If inhibition helps a person to overcome competition during retrieval, then the advantages bestowed by this process should be observed whenever there is competition to be overcome. In the context of the retrieval-practice paradigm, this straightforward principle implies that inhibition can have both costs and benefits for the eventual recall of Rp− items. To see why both costs and benefits can arise, we need to consider both the retrieval practice and final test phases of the procedure. During retrieval practice, inhibitory control is thought to inhibit competing Rp− items, rendering them less recallable. Thus, during retrieval practice, inhibition disrupts Rp− items, yielding a later *cost* to Rp− item performance on the final test. During the final test, however, engaging inhibitory control may enhance participants' ability to recall Rp− items because it helps to overcome retrieval competition from the strengthened Rp+ items. In particular, if inhibition serves to suppress stronger competitors, then any Rp− items that were not inhibited during the earlier retrieval practice phase—but that stand the risk of being forgotten due to competition from Rp+ items at test—ought to have a greater chance of being recalled. This *benefit* of inhibitory control at test should arise only when the final test that is used elicits competition from Rp+ items that could in turn contribute to the forgetting effect observed.

One very important prediction of this analysis (see Anderson & Levy, 2007, for a detailed discussion) is that the relative contributions of the costs and benefits of inhibitory control to the amount of retrieval-induced forgetting observed should vary depending on the type of final test used to measure retrieval-induced forgetting. Take, for example, two final tests that have been used extensively in the literature: category-cued recall and category-plus-stem-cued recall. In category-cued recall, participants receive category cues and are asked to recall all studied items associated with those cues, including both the practiced and non-practiced items. In category-plus-stem-cued recall, however, participants receive item-specific cues (e.g., tree: b) and are asked to recall the particular items associated with those cues. This latter test provides item-specific information that, when combined with the category cue, can uniquely identify the target item on the study list. Because participants search memory with this conjoint cue, the interference suffered from non-target exemplars that do not match those cues should be reduced. Indeed, this is part of the reason why performance often improves when multiple cues are provided (e.g., Dosher & Rosedale, 1997; Massaro, Weldon, & Kitzis, 1991; Rubin & Wallace, 1989; Tulving, Mandler, & Baumal, 1964; Weldon & Massaro, 1996). Adding item-specific stem cues, therefore, should reduce (though not eliminate) blocking from Rp+ items during the retrieval of Rp− items at final test. If the blocking component is reduced on a category-plus-stem-cued recall test (relative to a category-cued test), then a greater proportion of the measured retrieval-induced forgetting effect should be due to the persisting aftereffects of inhibition.

The costs and benefits analysis outlined above makes specific predictions about how individual differences in inhibitory control should relate to retrieval-induced forgetting. Specifically, whether superior inhibitory control is associated with higher levels of retrieval-induced forgetting should depend on how effectively the final test format used to measure forgetting eliminates blocking. Consider a category-plus-stem-cued recall test in which retrieval success for Rp− items is less influenced by blocking. On such a test, the inhibition component of retrieval-induced forgetting should be preserved. If so, this test should reveal a clear positive relationship between inhibitory control ability and the amount of retrieval-induced forgetting that is observed. In contrast, when a category-cued recall test is employed, forgetting of Rp− items should be driven in part by inhibition, and in part by blocking at test. Like the category-plus-stem-cued recall test, the component of retrieval-induced forgetting due to inhibition should be positively related to inhibitory control ability. The additional blocking component of retrieval-induced forgetting on such tests, however, should be negatively related to inhibition ability because blocking reflects a failure to deploy inhibition to overcome interference at test. Thus, inhibitory control ability should predict an increasing cost (more retrieval-induced forgetting due to inhibition), but also an increasing benefit (less retrieval-induced forgetting due to blocking). Because these costs and benefits are assumed to be correlated intrinsically with one another, being influenced by a common underlying inhibition process, the overall relationship between inhibitory ability and retrieval-induced forgetting should be muddied. Consequently, the correlation between inhibitory control ability and retrieval-induced forgetting should be stronger when retrieval-induced forgetting is measured using category-plus-stem cues at final test than when measured using category cues alone.

These dynamics are illustrated in Fig. 1, which depicts a hypothetical function relating inhibitory control ability to the two hypothesized components of retrieval-induced forgetting, separately for the two types of test (adapted from Anderson & Levy, 2007). In both the top and bottom panels the amount of retrieval-induced forgetting attributable to the persisting aftereffects of inhibition increases monotonically with increasing inhibitory control ability. Thus, for simplicity, we assume that regardless of the nature of the final test, the amount of retrieval-induced forgetting caused by the aftereffects of inhibition from the earlier retrieval practice phase remains the same. However, the two panels differ in the amount of retrieval-induced forgetting attributable to blocking at final test, with greater blocking arising on a category-cued final test than on a category-plus-stem final test, with this difference growing as inhibitory control ability weakens. This reflects our assumption that searching memory with a distinctive compound cue should greatly reduce competition, and focus search.

Crucially, because we assume both components may contribute to the observed retrieval-induced forgetting effect to varying degrees, the relationship between inhibitory control ability and overall forgetting should vary substantially by test type. Because persisting inhibition and blocking are oppositely related to inhibitory control ability, the contribution of blocking at test, when combined with the aftereffects of inhibition, should dilute the relationship between inhibition ability and forgetting. Specifically, the stronger the blocking component at test, the weaker the observed relationship between retrieval-induced forgetting and inhibition ability should become. For example, the correlation should be more strongly positive in the category-plus-stem condition than in the category-cued condition. Indeed, if the contribution of blocking to category-cued recall is great enough—as in the hypothetical example—then retrieval-induced forgetting may be unrelated or even negatively related to inhibitory control ability.

