Inhibition of task set: Converging evidence from task choice in the voluntary task-switching paradigm

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This study looked for evidence of task-set inhibition in a voluntary task-switching paradigm. Participants performed one of three tasks on a digit: parity (even or odd), size (less than or greater than 5), or distance (near or far from 5). On each trial, they were allowed to choose which task to perform, with encouragement to perform each task equally often overall and in a random sequence. The question was whether participants would avoid performing a task that they had recently switched away from (e.g., the task performed on trial $n-2$), because the task set was still inhibited. Results confirmed that participants strongly avoided performing the $n-2$ task (e.g., ABA) in favor of performing other tasks (e.g., ABC). This occurred both when participants were required to switch tasks every trial (Experiment 1) and when they were allowed to repeat tasks (Experiment 2). The results suggest that a task set is inhibited during switching to a new task, reducing the likelihood that this task will be selected in the near future.

Successful performance in many important real-world domains depends critically on the performer's ability to select and perform the proper task while ignoring other potential tasks. One popular approach to studying this ability, called *cognitive control*, is to have people repeat or switch tasks. In this paradigm, performance is typically slower following a task switch than following a task repetition (the *switch cost*; see, e.g., Allport, Styles, & Hsieh, 1994). Switch costs are robust, occurring even when people have ample time to prepare for the switch (e.g., Lien, Ruthruff, Remington, & Johnston, 2005; Meiran, 1996; Rogers & Monsell, 1995; Ruthruff, Remington, & Johnston, 2001). These residual switch costs suggest that the cognitive processes responsible for preparing a new task set are limited in their effectiveness.

Recent studies have suggested that preparatory processes might include inhibiting the previous task set, in order to increase the relative accessibility of the new task (e.g., Mayr & Keele, 2000). To support this claim, Mayr and Keele examined how performance varied as a function of how recently the task was performed. They used an explicit cuing paradigm, where a visual cue indicated what task should be performed next. Critically, they found slower responses for the task performed two trials earlier ($n-2$ repetition; e.g., ABA) than for less recent tasks ($n-2$ switch; e.g., CBA). This *$n-2$ repetition cost*, according to Mayr and Keele, reflects the need to overcome lingering task-set inhibition.

They assumed that the inhibition is applied when switching away from a task and then decays over time.

The bulk of the evidence for task-set inhibition comes from performance delays in ABA task sequences relative to CBA sequences (for a different approach, see Hübner, Dreisbach, Haider, & Kluwe, 2003; Kuhns, Lien, & Ruthruff, 2007). Such delays might reflect inhibition but could also reflect other factors (e.g., negative priming). Furthermore, most studies favoring task-set inhibition have used an explicit cue (e.g., a visual task label in Mayr & Keele, 2000; a symbolic cue in Schuch & Koch, 2003) in order to indicate the task to be performed next. Of the rare studies that looked for inhibition outside this paradigm, a few actually failed to find it (e.g., with tasks cued by location or by task sequence; Arbuthnott, 2005; Lien, Ruthruff, & Kuhns, 2006). It is conceivable that the processing delays in an ABA sequence reflect confusion over the fact that the cue seems very familiar, yet the task switches (but see Altmann, 2007). Thus, it is important to provide converging evidence for task-set inhibition and to show that it is a general phenomenon, not restricted to a particular paradigm. There is no obvious reason why inhibition should not occur in the absence of explicit task cues, as in many real-world scenarios in which one voluntarily chooses what to do next.

Recently, Arrington and Logan (2004, 2005) developed a voluntary task-switching procedure, in which partici-

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pants were free to select which of two digit tasks (odd/even or high/low) to perform on each trial. They found that participants tended to repeat rather than switch tasks. They also found that, even with switches presumably under top-down control, substantial switch costs were obtained. They argued that these switch costs reflect the time required to make the choice to switch tasks and to reconfigure the task set.

The voluntary task-switching paradigm, which does not utilize task cues, provides a new way to study task-set inhibition. Rather than comparing response time (RT) and accuracy in ABA and CBA task sequences, as has been done in previous studies, we examined task choice. To do so, it was necessary to use three tasks, rather than just two.

Suppose that people proactively inhibit the recently performed task set when switching to a new task.[1] If inhibition lingers over time, participants should avoid choosing to perform this strongly inhibited task in the near future. Thus, other things being equal, one would expect a higher probability of $n-2$ switches than of $n-2$ repetitions. If task switching does not involve inhibition, however, people might actually prefer to repeat the $n-2$ task, because it should be more active than less recently performed tasks (just as people prefer to perform $n-1$ repetitions).

