Published in final edited form as:

Psychol Sci. 2015 January ; 26(1): 27–38. doi:10.1177/0956797614553945.

Inhibition-induced forgetting: when more control leads to less memory

Yu-Chin Chiu¹ and Tobias Egner¹

¹Center for Cognitive Neuroscience, Duke University, Durham, NC 27708, United States

Abstract

The ability to inhibit pre-potent responses is a core executive function, but the relation of *response inhibition* to other cognitive operations is poorly understood. Here we examined inhibitory control through the lens of incidental memory. Participants categorized face stimuli by gender in a go/no-go task (Experiments 1 and 2) or a stop signal task (Experiment 3) and, following a short delay, performed a surprise recognition memory test for those faces. Memory was impaired for stimuli presented during no-go and stop trials compared to go trials. Experiment 4 showed that this “inhibition-induced forgetting” effect is not attributable to event congruency. In Experiment 5, we combined a go/no-go task with a dot-probe test and observed inferior probe detection during no-go than during go trials. This result supports the hypothesis that the inhibition-induced forgetting effect is due to response inhibition shunting attentional resources from perceptual stimulus encoding to action control.

Keywords

cognitive control; memory; attention; response inhibition

Introduction

Cognitive control denotes a collection of processes that allow us to flexibly guide our thoughts and behavior in line with internal goals (Norman & Shallice, 1980; Posner & Snyder, 1975). Key ingredients for successful cognitive control have been described as the ability to maintain task-relevant information (a task-set) to guide top-down biasing of information processing (Desimone & Duncan, 1995; Miller & Cohen, 2001); the ability to protect task-sets by detecting and resolving conflict stemming from task-irrelevant information (Botvinick, Braver, Barch, Carter, & Cohen, 2001); the ability to update task-sets in response to changing goals and circumstances (Monsell, 2003); and the ability to inhibit actions that are inappropriate in the current task-set (Logan & Cowan, 1984). However, what exactly the mechanisms are that mediate these abilities, how they relate to

Corresponding Author: Yu-Chin Chiu, Center for Cognitive Neuroscience, Duke University, LSRC, Box 90999, Durham, NC 27708, chiu.yuchin@duke.edu.

Author contributions

Y-C.C. and T.E. designed the experiment and wrote the paper. Y-C.C. conducted the experiment and analyzed the data.

each other, and how they interface with cognitive domains like perception, memory, and attention remains poorly understood (Jurado & Rosselli, 2007).

A promising recent approach for improving our understanding of cognitive control processes is to assess the consequences of different control operations on incidental memory of task-relevant (target) and task-irrelevant (distracter) stimuli. For instance, Richter & Yeung (2012) employed trial-unique objects and words as targets and distracters in a task-switching protocol, followed by a surprise recognition memory test. The authors showed that the control process of task-set updating (i.e., when participants switched from one type of classification to the other) decreases subsequent memory for task-relevant targets but increases memory for task-irrelevant distracters. This finding provided important new insights into the relationship between updating, attention, and perception, because it suggests that task-set updating involves a temporary loss of attentional selectivity for task-relevant perceptual inputs (Dreisbach & Wenke, 2011), thus impairing memory selectivity. Similarly, Krebs and colleagues (Krebs, Boehler, De Belder, & Egner, 2013) investigated the mnemonic consequences of the control process of detecting and resolving conflict. Following a Stroop task that employed trial-unique face stimuli as targets, incidental memory was higher for faces presented during incongruent than congruent trials, suggesting that conflict resolution, instead of diverting resources away from perceptual processing, involves the up-regulation of attention to task-relevant stimuli (Botvinick et al., 2001; Krebs et al., 2013; Rosner, D'Angelo, MacLellan, & Milliken, 2014).

In the present study, we harness this incidental memory approach to shed new light on response inhibition, which is considered a core cognitive control process (Miyake et al., 2000), and deficits in which contribute to impulsive traits in several psychiatric diseases, including obsessive compulsive disorder, substance abuse, and attention deficit/hyperactivity disorder (de Wit, 2009; Horn, Dolan, Elliott, Deakin, & Woodruff, 2003). How might response inhibition affect incidental memory encoding? On the one hand, it seems plausible that cues signaling a “no-go” response, thereby eliciting the inhibitory control, may be rendered behaviorally salient and therefore be encoded more faithfully than “go” cues. In other words, more control might lead to more memory, akin to the findings in the conflict-control study (Krebs et al., 2013). On the other hand, the inhibitory process might share resources (e.g., attention), and thus competes with, perceptual stimulus processing (Broadbent, 1958; Norman, 1968). Here, inhibition would divert resources away from stimulus encoding, and in turn reduce memory of no-go compared to go cues. In Experiments 1–3, we adjudicated between these two hypotheses.

Experiments 1 and 2: Go/no-go tasks and incidental memory

In the first two experiments, we used male and female face stimuli in a go/no-go task that required subjects to respond (“go”) to one gender and withhold responses (“no-go”) to the other gender. Finally, following a filler task, subjects were presented with a surprise recognition memory test. By comparing recognition memory for faces shown as either no-go or go cues in T1, we ask: does response inhibition promote or suppress incidental memory encoding of the inhibitory cue? We included 4 repetitions per face in Experiment 1 to establish the basic effect. In Experiment 2, we aimed to replicate memory effects with 6

repetitions, and to ensure that these effects would be robust to a shift toward a higher level of recognition memory.