Storm and White (2010) tested this prediction in a recent study by examining retrieval-induced forgetting in college students diagnosed with Attention Deficit Hyperactivity Disorder (ADHD), a disorder characterized by deficits in inhibition (Barkley, 1997; Nigg, 2001). When a category-cued final test was employed, individuals with ADHD exhibited the same amount of retrieval-induced forgetting as did individuals without ADHD. When a category-plus-stem final test was employed, however, individuals with ADHD exhibited significantly less retrieval-induced forgetting than did individuals without ADHD. In fact, individuals with ADHD failed to exhibit any evidence of retrieval-induced forgetting on the category-plus-stem final test, consistent with the proposal that the test provides a better estimate of the costs of inhibitory control. This prediction was also tested in research on inhibition deficits in schizophrenia and in development. Tests of the correlated costs and benefits account revealed that both young children (Aslan & Bäuml, 2010) and schizophrenics (Soriano, Jiménez, Román, & Bajo, 2009) show significant retrieval-induced forgetting on category-cued recall tests, even though they show significantly impaired retrieval-induced forgetting on tests involving item specific cuing (i.e., an item-recognition final test in which participants must determine whether exemplars had been previously studied). Taken together, these findings indicate that controlling for the benefits of inhibition at test may reveal theoretically important relationships between retrieval-induced forgetting and inhibitory control ability.

1.2. Goals of the present study

Although the findings concerning ADHD, schizophrenia, and development confirm important predictions of the correlated costs and benefits framework, a stronger and more direct test would seek to (a) relate retrieval-induced forgetting to an independent measure of inhibition ability,

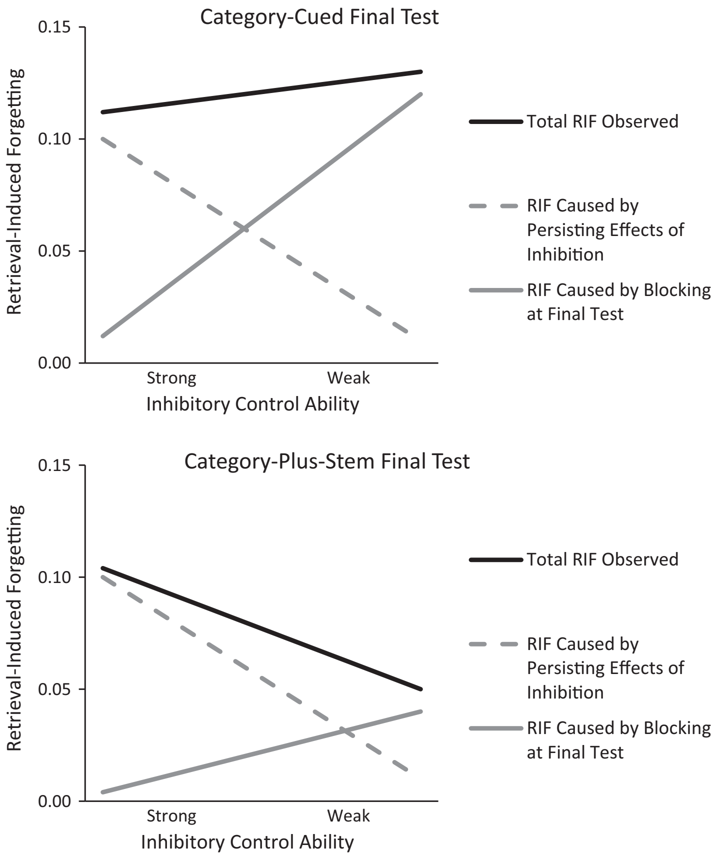

Fig. 1. Hypothesized amount of retrieval-induced forgetting as a function of inhibitory control ability and type of final test. The top panel shows hypothetical performance on a category-cued final test. The bottom panel shows hypothetical performance on a category-plus-stem final test. The dashed gray lines show the amount of retrieval-induced forgetting caused by the persisting consequences of inhibition during retrieval practice. For simplicity, this relationship is assumed to be linear, with increases in inhibitory control ability leading to equivalent increases in retrieval-induced forgetting. Importantly, the slope of this relationship is assumed to be the same in both final test conditions, as would be expected because the nature of the final test should not influence the amount of retrieval-induced forgetting caused by the aftereffects of inhibition during retrieval practice. The solid gray lines show the amount of retrieval-induced forgetting caused by blocking at final test. This relationship is again assumed to be linear, but with the slope of the relationship varying across the two final tests. In the category-plus-stem condition, decreases in inhibitory control ability are shown to lead to relatively small increases in retrieval-induced forgetting caused by blocking. In the category-cued condition, however, decreases in inhibitory control ability are shown to lead to much larger increases in retrieval-induced forgetting caused by blocking. The solid back lines show the total amount of retrieval-induced forgetting observed, calculated by summing the dashed and solid gray lines. Although the specific parameters are likely to vary, owing to differences in susceptibility to blocking at final test, the relationship between retrieval-induced forgetting and inhibitory control ability is predicted to be more positive in the category-plus-stem condition than in the category-cued condition.

and (b) show that this relationship varies by test type in the expected manner. Towards that end, the present study had two goals. First, we tested the relationship between retrieval-induced forgetting and performance on an established measure of inhibitory control: stop-signal reaction time (SSRT; Logan & Cowan, 1984). If retrieval-induced forgetting truly is the consequence of an inhibitory process that suppresses inappropriate responses, then measures of response inhibition, such as SSRT, should predict this form of forgetting. Briefly, in the typical stop-signal task, participants are asked to respond as quickly as possible to each stimulus they see, except on a minority of trials, in which they hear a tone, signaling them to withhold their response. By measuring participants' ability to stop their response (as reflected by their SSRT, to be explained in Methods), the stop-signal task has proven to be a robust and reliable measure of inhibitory control. For example, young children (e.g., Williams, Ponesse, Schachar, Logan, & Tannock, 1999), older adults (Kramer, Humphrey, Larish, Logan, & Strayer, 1994), impulsive individuals (Logan, Schachar, & Tannock, 1997), and children with ADHD (e.g., Schachar & Logan, 1990), all of whom are believed to suffer inhibitory deficits, exhibit slower SSRTs. Moreover, faster SSRTs predict greater levels of performance on the Flanker and Stroop tasks (Verbruggen, Liefooghe, & Vandierendonck, 2004), as well as negative control effects in the think-no-think paradigm (Depue, Burgess, Willcutt, Ruzic, & Banich, 2010). If retrieval-induced forgetting shares an inhibition mechanism with motor response inhibition, we should find that increases in forgetting are related to faster SSRTs. Thus, to test this prediction, we had participants perform both a retrieval-induced forgetting task and a stop-signal motor inhibition task.