EXPERIMENT 1

In Experiment 1, we tested whether people favor performing $n-2$ switches over performing $n-2$ repetitions in the voluntary task-switching paradigm. In order to ensure the use of top-down control and to minimize stimulus-driven activation of task set, each stimulus was associated with three different tasks. Participants could select freely among the three tasks, so long as they did not repeat the previous task (a requirement common to most studies of task-set inhibition).

The critical measure in this experiment was the proportion of $n-2$ repetition trials to $n-2$ switch trials. Because participants always had a choice between two tasks (after disallowing repetitions), a random task sequence would produce a 50/50 mixture of $n-2$ repetitions and switches. To uniquely determine which particular task participants chose to perform on a trial, we employed a unique set of response keys for each task.

Method

Participants. Thirty-six undergraduates at Oregon State University participated in this experiment. Data from 5 participants were excluded, because they tended to adhere to a fixed task sequence (see below).

Apparatus, Stimuli, and Procedure. On each trial, a digit ($0.83° \times 0.94°$) appeared in the center of the screen. Participants performed one of three tasks on this digit: parity (even or odd), size (less than or greater than 5), or distance (near or far from 5). For the parity task, participants pressed the "Z" key for odd digits (1, 3, 7, or 9) and the "M" key for even digits (2, 4, 6, or 8). For the size task, participants pressed the "X" key for digits less than 5 (1, 2, 3, or 4) and the "N" key for digits greater than 5 (6, 7, 8, or 9). For the distance task, participants pressed the "C" key for digits near 5 (3, 4, 6, or 7) and the "B" key for digits far from 5 (1, 2, 8, or 9). Participants pressed the "Z," "X," and "C" keys with the ring, middle, and index fingers of the left hand, respectively, and the "M," "N,"

and "B" keys with the ring, middle, and index fingers of the right hand, respectively.

Each trial started with a fixation cross, presented for 1,200 msec. After a 300-msec blank period, the stimulus appeared and remained until the participants responded. Next, auditory feedback (a beep on error trials, silence on correct trials) was presented for 200 msec. The fixation cross for the next trial appeared 300 msec later.

Participants performed a 15-trial practice block for each task, in a random order. The following seven experimental blocks contained 64 trials each. The participants were instructed to randomly select one of the three tasks to perform, without repeating the previous task. Whenever they violated this instruction, they received a visual warning message: "Do not repeat the task!" They were also encouraged to perform each task in roughly equal numbers across the session. After each block, participants received feedback regarding their mean RT and accuracy for that block.

Results and Discussion

We first categorized the task performed on each trial on the basis of which set of response keys was used. Trials could then be classified as an $n-1$ repetition or switch and as an $n-2$ repetition or switch. We omitted $n-1$ repetitions (5% of trials), as well as the subsequent trial, from all analyses, because participants were asked not to repeat tasks and because repetition trials presumably would not involve any task inhibition. Although our primary analysis was based on the task-choice data, we also analyzed RT and proportion of error (PE). For these RT and PE analyses, we treated RTs outside the range of 100–2,500 msec as outliers, eliminating approximately 5% of trials. We also omitted error trials from the RT analyses and omitted trials following errors from both RT and error analyses. For ANOVAs, p values were adjusted using the Greenhouse–Geisser epsilon correction for nonsphericity, where appropriate.

Before we report the $n-2$ repetition data, it is important to consider whether participants freely chose the task on each trial (a core assumption of our experimental logic) or simply responded in a fixed sequence. If participants choose tasks randomly on each trial, without repetition, then the probability that any sequence of three tasks would match the previous sequence of three tasks is .125. Four of the 36 participants, however, frequently repeated a three-task sequence (e.g., ABCABC; range = .440 to .720). In addition, 1 other participant frequently repeated a two-task sequence (e.g., ABABAB; proportion = .718). Because these participants appear to have violated a fundamental assumption of our experimental logic, they were excluded from the final data analyses. The remaining 31 participants repeated task sequences infrequently (.090 for three-task sequences and .040 for two-task sequences), close to what one would expect from completely random task selection.

Because participants always faced a choice between two tasks (after eliminating $n-1$ repetitions), the proportion of $n-2$ repetitions in a random task sequence would be .500. In the task choice analyses, the proportion of $n-2$ switches was $.553 \pm .038$ (95% confidence interval), whereas the proportion of $n-2$ repetitions was only $.447 \pm .038$. Thus, as predicted by task inhibition theory, participants systematically avoided repeating the $n-2$ task.