Method

Participants—Two cohorts of 54 Amazon Mechanical Turk (AMT) workers provided informed consent to participate in Experiment 1 ($M = 33.5$ years; $SD = 8.6$; 36 males) and 2 ($M = 32.5$; $SD = 9.0$; 28 males). For determining sample sizes for Experiments 1 and 2, we performed power calculations based on a comparable recent study on incidental memory effects of conflict-control processes (Krebs et al., 2013). Given a desire for high power (0.9) and a Type I error of 0.05 (2-tailed t-test), our calculation determined a target sample of 44. We over-recruited by 10 participants in anticipation of some drop-out due to potential technical errors or poor behavioral performance. For the remainder follow-up and control studies, we simply adhered to the same sample size. All protocols reported in this paper were approved by the Duke University Institutional Review Board. Participants were compensated with \$3 and \$4.5 in Experiment 1 and 2, respectively. Data from four participants were excluded in each experiment due to their overall hit rates lower than two standard deviations below the group mean.

Stimuli—We employed three hundred gray-scale face images collected from various databases (see Egner, Monti, & Summerfield, 2010) with unique identity (half males/females). Each face was randomly assigned to one of four stimulus sets for each subject. Set 1 included 120 faces (60 males) that were used in the go/no-go task (T1) and served as the 'old' stimuli in the recognition memory task (T3). Set 2 included 120 faces (60 males) that only appeared in T3, and served as the 'new' stimuli in the recognition memory task. Set 3 included 30 faces (15 males) that appeared in T1 and the filler task (T2). Set 4 included 30 faces (15 males) that appeared in T2 only (see below). Stimulus sets 1 and 2 were used to test our main question regarding how response inhibition affects incidental memory encoding, and stimulus sets 3 and 4 were used in T2.

Procedure—Participants read the task description and signed the informed consent form. They then received a practice block of 20 trials to familiarize themselves with the assigned stimulus-response mapping. Half of the participants received the instruction to 'go' for male faces (i.e., pressing 'g' on the keyboard) and 'no-go' for female faces (i.e., not pressing any key), and the other half received the reversed mapping.

Each participant performed T1, T2 and T3 sequentially (Fig. 1). T1 was a face-gender go/no-go task with 4 repetitions per face (Experiment 1). We chose 4 repetitions because this number should be sufficient to induce stimulus-no-go associations (Verbruggen & Logan, 2008), and to avoid a memory floor effect in T3. Experiment 2 was identical to Experiment 1 except that T1 included 6 repetitions per face. In T1, each trial started with a fixation cross at the center of the screen for 300 ms followed by a face for 800 ms. Participants could make a response within 1 sec of face onset, after which they received written feedback (correct or incorrect) for 1 sec. Participants were instructed to respond as fast as they could while being accurate.

Following T1, participants performed T2, which provided the encoding-retrieval delay (~5 minutes) between T1 and T3. In T2, we reversed the mapping of stimulus categories onto go/no-go responses, which allowed us to compare the performance of a subset of stimuli (set 3) participants had encountered in T1 to a novel set of stimuli (set 4). The result of this comparison ensured that subjects had in fact associated withholding a response with individual face stimuli (i.e., set 3) rather than with the broad gender categories (i.e., generalized to the novel set 4). Thus, with T2, we can demonstrate that our paradigm is valid for studying primed response inhibition as it provided a conceptual replication of previous studies using different stimuli and tasks (e.g., Chiu et al., 2012; Verbruggen & Logan, 2008). See Supplemental Material for details of this method and results. Lastly, participants performed a surprise recognition memory test (T3) with an equal number of old and new faces (sets 1 and 2). On each trial, a stimulus was presented until the participant selected one of the following responses: “definitely new”, “probably new”, “probably old”, or “definitely old” (mapped to v, b, n, m on the keyboard, or in a reversed order). For simplicity, we collapsed over “probably” and “definitely” responses in our main analyses, distinguishing only between “old” and “new” (see Supplemental Material for analysis of non-collapsed data). We then calculated hit and false alarm rates as well as d -prime (i.e., $z[\text{hit rate}] - z[\text{false alarm rate}]$) for each gender category. To assess recognition sensitivity, we focused on comparing d -prime between go and no-go cues. In all of the results sections, we report condition means along with their 95% confidence intervals (CIs). CIs were calculated from within-subject standard errors based on the pooled and scaled $\text{SEM}_{\text{pairDiff}}$ (Franz & Loftus, 2012). For paired t -tests, we report 2-tailed Bonferroni-corrected p values. For effect size measures, we reported Cohen’s d ($M_{\text{difference score}}/\sigma_{\text{difference score}}$) for paired t -tests, and partial eta-squared (η_p^2) for repeated measure ANOVAs.

Results

Go/no-go performance—In both experiments, overall accuracy in T1 was high (Exp 1: $M = 97.0$ [96.2, 97.8]; Exp 2: $M = 97.5$ [96.3, 98.6]). Although it was higher for go ($M = 98.0$ [97.5, 98.5]) than for no-go cues ($M = 95.9$ [95.4, 96.4]) in Experiment 1, $t(49) = 7.02$, $p < .001$; Cohen’s $d = 1.00$, there was no difference in accuracy between go ($M = 97.7$ [96.2, 99.1]) and no-go cues ($M = 97.3$ [95.8, 98.7]) in Experiment 2, $t(49) = .48$, $p > .5$. Furthermore, performance improved with repeated exposure to the go/no-go cues, as we found a monotonic decrease in go RTs (main effect of repetition, $F(3, 147) = 13.35$, $p < .001$, $\eta_p^2 = .21$), and in no-go commission error rates (main effect of repetition, $F(3, 147) = 4.54$, $p < .001$, $\eta_p^2 = .08$) for Experiment 1 (Fig. 2a), and for Experiment 2 (Fig. 2b) (go RTs: $F(5, 245) = 6.81$, $p < .001$, $\eta_p^2 = .12$; no-go error rates: $F(5, 245) = 2.44$, $p < .05$, $\eta_p^2 = .05$). See Table 1 for complete behavioral data.