Second, we examined how the nature of the relationship between SSRT and retrieval-induced forgetting varied as a function of the type of test used to measure retrieval-induced forgetting. In Experiment 1, half of the participants were given a category-cued final test, whereas the other half was given a category-plus-stem-cued final test. In Experiment 2, participants were given an item-recognition final test. In consideration of the dynamics discussed above, we predicted that better response inhibition ability on the stop-signal task (i.e., faster SSRTs) would predict increases in retrieval-induced forgetting when retrieval-induced forgetting was measured using the category-plus-stem and item-recognition final tests (in which blocking is better controlled), but that the ability of SSRT to predict retrieval-induced forgetting would suffer significantly when retrieval-induced forgetting was measured using the category-cued recall final test (in which blocking is not adequately controlled).

2. Experiment 1

2.1. Method

2.1.1. Participants

A total of 132 undergraduate students at the University of Illinois at Chicago participated for partial credit in an introductory psychology course.

2.1.2. Measuring retrieval-induced forgetting

The retrieval-practice paradigm, which was administered first, consisted of three phases: study, retrieval practice, and final test. Participants studied 64 category-exemplar pairs, received retrieval practice for half of the exemplars from half of the categories, and were finally tested on each of the 64 category-exemplar pairs. Based on random assignment, half of the participants were given a category-cued final test, whereas the other half was given a category-plus-stem-cued final test.

2.1.2.1. Study. The study list consisted of 64 category-exemplar pairs of medium taxonomic frequency (i.e., the exemplars' *M* rank order was 4.5 within their respective categories, Battig & Montague, 1969). The study list was arranged in blocks of eight items, one from each category, randomly ordered. Each pair appeared individually on the computer screen for 3 s and participants were instructed to try to remember the pairs and to study them by considering the relationship between the exemplar and its category.

2.1.2.2. Retrieval practice. Four subsets of 16 items were created, with each subset consisting of four exemplars from each of four categories. Participants performed retrieval practice on one of these subsets, thus creating three types of items: Practiced exemplars (Rp+ items), non-practiced exemplars from practiced categories (Rp− items), and exemplars from non-practiced categories (Nrp items). The particular subset practiced was counterbalanced across participants. During retrieval practice, which took place immediately following the study phase, participants received category-plus-two-letter-stem retrieval cues (e.g., fruit-ba) for each of the 16 to-be-practiced exemplars, and were given 5 s to say each response out loud for the experimenter to record. The order of items in the retrieval-practice task was determined via blocked randomization with each block of four items consisting of one cue from each of the four practiced categories. There were three rounds of retrieval practice, each consisting of the same cues presented in a new block-randomized order.

2.1.2.3. Final test. The final test immediately followed retrieval practice. One test was constructed for the category-cued condition in which the eight category labels appeared in a randomized order. Owing to the counterbalancing of categories receiving retrieval practice, the test position of the Rp and Nrp categories was equated across participants. The only constraint on the randomized order of the test was that no more than two Rp or Nrp categories were presented consecutively. For each category cue, participants were given 40 s to recall the studied exemplars. Retrieval-induced forgetting was calculated by subtracting the final-recall performance of Rp− items from that of Nrp items. The benefit of retrieval practice (or the practice effect) was calculated by subtracting the final-recall performance of Nrp items from that of Rp+ items.

Participants in the category-plus-one-letter-stem final-test condition were shown each cue (e.g. METAL – i for *iron*) for 5 s and asked to recall the associated exemplar. The order of the cues was determined via blocked randomization, with one exemplar from each category being tested in each round of eight trials. Owing to the counterbalancing of categories receiving retrieval practice, the test position of the Rp and Nrp items was equated across participants. Two versions of the final test were created to ensure that participants were cued to recall Rp− items (and half of the Nrp items) prior to being cued to recall Rp+ items (and the other half of the Nrp items). Thus, the first 32 test items always consisted of non-practiced exemplars from practiced categories (Rp− items) and half of the exemplars from non-practiced categories (referred to as Nrp− items), and the final 32 test items always consisted of practiced exemplars (Rp+ items) and the other half of the exemplars from non-practiced categories (referred to as Nrp+ items). The particular set of Nrp items serving as Nrp− vs. Nrp+ was counterbalanced. Retrieval-induced forgetting was calculated by subtracting the final-recall performance of Rp− items from that of Nrp− items. The benefit of retrieval practice (or the practice effect) was calculated by subtracting the final-recall performance of Nrp+ items from that of Rp+ items.

2.1.3. Measuring stop-signal performance

The stop-signal task (i.e., STOP-IT; Verbruggen, Logan, & Stevens, 2008) was administered to measure response inhibition. An initial practice session of 32 trials was followed by an experimental phase of four blocks of 64 trials. Each trial began with a 250 ms fixation cross, followed by a circle or square. Participants were asked to press a corresponding "circle" or "square" key, as appropriate.

After the participant responded, or 1250 ms had elapsed, the shape disappeared, followed by a 2 s inter-trial interval. A 10 s interval separated blocks.

Participants were urged to respond as quickly as possible on all trials. However, on 25% of the trials a stop-signal tone (750 Hz, 75 ms) sounded shortly after the shape appeared indicating that participants should withhold their response. At the beginning of the session, the stop signal was delivered at a 250 ms delay after the shape appeared. This stop-signal delay (SSD) was adjusted across trials using an adaptive tracking procedure. When a response was withheld correctly on a stop-signal trial the SSD increased by 50 ms, making it more difficult to withhold their response on the next stop trial; upon failing to withhold their response on a stop trial the SSD decreased by 50 ms, making it easier to withhold their response.

The critical measure in the stop-signal task is stop-signal reaction time (SSRT), which estimates the time it takes to stop an ongoing response. A participant's SSRT is calculated by subtracting their mean SSD from their mean RT on go trials. A fast SSRT indicates that participants can stop their response quickly, whereas a slow SSRT indicates that participants need additional time to stop.