Recognition memory

Experiment 1: As expected, overall hit rate was poor ($M = 60.8$ [55.5, 66.1]). However, hit rates for go and no-go cues were greater than their respective false alarm rates (no-go: $t(49) = 8.96$, $p < .001$, Cohen’s $d = 1.28$; go: $t(49) = 10.34$, $p < .001$, Cohen’s $d = 1.48$; see Table 2 for means $\pm$ 95% CI), indicating that recognition memory was well above chance. Importantly, d -prime was significantly lower for no-go ($M = .77$ [.69, .85]) than for go cues

($M = .86$ [.78, .94]), $t(49) = 1.97$, $p = .05$, Cohen's $d = .28$ (Fig. 2c), suggesting that response inhibition caused forgetting of no-go cues.

The same pattern of results was obtained when only stimuli from correctly performed go and no-go T1 trials were entered into the subsequent memory analysis, $t(49) = 2.47$, $p < .05$, Cohen's $d = .35$ (no-go: $M = .74$ [.65, .82]; go: $M = .87$ [.78, .95]), thus showing that inferior recognition memory for no-go cues was not driven by no-go trials where response inhibition had failed in T1.

Experiment 2: Overall hit rate was better in Experiment 2 ($M = 66.8$ [61.0, 72.5]), and, similar to Experiment 1, hit rates for go and no-go cues were greater than their respective false alarm rates (no-go: $t(49) = 11.16$, $p < .001$, Cohen's $d = 1.59$; go: $t(49) = 13.98$, $p < .001$, Cohen's $d = 2.00$; Table 2). Importantly, replicating the findings of experiment 1, d' -prime was significantly lower for no-go ($M = 1.08$ [.96, 1.19]) than for go cues ($M = 1.30$ [1.18, 1.42]), $t(49) = 3.15$, $p < .01$, Cohen's $d = .45$ (Fig. 2c). These results demonstrate that this effect is not limited to a context where overall memory is very poor. Interestingly, more repetitions also did not further impair memory for no-go cues, as the two experiments showed a similar magnitude of memory effect, $t(98) = 1.48$, $p > .1$ (go vs. no-go; Exp 1: $.10 \pm .05$; Exp 2: $.22 \pm .07$).

Experiments 3: Stop signal task and incidental memory

In Experiments 1–2, we observed poorer memory for stimuli previously encountered on no-go trials than on go trials. This result is compatible with the idea that response inhibition and perceptual stimulus processing compete for shared resources and incompatible with the hypothesis that inhibitory control renders no-go cues more salient. The results cannot be explained by error-processing associated with inhibition failure, as memory differences in Experiment 1 were robust to the exclusion of error stimuli in T1. Additionally, no-go cues were neither more physically salient nor less frequent than go cues (Logan, 1983), such that the only difference between these conditions lies with the exertion of response inhibition. To further probe the generalizability of this inhibition-induced forgetting effect, in Experiment 3 we adapted our design to the stop signal task, another well-established protocol of response inhibition (Logan & Cowan, 1984).

Method

Participants—A new cohort of 53 Amazon Mechanical Turk (AMT) workers provided informed consent to participate in Experiment 3 ($M = 32.1$ years; $SD = 10$; 21 males). Participants were compensated with \$3. Data from four participants were excluded due to their stop signal task ($N = 2$) or overall hit rates ($N = 2$) lower than two standard deviations below the group mean.

Stimuli—We employed 296 gray-scale face images with unique identity (half males/females). Similar to Experiments 1 and 2, each face was randomly assigned to one of four stimulus sets. Set 1 included 120 faces (60 males) that were used in the stop signal task (T1) and served as the 'old' stimuli in the recognition memory task (T3). In Set 1, half of the faces (half males/females) were 'go' stimuli (never paired with a stop signal) and the remaining

half were 'stop' stimuli (always paired with a stop signal). Set 2 included 120 faces (60 males) that only appeared in T3, and served as the 'new' stimuli in the recognition memory task. Set 3 included 28 faces (14 males) that appeared in T1 and T2. Set 4 included 28 faces (14 males) that appeared in T2 only. Stimulus sets 1 and 2 were used to test our main question regarding how response inhibition affects incidental memory encoding, and stimulus sets 3 and 4 were used in T2 (see Supplemental Material for results of T2).

Procedure—Participants followed the same procedure (i.e., performed T1, T2 and T3 sequentially) as Experiments 1 and 2, except that T1 was a stop-signal task rather than a go/no-go task. Half of the participants were instructed to press 'v' for male faces and 'n' for female faces and the other half received the reversed mapping. However, they were instructed to inhibit responding whenever an auditory beep (the stop signal) was played. The delay between the onset of the face stimulus and the stop signal was variable (50 ms ~ 650 ms, step-size = 50 ms) and was titrated to produce ~67% stop accuracy (two-up one-down staircase). This rate was selected to ensure that there were successful stimulus-stop associations across 4 exposures, because stimulus-stop associations are less likely to be learned when inhibition is unsuccessful (e.g., 50% stop accuracy) (Verbruggen & Logan, 2008).

Results

Stop signal task performance—As expected, accuracy for go trials in T1 was high ($M = 85.2$ [82.9, 87.5]) whereas the mean stop accuracy ($M = 67.2$ [64.9, 69.5]) conformed to the titrated target accuracy (67%) set prior to the experiment. Unlike the go/no-go version, go-RT did not improve with repeated exposure to the go/stop stimuli ($p > .09$). This was likely due to the variable stop signal delays (SSDs), which cautioned participants against responding too quickly in case a stop signal appeared. There was a main effect of repetition on stop accuracy, $F(3, 144) = 16.08$, $p < .001$, $\eta_p^2 = .25$. Post-hoc t -tests revealed that this main effect was driven by the slightly higher stop accuracy during the 1st exposure than later ones (Rep 1: 72.9% vs. Rep 2, 3, 4: 64.6%, 65.9%, 65.4%, p 's $< .01$), likely because the SSDs were too short (easier to stop) during the 1st exposure. See Table 1 for complete data for T1.