Because of the way in which the STOP-IT program is designed, valid estimates of SSRT can only be obtained when a subject successfully withholds their response on approximately half of the stop-signal trials (Verbruggen et al., 2008). Although the program was designed to ensure that subjects succeed on approximately 50% of the trials by dynamically adjusting the SSD in response to each subject's performance, nine subjects deviated significantly from the 50% criterion, thus precluding valid estimates of SSRT (the criterion range was predetermined by recommendations from Verbruggen et al., 2008). Most of these subjects did not follow the STOP-IT instructions, waiting for the stop signal to sound instead of responding as quickly as possible on each trial. Fortunately, three of these subjects successfully completed STOP-IT in an unrelated experiment, so we were able to use the SSRTs from that study. The remaining six participants, however, had to be excluded. One further subject was removed because they had trouble understanding the STOP-IT task and because their SSRT was 3.4 SDs from the mean. Altogether, data from 125 of the 132 subjects were included.

2.2. Results and discussion

2.2.1. Retrieval-practice performance

Participants retrieved 81% ($SD = 14\%$) of the exemplars during retrieval practice and this did not vary significantly between the category-cued and category-plus-stem-cued conditions, $t < 1$.

2.2.2. Practice effects

The effect of retrieval practice was analyzed using a 2 (Item type: Rp+ vs. Nrp) × 2 (Test type: category-cued vs. category-plus-stem-cued) Analysis of Variance (ANOVA). We observed a significant main effect of item type such that Rp+ items ($M = 64.4\%$, $SE = 1.6\%$) were better recalled than Nrp items ($M = 36.4\%$, $SE = 1.2\%$), $F(1, 123) = 294.71$, $MSE = .02$, $p < .001$, replicating the benefits of retrieval practice (e.g., Bjork, 1975; Roediger & Karpicke, 2006). Importantly, as shown in Table 1, participants in the category-cued and stem-cued conditions showed similar practice benefits (interaction of practice effect with group, $F < 1$).

2.2.3. Retrieval-induced forgetting

Retrieval-induced forgetting was analyzed using a 2 (Item type: Rp− vs. Nrp) × 2 (Test type: category-cued vs. stem-cued) ANOVA. The results confirmed a significant main effect of item type such that Rp− items ($M = 31.9\%$, $SE = 1.3\%$) were recalled less well than Nrp items ($M = 42.0\%$, $SE = 1.2\%$), $F(1, 123) = 61.19$, $MSE = .01$, $p < .001$. The interaction between item type and test type was not significant, $F(1, 123) = 3.54$, $MSE = .01$, $p = .11$. As shown in Table 1, although significant retrieval-induced forgetting was observed in both conditions (p values < .001), the effect was numerically larger in the category-cued condition than it was in the stem-cued condition, a tendency that has been generally observed in the literature.

Because our central goal was to evaluate the correlation between retrieval-induced forgetting and SSRT, we quantified the amount of retrieval-induced forgetting observed for each individual participant. One problem, however, is that different participants received different items in the Rp− and Nrp conditions. Because item sets may differ in their intrinsic memorability, a raw difference score (Nrp–Rp−) is likely to reflect both the effect of inhibition and also a contribution of differences in intrinsic memorability across Nrp and Rp− sets. To account for this problem, we z-normalized each participant's retrieval-induced forgetting score (hereinafter referred to as RIF-z) relative to the mean and standard deviation of all other participants in their matched counterbalancing condition. Thus, this RIF-z score expresses how unusual (either in the positive or negative direction, relative to the mean of that counterbalancing group) a given score is in a group of subjects who received the same items in Rp− and Nrp conditions. This therefore accounts for item differences while facilitating comparison across all counterbalancing groups. We did this separately for each testing condition.

The univariate distributions of RIF-z scores were examined within each of the test conditions. Measures of skewness (category-cued: .10, $SE = .30$; category-plus-stem: −.10, $SE = .31$) and kurtosis (category-cued: −.51, $SE = .59$; category-plus-stem: −.43, $SE = .61$) were neither significant not remarkably different between the two distributions.

2.2.4. Stop-signal reaction time

Stop-signal reaction time scores (SSRTs) were estimated for each participant using the ANALYZE-IT software provided by Verbruggen et al. (2008). The mean stop-signal delay was calculated and then subtracted from the mean untrimmed response time for all go trials. The overall mean SSRT was 273 ms ($SD = 37$ ms), and SSRTs in the category-cued ($M = 271$ ms, $SD = 38$ ms) and category-plus-stem ($M = 275$ ms, $SD = 35$ ms) conditions did not differ, $t < 1$. Further analysis of the distribution of SSRT scores failed to observe significant skew (category-plus-stem: .23,

Table 1
Recall performance (with standard errors) and Cohen's d effect sizes as a function of final test condition.

Test condition	Practice effects			RIF		
	Rp+	Nrp(+)	*d*	Rp−	Nrp(−)	*d*
Category-cued	.68 (.02)	.39 (.02)	1.50	.27 (.02)	.39 (.02)	.92
Category-plus-stem	.61 (.02)	.33 (.02)	1.58	.37 (.02)	.45 (.02)	.52

SE = .31; category-cued: .01, SE = .30) or kurtosis (category-plus-stem: −.04, SE = .61; category-cued: −.20, SE = .59) in either condition.

To examine our hypothesis about the role of inhibitory control in retrieval-induced forgetting, we first examined the relationship between SSRT and retrieval-induced forgetting in the category-plus-stem-cued recall group, in which the effects of competition at test are better controlled. As shown in the bottom panel of Fig. 2, a significant negative correlation between SSRT and RIF-Z was observed, $r = -.31$, $p = .02$. That is, the faster the stop-signal reaction time, the greater the level of retrieval-induced forgetting for participants in the category-plus-stem condition, consistent with the expectation that retrieval-induced forgetting on this test is positively related to inhibitory control ability.