Recognition memory—Mean incidental hit rate was poor ($M = 54.1$ [49.2, 59.0]), but hit rates for stop and go cues were both significantly higher than the false alarm rate (stop: $t(48) = 4.37$, $p < .001$, Cohen's $d = .63$; go: $t(48) = 4.88$, $p < .001$, Cohen's $d = .70$; Table 2), indicating that recognition memory was nevertheless above chance. Importantly, d -prime was significantly lower for stop cues ($M = .31$ [.26, .37]) than for go cues ($M = .40$ [.35, .46]), $t(48) = 2.61$, $p < .05$, Cohen's $d = .38$ (Fig. 3).

Note though that the comparison between go and stop trials entails a potential confound, namely, the stop signal itself, which could impair memory by drawing attention away from the stimulus (Logan, 1983). We therefore also compared subsequent memory for successful vs. unsuccessful stop cue trials, which allowed us to compare the memory consequences of successful inhibition versus inhibition failure while controlling for the presence of a stop signal. Recall that each face was presented 4 times during the stop signal task and therefore

each face was associated with 0–4 stopping success. As there were too few trials with 0% or 25% stop accuracy, we compared stop cues with 50% vs. 75% and 100% stop accuracy. As expected, d -prime was significantly lower for successful stop cues ($M = .27$ [.19, .36] for 75% and 100% combined as there was no difference between the two, $p > .5$) than for unsuccessful stop cues ($M = .42$ [.34, .51]), $t(47) = 2.97$, $p < .01$, Cohen's $d = .43$ (one subject was excluded here due to a lack of trials with $> 50\%$ stop accuracy). This result suggests that it was successful inhibition that led to the poor subsequent memory. In sum, the stop signal task results replicated the inhibition-induced forgetting effect we had observed in the go/no-go task in Experiments 1–2.

Experiments 4: Yes/No task and incidental memory

Experiments 1–3 revealed a consistent pattern of poorer incidental memory for inhibitory cues, which we interpret as an inhibition-induced forgetting effect. However, our result could be explained by the “event congruency effect” (Craik & Tulving, 1975) – i.e., congruous events, such as saying ‘yes’ to a stimulus, result in better subsequent memory than incongruous events, such as saying ‘no’ to a stimulus. For instance, the stimulus ‘car’ is better recalled if ‘car’ appeared in a context eliciting a yes response (e.g., is a car a manmade object) than one eliciting a no response (e.g., is a car a natural object). If the participants in Experiments 1–3 had conceived of our tasks as “yes/no” tasks (i.e., not responding = saying ‘no’), then the forgetting effect could be attributable to event congruency. To test this hypothesis, we used the same protocol as our Experiment 1 except that now participants responded “yes” to one gender and “no” (rather than to withhold a response) to the other gender. We expected to observe no difference in memory, which would provide evidence against the event congruency account.

Method

Participants—A new cohort of 56 Amazon Mechanical Turk (AMT) workers provided informed consent to participate in Experiment 4 ($M = 32.53$ years; $SD = 10.1$; 29 males). Participants were compensated with \$3. Data from 3 participants were excluded due to their overall hit rates lower than two standard deviations below the group mean.

Stimuli—We employed the same 300 face images and the same stimulus assignment procedure as in Experiments 1 and 2.

Procedure—Participants followed the same procedure as Experiment 1 and 2, except that in T1 instead of a go/no-go task, they performed a “yes/no” task – i.e., categorize faces by responding ‘yes’ to one gender (e.g., male) and ‘no’ to the other gender. Each participant received a response mapping rule of “press ‘h’ for yes; press ‘j’ for no” or the reversed one, and received a practice session before the main experiment. As before, our main question concerned recognition memory in T3.

Results

Yes/No task performance—Overall accuracy in T1 was high ($M = 94.9$ [93.9, 95.8]). There was no difference between accuracy for ‘yes’ and ‘no’ cues (*mean difference* = .06 [–.

67, .79], $t(52) = .18, p > .5$). Furthermore, performance improved with repeated exposure to the yes/no stimuli, as we found a monotonic decrease in RTs (main effect of repetition, $F(3, 156) = 11.40, p < .001, \eta_p^2 = .18$) and a marginal effect in error rates (main effect of repetition, $F(3, 156) = 2.39, p = .07, \eta_p^2 = .04$). See Table 1 for complete data.

Recognition memory—Mean hit rate was 62.7% [57.9, 67.4], and hit rates for ‘no’ and ‘yes’ stimuli were greater than their respective false alarm rates (no: $t(52) = 10.17, p < .001$, Cohen’s $d = 1.41$; yes: $t(52) = 11.14, p < .001$, Cohen’s $d = 1.54$; Table 2). Importantly, d' -prime did not differ between ‘no’ ($M = .81$ [.70, .92]) and ‘yes’ response stimuli ($M = .87$ [.76, .98]), $t(52) = 0.88, p > .1$, Cohen’s $d = .12$) (Fig. 3). Therefore, it is unlikely that the forgetting effect observed in Experiments 1–3 were due to event congruency, thus supporting an inhibition-based account.