According to the correlated costs and benefits argument, however, the relationship between retrieval-induced forgetting and SSRT should be weaker on tests in which blocking has a greater potential of affecting performance on the final test. Consistent with this prediction, and as shown in the top panel of Fig. 2, a very different relationship emerged for participants in the category-cued condition, with participants in that condition showing a significant positive correlation between SSRT and RIF-Z, $r = .27$, $p = .03$.

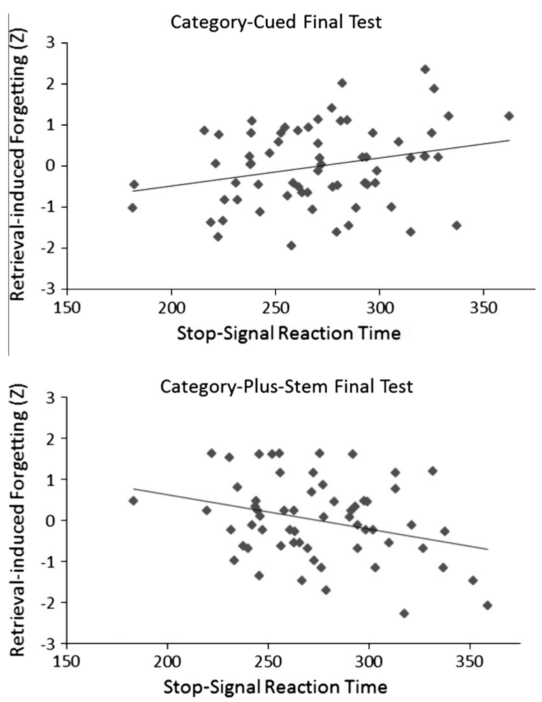

Fig. 2. The top and bottom scatterplots show the relationship between stop-signal reaction time and z-normalized retrieval-induced forgetting for the category-cued ($r = -.31$, $p = .02$) and category-plus-stem ($r = .27$, $p = .03$) final test conditions of Experiment 1, respectively.

To further establish the importance of test conditions on the relationship between SSRT and retrieval-induced forgetting, a hierarchical regression analysis was carried out to examine the proportion of variance in RIF-Z scores explained by SSRT, Type of Test, and the SSRT × Type of Test interaction. As expected, the first step, which included SSRT and Type of Test as predictors, did not produce a significant model, $F(2, 122) < 1$, $R^2 = .00$. Including the SSRT × Type of Test interaction term in the second step, however, did produce a significant model, $F(3,121) = 3.18$, $p = .02$, $R^2 = .08$, and the interaction term accounted for significant additional variance, $F(1, 121) = 10.75$, $p = .001$, $\Delta R^2 = .08$, thus confirming that the relationship between SSRT and retrieval-induced forgetting did vary significantly as a function of test condition.

Importantly, the relationship between SSRT and retrieval-induced forgetting observed in the category-plus-stem-cued condition cannot be explained by greater strengthening of practiced items during retrieval practice for subjects with faster SSRTs. One might wonder, for example, whether participants with superior response inhibition performed better during retrieval practice and strengthened Rp+ items to a greater extent than individuals with inferior response inhibition. Although faster SSRTs did predict modestly better performance during retrieval practice ($r = -.13$, $p = .34$), as well as marginally greater benefits from retrieval practice on the final test ($r = -.23$, $p = .08$), the correlation between retrieval-induced forgetting and SSRT remained significant even when controlling for variance in these benefits. Indeed, the partial correlation observed between SSRT and RIF-Z controlling for both practice performance and practice benefits ($r = -.29$, $p = .03$) was quite similar to the non-partial correlation observed ($r = -.31$). Furthermore, for completeness, we repeated the regression analysis while controlling for practice performance and practice benefits, and the same pattern of results was observed.

2.2.5. Retrieval-induced forgetting arising at the time of final test from retrieval on the category-plus-stem test: a within-experiment replication

Recall performance generally declines as a function of serial position in a test sequence. This output interference effect is another manifestation of retrieval-induced forgetting (Anderson et al., 1994). As such, we can also examine the relationship between SSRT and this effect of forgetting. In particular, in the category-plus-stem final test condition, we tested participants on the Rp− items before testing the Rp+ items to ensure that any impairment observed for Rp− items did not arise from the prior output of Rp+ items.

Correspondingly, we tested half of the Nrp items in the first half of the test, to use as a baseline for Rp− items, and the other half of the Nrp items in the second test half, to use as a baseline for Rp+ items. This arrangement provides a controlled manipulation of output position for Nrp items that allows us to estimate retrieval-induced forgetting at test. Specifically, as a result of testing Nrp− items first, the retrieval process engaged on those test trials should cause the retrieval-induced forgetting of the as-of-yet to-be-recalled Nrp+ items. Indeed, as would be predicted, Nrp+ items were recalled significantly less well than were Nrp− items, $t(59) = 5.43$, $p < .001$, $d = -.70$, thus demonstrating that Nrp+ items suffered retrieval-induced forgetting as the result of the earlier testing of Nrp− items. Using these data, an additional retrieval-induced forgetting score was calculated for each participant by subtracting Nrp+ recall from Nrp− recall, and then z-normalizing the scores within each counterbalancing condition. Importantly, individual differences in SSRT correlated significantly with this independent measure of retrieval-induced forgetting, with faster SSRTs (better inhibitory control) predicting larger test-based retrieval-induced forgetting effects, $r = -.44$, $p < .001$. This finding provides converging evidence for the view that when the potential for associative blocking at test is controlled, motor response inhibition ability predicts larger inhibitory aftereffects in retrieval-induced forgetting, consistent with a common underlying inhibitory control process mediating the control actions and memories.

3. Experiment 2

Experiment 2 sought to replicate the correlation between retrieval-induced forgetting and SSRT using item-specific test cues that effectively reduce blocking at the time of final test. We did this by employing an item-recognition task that required participants to determine whether a given exemplar had been presented during the earlier study phase. The exemplars were presented alone and without their associated category, intermixed with unstudied lures from the same categories. Research has shown that this form of item-recognition task can be used to measure retrieval-induced forgetting, and that such forgetting varies significantly across populations thought to vary in inhibition ability (e.g., Aslan & Bäuml, 2010; Aslan & Bäuml, 2011; Soriano et al., 2009). Thus, just as in the category-plus-stem condition of Experiment 1, we predicted that faster SSRT scores would predict greater retrieval-induced forgetting, a finding that would provide further evidence for the correlated costs and benefits of inhibition framework and confirm the significant relationship between response inhibition and retrieval-induced forgetting.