Experiment 5: Go/no-go task with dot-probes

We hypothesize that the forgetting effect was due to inhibition sapping (attentional) resources away from perceptual processing. To measure resources available for perceptual processing, here we introduced occasional “dot probes” in the go/no-go task such that on some trials, additional probes would appear and participants would report their detection. If response inhibition were to draw on attentional resources, the attention allocated to stimulus encoding should be reduced, thus decreasing the likelihood of detecting the dot probes in no-go trials. Moreover, we varied the stimulus onset asynchronies (SOAs) between face stimuli and dot probes (i.e., 200, 400, 600ms) to examine at what point in time exactly attention to the stimuli might be diminished in no-go trials. We expected dot-probe detection to be equivalent between go and no-go trials at the shortest SOA (200ms), at which point participants should be engaged in gender categorization. By contrast, we expected detection to be worse for no-go than for go trials at longer SOAs as these SOAs likely coincide with the timing of response execution/inhibition (go-RTs were ~560ms).

Method

Participants—A new cohort of 51 AMT workers participated in this experiment ($M = 34.2$; $SD = 12.3$; 22 males). The protocol was approved by the Duke University Institutional Review Board. Participants were compensated with \$2.5. Data from one participant was excluded due to probe detection accuracy of 0%.

Stimuli and procedure—The experimental task was identical to that of Experiment 1 with two modifications. First, there was no T2 or T3. Second, a dot-probe detection task was included within T1. Participants were informed that occasionally (but rarely), a dim asterisk (Hex color code: #a1a100) might appear on one of the four possible locations (left forehead, right forehead, left cheek and right cheek) for 200 ms. There were 3 different face-to-probe SOAs: 200, 400 and 600ms. On 24% of trials, a probe question was presented after the end of a trial. Half of the probe questions followed probe trials, and half of them followed no-probe trials. Participants responded by pressing ‘y’ or ‘n’ to indicate whether or not they had detected a probe (no response deadline), after which there was an 800ms inter-trial interval.

Results

Go/no-go performance—Despite the additional probe detection task, participants exhibited similar go/no-go performance as in Experiments 1–2. Overall accuracy was high ($M = 96.9$ [96.3, 97.5]), and was higher for go ($M = 97.5$ [97.0, 98.0]) than for no-go ($M = 96.3$ [95.8, 96.8]), $t(49) = 3.8$, $p < .01$) stimuli. Moreover, there were significant main effects of repetition for go RTs, $F(3, 147) = 56.31$, $p < .001$, $\eta_p^2 = .53$, and for no-go commission errors, $F(3, 147) = 3.59$, $p < .05$, $\eta_p^2 = .07$ (Fig. 4a). See Table 1 for complete data for T1.

Dot-Probe Detection—For the dot-probe task, there was no difference in accuracy for trials where no probe was presented ($p > .05$). Focusing on probe-present trials, we conducted a 2 (trial type: go, no-go) $\times$ 3 (probe SOA: 200, 400, 600ms) repeated measure ANOVA, which revealed a main effect of trial type, $F(1, 49) = 15.24$, $p < .01$, $\eta_p^2 = .24$, and probe SOA, $F(2, 98) = 5.04$, $p < .01$, $\eta_p^2 = .09$; and a marginal trial type $\times$ probe SOA interaction, $F(2, 98) = 2.71$, $p = .07$, $\eta_p^2 = .05$ (Fig. 4b). Planned post-hoc comparisons revealed that there was no difference in accuracy for SOA of 200ms ($p > .5$). However, there was an inferior dot detection accuracy for no-go than for go trials at SOAs of 400ms, $t(49) = 2.65$, $p < .05$, Cohen's $d = .38$, and at 600ms, $t(49) = 3.48$, $p < .01$, Cohen's $d = .50$. These results are in line with the explanation of inhibition-induced forgetting based on the “common resource” hypothesis, namely that response inhibition saps attention away from stimulus processing. As a consequence, memory encoding of stimuli encountered during no-go trials is impaired, rendering these stimuli less recognizable later on.

However, an alternative explanation for these probe detection results could be that participants completed the processing of no-go trials sooner than that of go trials and, once no-go processing was complete, they stopped attending to the stimuli and therefore missed the dot probes at 400 and 600ms SOAs. *Prima facie*, this appears unlikely since participants had been instructed explicitly to detect the probes, and it seems improbable that response inhibition on no-go trials was already complete at 400ms after stimulus onset. However, to rule out this possibility empirically, we examined the relationship between go trial RTs and probe accuracy. If it were the case that once processing (either go or no-go) was completed, participants stopped attending to the stimuli, we would expect to find inferior probe detection when go RTs were shorter than the probe SOA. We tested this prediction on the 600ms SOA probes, as here the majority of participants had some trials with shorter and some trials with longer RTs than the probe SOA. Contrary to the idea that early completion of face stimulus processing would reduce attention to the dot probes, dot-probe accuracy was no different between go trials with RTs shorter than 600ms and trials with RTs longer than 600ms ($M = 97.8$ [93.4, 102.3] vs. $M = 94.3$ [89.9, 98.8]; $t(44) = 1.31$, $p > .05$; $N = 45$ because 5 of the participants did not have go trials with RTs longer than 600ms). Therefore, it is highly unlikely that the low probe detection accuracy during no-go trials was attributable to participants switching attention away after they had finished stimulus processing.

Discussion

Assessing the mnemonic consequences of the control process of response inhibition, in Experiments 1–2, we showed that incidental memory for no-go cues was worse than go cues. In Experiment 3, we extended this finding to a stop signal paradigm and, moreover, successful stop trials were associated with worse memory than unsuccessful stop trials. In Experiment 4, we showed that this effect is not attributable to event congruency. Instead, the most parsimonious interpretation of our results is that response inhibition impairs concurrent stimulus encoding, which leads to forgetting. Greater control engaged during response inhibition thus appears to compete for attention, which is consistent with the common resource hypothesis (Broadbent, 1958; Norman, 1968). This conclusion is further directly supported by Experiment 5, which showed that the ability to detect dot-probes is reduced at the time that inhibitory control is being exerted.