3.1. Method

3.1.1. Participants

A total of 106 undergraduate students at the University of Illinois at Chicago participated for partial credit in an introductory psychology course.

3.1.2. Measuring retrieval-induced forgetting

The retrieval-practice paradigm consisted of three phases: study, retrieval practice, and final test. Participants studied 64 category-exemplar pairs, received retrieval practice for half of the exemplars from half of the categories, and were then given a final test. All aspects of the materials and procedure were the same as those employed in Experiment 1 except for one important difference—at the time of the final test, participants were presented with a list of 128 exemplars and asked to indicate whether each item had been studied in the earlier study phase (i.e., to determine whether each exemplar was old or new). Half of the exemplars had been studied (and thus old), whereas the other half of the exemplars was new (and thus lures). The exemplars were shown individually, without their associated category cues, and participants were given 5 s to respond. The order of the exemplars was determined via blocked randomization such that every block of eight items consisted of one item from each category, with the old and new exemplars and practiced and non-practiced exemplars randomly distributed across the test list.

Three subjects were removed because they did not understand the final test instructions, responding "old" to items regardless of whether they remembered studying them during the earlier study phase, or responding "old" only if they remembered retrieving them during retrieval practice. It should be noted, however, that the same pattern of results was observed even when data from these three participants was included in the analysis.

3.1.3. Measuring stop-signal performance

Once again, STOP-IT was employed to measure response inhibition (Verbruggen et al., 2008). The parameters, instructions, and exclusion criteria were the same as those employed in Experiment 1. Six subjects were removed because they performed in a way that did not allow valid estimates of SSRT to be obtained. Specifically, these subjects withheld their response on significantly more or less than the 50% criterion. One additional subject was removed for having considerable difficulty with the task and exhibiting an SSRT score 15.8 SDs above the mean. Altogether, data from 96 of the 106 subjects were included.

3.2. Results and discussion

3.2.1. Retrieval-practice performance

Retrieval-practice performance data was lost for 18 of the 96 subjects. The remaining 78 subjects successfully retrieved 82% ($SD = 13\%$) of the exemplars during retrieval practice, a rate very similar to that observed in Experiment 1.

3.2.2. Recognition performance

Hit rates for Rp+, Rp−, and Nrp items and false alarm rates for lures associated with Rp and Nrp categories are shown in the top row of Table 2. To analyze recognition accuracy, *d'* was computed for all three item types by calculating $Z_{\text{hit rate}}–Z_{\text{false-alarm rate}}$.

As expected, a significant effect of retrieval practice was observed such that Rp+ items ($M = 2.57$, $SE = .07$) were

Table 2
Recognition performance in Experiment 2 with SEs in parenthesis.

Test condition	Hit rates			False alarms	
	Rp+	Rp−	Nrp	Rp	Nrp
Prop. Responses	.87 (.01)	.66 (.02)	.72 (.02)	.12 (.01)	.14 (.01)
d'	2.57 (.07)	1.80 (.08)	1.89 (.07)		

better recognized than Nrp items ($M = 1.89$, $SE = .07$), $t(95) = 8.28$, $p < .001$, $d = .85$.

As shown in the bottom row of Table 2, d' values were numerically lower for Rp− items ($M = 1.80$, $SE = .08$) than they were for Nrp items ($M = 1.89$, $SE = .07$). Although a paired-samples t test indicated that this difference was not statistically significant, $t(95) = 1.24$, $p = .22$, a repeated-measures ANCOVA with SSRT scores serving as a covariate—thus controlling for additional error variance—found that it was, $F(1, 94) = 6.69$, $MSE = .24$, $p = .01$. This finding replicates the many studies that have observed RIF using item recognition (e.g., Aslan & Bäuml, 2010; Aslan & Bäuml, 2011; Hicks & Starns, 2004; Ortega, Gómez-Ariza, Román, & Bajo, 2012; Román et al., 2009; Soriano et al., 2009; Spitzer & Bäuml, 2007). The fact that including SSRT as a covariate had such a large effect suggests that it accounted for a large proportion of the variance in retrieval-induced forgetting, a possibility we explore more directly below.

Before analyzing the correlation between retrieval-induced forgetting and SSRT, we computed the amount of retrieval-induced forgetting observed for each participant. As in Experiment 1, we did this by z-normalizing each participant's retrieval-induced forgetting score relative to the mean and standard deviation of all other participants in their matched counterbalancing condition. An analysis of the resulting RIF-z scores failed to reveal evidence of significant skew (.13, $SE = .25$) or kurtosis (−.39, $SE = .49$), and these statistics did not vary significantly from those observed in Experiment 1.

3.2.3. Stop-signal reaction time

Stop-signal reaction time scores (SSRTs) were estimated for each participant using the ANALYZE-IT software provided by Verbruggen et al. (2008). The mean stop-signal delay was calculated and then subtracted from the mean untrimmed response time for all go trials. The overall mean SSRT was 262 ms ($SD = 35$ ms). Further analysis of the distribution of scores failed to observe significant evidence of significant skew (.20, $SE = .25$) or kurtosis (.46, $SE = .49$).

As predicted, a significant negative correlation was observed between SSRT and RIF-z, $r = -.22$, $p = .03$. As shown in Fig. 3, faster SSRT scores predicted greater levels of retrieval-induced forgetting. This finding replicates the results in the category-plus-stem condition of Experiment 1, and confirms the prediction that retrieval-induced forgetting is positively related to inhibitory control. Importantly, the relationship between retrieval-induced forgetting and SSRT could not be explained by greater strengthening of practiced items during retrieval practice for subjects with faster SSRTs. SSRT scores did not predict

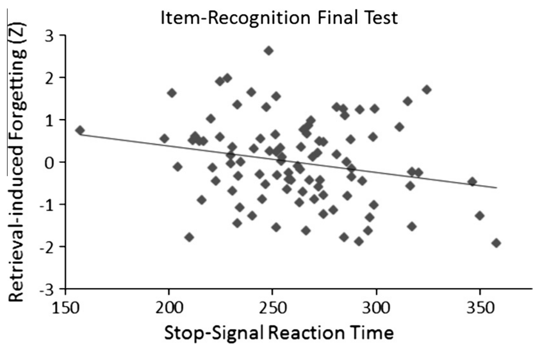

Fig. 3. Scatterplot shows the relationship between stop-signal reaction time and retrieval-induced forgetting for the item-recognition final test in Experiment 2, $r = -.22$, $p = .03$. The correlation remained significant even after removing the participant with a particularly fast SSRT score, $r = .21$, $p = .04$.

greater benefits from retrieval practice on the final test ($r = .10$, $p = .32$), and the correlation between retrieval-induced forgetting and SSRT remained significant even when controlling for variance in these benefits ($pr = -.20$, $p < .05$).

4. General discussion

The present findings support the correlated costs and benefits framework of inhibitory control. Inhibition has the capacity to both impair and facilitate cognitive processes and, as a consequence, predicting the relationship between hypothesized individual differences in inhibitory control ability and inhibitory aftereffect phenomena (like retrieval-induced forgetting) requires a careful consideration of how they are measured. For example, in the present example of retrieval-induced forgetting, although significant negative correlations were observed between stop-signal reaction time (SSRT) and retrieval-induced forgetting in the category-plus-stem and item-recognition conditions, a significant positive correlation was observed in the category-cued condition. That is, participants with faster SSRTs, indicating better inhibitory control abilities (Logan & Cowan, 1984), exhibited more retrieval-induced forgetting in the item-specific conditions than did participants with slower SSRTs, whereas the opposite effect was observed in the category-cued final test condition. This pattern confirms the predictions made by the correlated costs and benefits framework (Anderson & Levy, 2007): when a category-cued test is employed, participants become vulnerable to interference at final test, thus increasing the proportion of the retrieval-induced forgetting effect caused by interference and reducing its relationship to the measure of inhibition.

We predicted that the correlation between inhibitory control ability and retrieval-induced forgetting would be less positive in the category-cued condition than in the category-plus-stem condition, which was confirmed. However, this relationship was not simply less positive, it was significantly negative. That the correlation with SSRT was not merely eliminated but reversed suggests that when it comes to recalling Rp− items on a category-cued final test, the benefits of inhibitory control can overshadow the persisting costs. According to this interpretation, participants with superior inhibition (faster SSRTs) exhibited less retrieval-induced forgetting on the category-cued recall test because, unlike participants with poor inhibition, they could recall more Rp− items that would otherwise have been forgotten due to interference from strengthened Rp+ items. This benefit must have outweighed the added costs the Rp− items would have suffered for those participants due to the aftereffects of inhibition caused by retrieval practice. This pattern would not have arisen in the other test conditions because of the additional cue information, which would be expected to make the tests less sensitive to the blocking component of retrieval-induced forgetting. As predicted in Fig. 1, even though the aftereffects of inhibition during retrieval practice contributed on both tests, the additional blocking component was superimposed on this effect for the category cued recall test, changing the direction of the relationship. The outcome of these dynamics is illustrated strikingly in Fig. 4, highlighting how the direction of the correlation between retrieval-induced forgetting and inhibitory control was reversed when category-cued recall is employed.

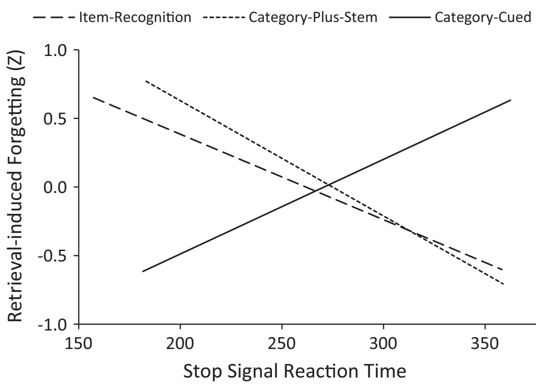

Fig. 4. Best-fitting linear regression lines illustrating the relationship between stop-signal reaction time (SSRT) and retrieval-induced forgetting (RIF-z). Note that RIF-z scores of 0.0 or lower do not reflect a lack of forgetting, but simply average or below average levels of RIF relative to participants in the same experimental and counterbalancing condition. Significant negative correlations between SSRT and RIF-z were observed in the item-recognition and category-plus-stem final test conditions, demonstrating that superior inhibitory control predicted greater retrieval-induced forgetting when the final test reduced blocking and better isolated the costs of inhibition. In contrast, a significant positive correlation between SSRT and RIF-z was observed in the category-cued final test condition, showing that inhibitory control predicted reduced retrieval-induced forgetting on tests that allow for a greater influence of blocking.

The finding that individuals with slower SSRT scores (poorer inhibition) still exhibited robust retrieval-induced forgetting on a category-cued final test is consistent with recent research on individuals with ADHD (Storm & White, 2010), schizophrenia patients (Soriano et al., 2009), and young children (Aslan & Bäuml, 2010). In each of these studies, individuals with presumed inhibition deficits exhibited normal levels of retrieval-induced forgetting on a category-cued test final compared to control participants, yet failed to exhibit any retrieval-induced forgetting on an item-specific final test (i.e., a category-plus-stem or item-recognition test). The present findings therefore may help explain why previous studies employing category-cued final tests have observed intact levels of retrieval-induced forgetting in populations with postulated inhibitory deficits (e.g., Conway & Fthenaki, 2003; Ford, Keating, & Patel, 2004; Moulin et al., 2002; Nestor et al., 2005; Zellner & Bäuml, 2005). Although many of these observations have been interpreted as evidence of intact inhibition, the present findings, in conjunction with the findings of the above-mentioned research, suggest otherwise.