Interestingly, the detrimental effect of response inhibition on memory is in stark contrast to the memory consequences of the control process of detecting and resolving conflict, which has been found to enhance subsequent memory for task-relevant stimuli (Krebs et al., 2013; Rosner et al., 2014). We argue that these differential effects arise from the fact that conflict-resolution involves the reinforcement of top-down attention toward target stimuli (Botvinick et al., 2001; Egner & Hirsch, 2005), thus facilitating their encoding into memory. By contrast, the opposite appears to be the case for response inhibition, which saps attention away from concurrent stimulus encoding.

We propose that inhibition-induced forgetting stems from resource-sharing between inhibitory control and concurrent perceptual encoding. The resource-sharing discussed here is different from prior work that assessed the resource demands of response inhibition by examining whether a concurrent response could be executed in a secondary task (e.g., Yamaguchi, Logan, & Bissett, 2012). These studies found no dual-task interference, whereas we show that perceptual encoding processes are in fact impoverished by concurrent response inhibition. Corollary evidence for our proposition that response inhibition shares resources with perceptual stimulus processing can be found in neuroimaging studies of response inhibition and memory encoding. For example, the right ventrolateral prefrontal cortex has been implicated in response inhibition including in go/no-go tasks (Aron, Behrens, Smith, Frank, & Poldrack, 2007; Chikazoe, 2010; Levy & Wagner, 2011), in the context of attentional control during inhibition tasks (Chatham et al., 2012; Dodds, Morein-Zamir, & Robbins, 2011) as well as in the successful memory encoding of visual objects (Brewer, Zhao, Desmond, Glover, & Gabrieli, 1998; Bunge, Burrows, & Wagner, 2004). Future neuroimaging work could test directly the hypothesis that inhibition-induced forgetting arises from a competition between response inhibition and memory encoding for shared, limited neural resources in frontal cortex. One alternative account could be that inhibition-induced forgetting reflects the consequence of a “global” inhibition process, hypothesized to be mediated by the subthalamic nucleus (Gillies & Willshaw, 1998). This hypothesis holds that response inhibition triggers a widespread inhibition signal that acts not only on the classical motor circuit (Mink, 1996), but also on perceptual processing and memory encoding (see Eagle & Baunez, 2010). According to this account though, we would have expected to obtain stronger forgetting effects with 6 than 4 repetitions of no-go stimuli

(Experiments 1–2), which was not the case. Nonetheless, this null result does not represent strong evidence against the global inhibition hypothesis, and the latter could also feasibly be tested in future neuroimaging studies.

It is important to note that inhibition-induced forgetting appears to be a distinct phenomenon from other similar effects reported in the literature. First, it is distinct from “directed forgetting” observed in the think-no-think paradigm (Anderson & Green, 2001); in the latter, subjects are asked to intentionally suppress an unwanted memory, whereas we examined purely incidental memory effects of response inhibition. By the same token, our study cannot answer whether memory effects of directed forgetting is attributable to response inhibition or to other means (but see Fawcett & Taylor, 2010). Similarly, the phenomenon we demonstrated here cannot be accounted for by “retrieval-induced forgetting” effects (Anderson et al., 1994). In the latter, repeated practice of a subset of previously learned material can impair memory for unpracticed but closely related items, which is thought to be due to inhibition of close competitors during retrieval (Anderson, 2003). By contrast, the present protocol involves neither retrieval practice nor the need to inhibit competing memories. Finally, inhibition-induced forgetting does not mimic the “attentional boost” effect (e.g., Swallow & Jiang, 2010) where poor memory produced by a divided attention condition can be restored (to the level of memory in the focused attention condition) if the memory item was paired with a target detection event that summons attention.

In summary, the current study establishes a novel cognitive phenomenon of inhibition-induced forgetting, and it provides a mechanistic account for this effect, namely that the control-demands of response inhibition divert attention away from stimulus encoding, resulting in a weaker memory trace for inhibitory cues. These findings shed new light on the relation between the control process of response inhibition and the cognitive domains of perception, attention, and memory.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

We thank Drs. Elizabeth Marsh and Ruth Krebs for comments. This work was supported in part by National Institute of Mental Health award R01 MH 087610 (T.E.).

References

- Anderson M. Rethinking interference theory: Executive control and the mechanisms of forgetting. *Journal of Memory and Language*. 2003; 49:415–445.
- Anderson MC, Bjork Ra, Bjork EL. Remembering can cause forgetting: retrieval dynamics in long-term memory. *Journal of Experimental Psychology. Learning, Memory, and Cognition*. 1994; 20(5): 1063–1087. Retrieved from <http://www.ncbi.nlm.nih.gov/pubmed/7931095>.
- Anderson MC, Green C. Suppressing unwanted memories by executive control. *Nature*. 2001; 410(6826):366–369. [PubMed: 11268212]
- Aron AR, Behrens TE, Smith S, Frank MJ, Poldrack Ra. Triangulating a cognitive control network using diffusion-weighted magnetic resonance imaging (MRI) and functional MRI. *The Journal of*