Indeed, the implications of the present results extend beyond the study of individual differences. If retrieval-induced forgetting observed on category-cued final tests does not solely reflect the persisting consequences of inhibition during retrieval practice, then studies employing such tests may not be ideal for testing predictions of the inhibitory control account. For example, the major assumptions of the inhibitory account (e.g., that retrieval-induced forgetting is cue independent, competition dependent, strength independent) apply if, and only if, a particular observation of retrieval-induced forgetting is primarily caused by inhibition. Thus, by increasing the role of blocking on the final test, the use of category-cued recall complicates inferences that can be made about why a given effect of retrieval-induced forgetting is observed.

Although better motor response inhibition, as reflected by faster SSRTs, predicted lower amounts of retrieval-induced forgetting in the category-cued condition, it predicted greater retrieval-induced forgetting in the category-plus-stem and item-recognition conditions. This finding provides clear support for response-override hypothesis of memory control (e.g., Anderson, 2005; Levy & Anderson, 2002). According to this hypothesis, controlling memory retrieval is a special case of the broader need to override prepotent responses, a function thought to be achieved by the executive control processes of inhibition. Consistent with this view, the faster participants were able to stop motor responses in the stop-signal motor inhibition task, the more retrieval-induced forgetting they exhibited on tests likely to better isolate inhibition aftereffects. Whereas the stop-signal task requires participants to override a prepotent motor response, the retrieval-practice task requires them to override inappropriate traces in memory that interfere with the retrieval of a target item. Both tasks require contextually-inappropriate responses to be overridden, a goal presumably accomplished by inhibitory control.

The present results are difficult for purely competition-based accounts of retrieval-induced forgetting to explain. If retrieval-induced forgetting was simply the consequence of blocking at test then we would have expected individuals who showed more forgetting to exhibit slower SSRT scores, regardless of the type of test used to measure retrieval-induced forgetting. The fact that such individuals exhibited faster SSRTs suggests that retrieval-induced forgetting can reflect the aftereffects of an active goal-directed inhibitory process, one that may play a more important role in the functioning of memory than has previously been assumed. Indeed, this finding fits well with other recent work exploring individual differences in retrieval-induced forgetting. For example, retrieval-induced forgetting is associated with greater working memory capacity (Aslan & Bäuml, 2011; but see Mall & Morey, 2013), the ability to overcome mental fixation in creative problem solving (Koppel & Storm, 2014; Storm & Angello, 2010), and the ability to avoid unpleasant autobiographical memories (Storm & Jobe, 2012). Each of these findings suggests that individuals who exhibit greater levels of retrieval-induced forgetting enjoy advantages in memory and cognition—not disadvantages. It is worth noting that all of these studies employed item-specific final tests (i.e., category-plus-stem, recognition).

The present findings are also consistent with behavioral and neuroimaging work showing that retrieval-induced forgetting is accomplished via executive control. For example, Román et al. (2009) found that giving participants a concurrent updating task during retrieval practice reduced retrieval-induced forgetting, presumably because the task interfered with the executive processes necessary for inhibition. Furthermore, Kuhl et al. (2007) found that the prefrontal regions previously shown to be involved in the detection and resolution of interference are activated during retrieval practice. Moreover, the extent to which activation in these regions declined over retrieval practice trials predicted later retrieval-induced forgetting that a participant eventually exhibited. Kuhl et al. (2007) argued that activity in these regions was reduced for these subjects because they had inhibited the non-target items that were causing interference, thus reducing demands on cognitive control.

Finally, it should be noted that although SSRT has been shown to be a reliable measure of the ability to overcome distraction and prevent unwanted and inappropriate responses (e.g., Logan et al., 1997; Verbruggen et al., 2004), there is also evidence that it—and other measures of response inhibition—are not strongly associated with the ability to resist proactive interference in memory (e.g., Friedman & Miyake, 2004). This latter finding, at first blush, may seem at odds with the present results and more generally with findings pointing to common neural systems engaged by memory and motor inhibition (for examples, see Anderson & Huddleston, 2011; Anderson & Hanslmayr, 2014). An intriguing possibility that may contribute to this discrepancy is that the role of response inhibition in resisting proactive interference may be better estimated by the *aftereffects* of a mechanism acting to resist proactive interference than it is by one's overall ability to resist proactive interference. This may be particularly true when those aftereffects are measured in a way that reduces correlated costs and benefits problems, as argued here, a potentially fruitful possibility that should be explored in future research.

5. Concluding comments

The present research examined the correlated costs and benefits problem, a theoretically important issue in inhibitory control. By addressing this problem in the context of memory retrieval, the present findings help to clarify the processes that contribute to a particular memory phenomenon—retrieval-induced forgetting—and address its relation to inhibitory control processes in cognition more broadly. Critically, these findings support the operation of a common inhibition process that contributes to controlling memories and motor responses. They also highlight, however, that measures of memory inhibition can be influenced by blocking at test in a way that complicates the measurement of inhibition. At a broader level, the problems associated with the correlated costs and benefits of inhibition are not limited to research on retrieval-induced forgetting. For instance, research on inhibitory processes in other cognitive domains such as executive function (e.g., task-set switching), language comprehension (e.g., lexical ambiguity resolution, anaphoric reference, metaphor comprehension—e.g., Gernsbacher & Faust, 1991; Gernsbacher, Keysar, Robertson, & Werner, 2001), and visual selective attention (e.g., negative priming) has provided evidence that engaging putative inhibitory control processes creates inhibition aftereffects much like retrieval-induced forgetting (e.g., backwards inhibition, Mayr & Keele, 2000) that have been used to test for the existence of inhibition deficits in these functions (e.g., Mayr, 2001). The correlated costs and benefits problem affects conclusions about inhibitory deficits in research in these contexts as well (see Anderson & Levy, 2007 for a discussion). A more complete and accurate characterization of the role of inhibitory control in the broad array of circumstances in which it is thought to operate in mental life will require consideration of how inhibitory mechanisms can act to both impede and facilitate performance and the relative contributions of its costs and benefits to measures of inhibitory function.

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