- Neuroscience : The Official Journal of the Society for Neuroscience. 2007; 27(14):3743–3752. [PubMed: 17409238]
- Botvinick MM, Braver TS, Barch DM, Carter CS, Cohen JD. Conflict monitoring and cognitive control. *Psychological Review*. 2001; 108(3):624–652. Retrieved from <http://www.ncbi.nlm.nih.gov/pubmed/11488380>. [PubMed: 11488380]
- Brewer JB, Zhao Z, Desmond JE, Glover GH, Gabrieli JD. Making memories: brain activity that predicts how well visual experience will be remembered. *Science (New York, N.Y.)*. 1998; 281(5380):1185–1187.
- Broadbent, DE. *Perception and communication*. Oxford: Pergamon Press; 1958.
- Bunge, Sa; Burrows, B.; Wagner, aD. Prefrontal and hippocampal contributions to visual associative recognition: interactions between cognitive control and episodic retrieval. *Brain and Cognition*. 2004; 56(2):141–152. [PubMed: 15518931]
- Chatham CH, Claus ED, Kim A, Curran T, Banich MT, Munakata Y. Cognitive control reflects context monitoring, not motoric stopping, in response inhibition. *PLoS One*. 2012; 7(2):e31546. [PubMed: 22384038]
- Chikazoe J. Localizing performance of go/no-go tasks to prefrontal cortical subregions. *Current Opinion in Psychiatry*. 2010; 23(3):267–272. [PubMed: 20308899]
- Chiu Y-C, Aron AR, Verbruggen F. Response suppression by automatic retrieval of stimulus-stop association: evidence from transcranial magnetic stimulation. *Journal of Cognitive Neuroscience*. 2012; 24(9):1908–1918. [PubMed: 22624606]
- Craik FI, Tulving E. Depth of processing and the retention of words in episodic memory. *Journal of Experimental Psychology: General*. 1975; 104(3):268–294.
- De Wit H. Impulsivity as a determinant and consequence of drug use: a review of underlying processes. *Addiction Biology*. 2009; 14(1):22–31. [PubMed: 18855805]
- Desimone R, Duncan J. Neural mechanisms of selective visual attention. *Annual Review of Neuroscience*. 1995; 18:193–222.
- Dodds CM, Morein-Zamir S, Robbins TW. Dissociating inhibition, attention, and response control in the frontoparietal network using functional magnetic resonance imaging. *Cerebral Cortex (New York NY:1991)*. 2011; 21(5):1155–1165.
- Dreisbach G, Wenke D. The shielding function of task sets and its relaxation during task switching. *Journal of Experimental Psychology: Learning, Memory, and Cognition*. 2011; 37(6):1540–1546.
- Eagle DM, Baunez C. Is there an inhibitory-response-control system in the rat? Evidence from anatomical and pharmacological studies of behavioral inhibition. *Neuroscience and Biobehavioral Reviews*. 2010; 34(1):50–72. [PubMed: 19615404]
- Egner T, Hirsch J. Cognitive control mechanisms resolve conflict through cortical amplification of task-relevant information. *Nature Neuroscience*. 2005; 8(12):1784–1790.
- Egner T, Monti JM, Summerfield C. Expectation and surprise determine neural population responses in the ventral visual stream. *The Journal of Neuroscience : The Official Journal of the Society for Neuroscience*. 2010; 30(49):16601–16608. [PubMed: 21147999]
- Fawcett JM, Taylor TL. Directed forgetting shares mechanisms with attentional withdrawal but not with stop-signal inhibition. *Memory & Cognition*. 2010; 38(6):797–808. [PubMed: 20852242]
- Franz VH, Loftus GR. Standard errors and confidence intervals in within-subjects designs: generalizing Loftus and Masson (1994) and avoiding the biases of alternative accounts. *Psychonomic Bulletin & Review*. 2012; 19(3):395–404. [PubMed: 22441956]
- Gillies AJ, Willshaw DJ. A massively connected subthalamic nucleus leads to the generation of widespread pulses. *Proceedings. Biological Sciences / The Royal Society*. 1998; 265(1410):2101–2109. [PubMed: 9842737]
- Horn NR, Dolan M, Elliott R, Deakin JFW, Woodruff PWR. Response inhibition and impulsivity: an fMRI study. *Neuropsychologia*. 2003; 41(14):1959–1966. [PubMed: 14572528]
- Jurado MB, Rosselli M. The elusive nature of executive functions: a review of our current understanding. *Neuropsychology Review*. 2007; 17(3):213–233. [PubMed: 17786559]
- Krebs RM, Boehler CN, De Belder M, Egner T. Neural Conflict-Control Mechanisms Improve Memory for Target Stimuli. *Cerebral Cortex (New York, N.Y.: 1991)*. 2013

- Levy BJ, Wagner AD. Cognitive control and right ventrolateral prefrontal cortex: reflexive reorienting, motor inhibition, and action updating. *Annals of the New York Academy of Sciences*. 2011; 1224(Ba 45):40–62. [PubMed: 21486295]
- Logan GD. On the ability to inhibit simple thoughts and actions: I. Stop-signal studies of decision and memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*. 1983; 9(4):585–606.
- Logan GD, Cowan WB. On the ability to inhibit thought and action: A theory of an act of control. *Psychological Review*. 1984; 91(3):295–327.
- Miller EK, Cohen JD. An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience*. 2001; 24:167–202.
- Mink JW. The basal ganglia: focused selection and inhibition of competing motor programs. *Progress in Neurobiology*. 1996; 50(4):381–425. [PubMed: 9004351]
- Miyake, a; Friedman, NP.; Emerson, MJ.; Witzki, aH; Howerter, a; Wager, TD. The unity and diversity of executive functions and their contributions to complex “Frontal Lobe” tasks: a latent variable analysis. *Cognitive Psychology*. 2000; 41(1):49–100. [PubMed: 10945922]
- Monsell S. Task switching. *Trends in Cognitive Sciences*. 2003; 7(3):134–140. [PubMed: 12639695]
- Norman DA. Toward a theory of memory and attention. *Psychological Review*. 1968; 75(6):522–536.
- Norman, DA.; Shallice, T. *Attention to Action: Willed and Automatic Control of Behavior*. 1980. Retrieved from <http://oai.dtic.mil/oai/oai?verb=getRecord&metadataPrefix=html&identifier=ADA094713>
- Posner, MI.; Snyder, CRR. Attention and cognitive control. In: Solso, RL., editor. *Information processing and cognition: The Loyola symposium*. Hillsdale, NJ: Lawrence Erlbaum; 1975. Retrieved from <http://philpapers.org/rec/POSAAC>
- Richter FR, Yeung N. Memory and cognitive control in task switching. *Psychological Science*. 2012; 23(10):1256–1263. [PubMed: 22972906]
- Rosner TM, D’Angelo MC, MacLellan E, Milliken B. Selective attention and recognition: effects of congruency on episodic learning. *Psychological Research*. 2014
- Swallow KM, Jiang YV. The Attentional Boost Effect: Transient increases in attention to one task enhance performance in a second task. *Cognition*. 2010; 115(1):118–132. [PubMed: 20080232]
- Verbruggen F, Logan GD. Automatic and controlled response inhibition: associative learning in the go/no-go and stop-signal paradigms. *Journal of Experimental Psychology. General*. 2008; 137(4):649–672. [PubMed: 18999358]
- Yamaguchi M, Logan GD, Bissett PG. Stopping while going! Response inhibition does not suffer dual-task interference. *Journal of Experimental Psychology. Human Perception and Performance*. 2012; 38(1):123–134. [PubMed: 21574740]

Fig. 1. Tasks and procedures
Participants first performed T1, which was to categorize face stimuli by gender in a go/no-go task (e.g., “go” for males, “no-go” for females) and, following a short delay, performed a surprise recognition memory test (T3) for those faces. During the delay, participants performed T2, which provided the encoding-retrieval delay (~5 minutes) between T1 and T3. The table in the inset documents the task in which each stimulus set appeared and the number of unique faces in each set.

Fig. 2. (a–b) Go/no-go performance in T1 for Experiment 1 and 2. Mean RTs for go cues and mean commission error for no-go cues plotted as a function of stimulus repetitions (i.e., Rep 1–4 for Experiment 1 and Rep 1–6 for Experiment 2). (c) Means ± 95% CIs of d-prime for no-go, go cues in the recognition memory task for Experiment 1 and 2.

Fig. 3. Recognition sensitivity

Means $\pm$ 95% CIs of d-prime for stop, go cues for Experiment 3 and for 'no', 'yes' cues for Experiment 4.

Fig. 4. Performance of Experiment 5

(a) Means $\pm$ 95% CIs of RTs for go cues and commission error for no-go cues plotted by stimulus repetitions (Rep 1–4). (b) Means $\pm$ 95% CIs of probe detection accuracies plotted as a function of face-to-probe SOAs (ms).

Table 1

Means and 95% CIs for behavioral measures as a function of stimulus repetitions for Experiments 1–5

		Exposure					
		R1	R2	R3	R4	R5	R6
Exp 1	<i>go RT (ms)</i>	555.06 [548.9, 561.2]	542.16 [536.0, 548.3]	535.60 [529.5, 541.7]	533.58 [527.4, 538.7]		
	<i>nogo error (%)</i>	5.01 [4.2, 5.8]	3.60 [2.8, 4.4]	3.41 [2.6, 4.2]	3.44 [5.6, 4.3]		
Exp 2	<i>go RT (ms)</i>	548.31 [541.4, 555.3]	535.03 [528.1, 542.0]	534.31 [527.4, 541.3]	529.94 [523.0, 536.9]	527.86 [520.9, 534.8]	526.51 [519.6, 533.5]
	<i>nogo error (%)</i>	3.39 [2.8, 4.0]	3.12 [2.5, 3.7]	2.51 [1.9, 3.1]	2.48 [1.9, 3.1]	2.67 [2.1, 3.2]	2.51 [1.9, 3.1]
Exp 3	<i>go RT (ms)</i>	746.30 [733.1, 759.5]	755.57 [742.3, 768.8]	761.68 [748.5, 774.9]	766.75 [753.5, 780.0]		
	<i>stop error (%)</i>	27.11 [24.9, 29.3]	35.44 [33.2, 37.6]	34.09 [31.9, 36.3]	34.64 [32.4, 36.8]		
Exp 4	<i>go RT (%)</i>	588.24 [582.1, 594.4]	577.30 [571.1, 583.5]	570.43 [564.3, 576.6]	568.19 [562.0, 574.3]		
	<i>error (%)</i>	5.72 [5.1, 6.4]	5.11 [4.5, 5.7]	4.69 [4.1, 5.3]	5.16 [4.5, 5.8]		
Exp 5	<i>go RT (%)</i>	588.96 [583.0, 584.9]	558.62 [552.7, 564.6]	549.73 [543.8, 555.7]	544.70 [538.7, 550.7]		
	<i>nogo error (%)</i>	4.48 [3.8, 5.2]	3.44 [2.7, 4.2]	3.17 [2.4, 3.9]	3.33 [2.6, 4.1]		

Table 2

Means and 95% CIs for hit and false alarm rates for Experiments 1–4

		Exp 1	Exp 2	Exp 3	Exp 4
no-go/stop/no' cues	<i>Ht rate (%)</i>	57.3 [58.2, 61.9]	63.2 [58.1, 68.2]	52.5 [48.9, 58.0]	62.0 [58.2, 65.8]
	<i>raise alarm rate (%)</i>	31.2 [26.7, 35.8]	26.8 [21.8, 31.9]	41.3 [37.7, 44.9]	33.7 [31.2, 36.2]
go/yes' cues	<i>Ht rate (%)</i>	64.3 [60.0, 68.6]	70.3 [65.9, 74.7]	55.7 [52.2, 59.3]	63.4 [59.6, 67.1]
	<i>raise alarm rate (%)</i>	35.1 [30.8, 39.5]	27.8 [23.3, 32.2]	41.3 [37.7, 44.9]	33.1 [30.6, 35.6]