Table 1
Mean Proportion of Trials for Each Combination of
Task Type (With Standard Error of the Mean, *SEM*)
and $n-2$ Task Transition in Experiments 1 and 2

| | $n-2$ Task Transition | | | |
| | Repetition | | Switch | |
Task Type	M	SEM	M	SEM
Experiment 1				
Parity	.191	.018	.176	.008
Size	.150	.009	.190	.007
Distance	.106	.009	.187	.006
Total	.447	.019	.553	.019
Experiment 2				
Parity	.132	.011	.203	.010
Size	.150	.012	.186	.008
Distance	.104	.009	.225	.008
Total	.386	.018	.614	.018

We also conducted an ANOVA on the mean proportion of $n-2$ repetitions as a function of task type (parity, size, or distance). As can be seen in Table 1, the proportions of $n-2$ repetitions were higher for the parity and size tasks than for the distance task [$F(2,60) = 9.10, p < .001, \eta_p^2 = .23$]. This effect makes sense in light of task inhibition theory and in light of the fact that the distance task had the longest mean RT (as noted below). Participants should avoid a task that is both strongly inhibited and inherently difficult compared with the alternative task. But they might sometimes perform an inhibited task ($n-2$ repetition) if that task is inherently easy compared with the alternative task. For example, they might willingly perform an inhibited parity task if the alternative is the difficult distance task.

The preceding comments suggest that a more sensitive test of inhibition could be obtained by examining only trials on which participants faced a choice between equal rivals (the parity and size tasks). Indeed, on such trials the proportion of $n-2$ repetitions was especially low (only $.390\pm.040$).

RT and PE data were analyzed as a function of task type and $n-2$ task transition. Table 2 shows the resulting RTs and PEs. For the RT analyses, mean RT was shorter for the parity task than for the size task or for the distance task [$F(2,60) = 16.94, p < .0001, \eta_p^2 = .36$]. These numbers are generally consistent with the proportions of $n-2$ repetitions for those tasks, on the assumption that people prefer to perform tasks that take less time (see Figure 1). Participants performed $n-2$ repetitions more slowly than $n-2$ switches [$F(1,30) = 19.10, p < .0001, \eta_p^2 = .39$], reflecting an $n-2$ repetition cost of 52 msec. Although the $n-2$ repetition cost was numerically larger for the size task and parity task than for the distance task, the differences were not significant ($Fs < 1$).

For the PE data analyses, the only significant effect was task type [$F(2,60) = 32.70, p < .0001, \eta_p^2 = .52$]. Mean PEs were .047, .024, and .159 for the parity, size, and distance tasks, respectively.

In sum, participants avoided performing $n-2$ repetitions. Also, there was a substantial $n-2$ repetition cost of 52 msec on RT. Thus, the present data provide two converging lines of evidence for task-set inhibition. The evidence that inhibition is applied even in the voluntary task-switching paradigm (with no task cues) indicates that inhibition is not an artifact of using explicit task cues.

EXPERIMENT 2

In Experiment 1, we required participants to always switch tasks, which simplified the predictions and data analyses. It could be argued, however, that a prohibition against $n-1$ repetition might be mistakenly interpreted as a prohibition against $n-2$ repetition as well. Also, because the number of task options was reduced, participants might have tended to adopt the simplest repeating task sequence rather than voluntarily choosing a task. We dealt with this problem by eliminating participants who consistently used a fixed sequence, but clearly, it would be advantageous to reduce such tendencies in the first place.

In Experiment 2, therefore, we allowed participants to either repeat or switch tasks. Allowing task repetitions increased the number of task options on each trial from two to three, reducing the likelihood that participants would adhere to any particular task sequence. This procedure also more closely resembled the voluntary task-switching procedure developed by Arrington and Logan (2004), with the exception that we used three tasks instead of two.

Method

Participants. There were 34 new participants, drawn from the same participant pool as in Experiment 1. Three participants' data were excluded from the final data analyses (see below).

Table 2
Mean Response Times (RTs, in Milliseconds) and
Proportions of Errors (PEs) in Experiments 1 and 2
As a Function of Task Type and $n-2$ Task Transition,
With Standard Errors of the Mean (*SEM*s)

| | $n-2$ Task Transition | | | | $n-2$ Repetition Cost | |
| | Repetition | | Switch | | | |
	M	SEM	M	SEM	M	SEM
	Experiment 1					
RT						
Parity	1,006	42	950	41	56	19
Size	1,065	61	991	58	74	24
Distance	1,168	60	1,143	50	25	27
PE						
Parity	.045	.009	.048	.008	−.003	.008
Size	.026	.005	.022	.004	.004	.006
Distance	.177	.027	.142	.019	.035	.019
	Experiment 2					
RT						
Parity	871	37	832	38	39	27
Size	905	49	803	40	102	35
Distance	962	48	940	43	22	29
PE						
Parity	.069	.015	.047	.009	.022	.015
Size	.040	.011	.030	.008	.010	.008
Distance	.116	.023	.106	.020	.010	.014

Note—The $n-2$ repetition cost was measured by subtracting performance measures in the $n-2$ switch condition from performance measures in the $n-2$ repetition condition.
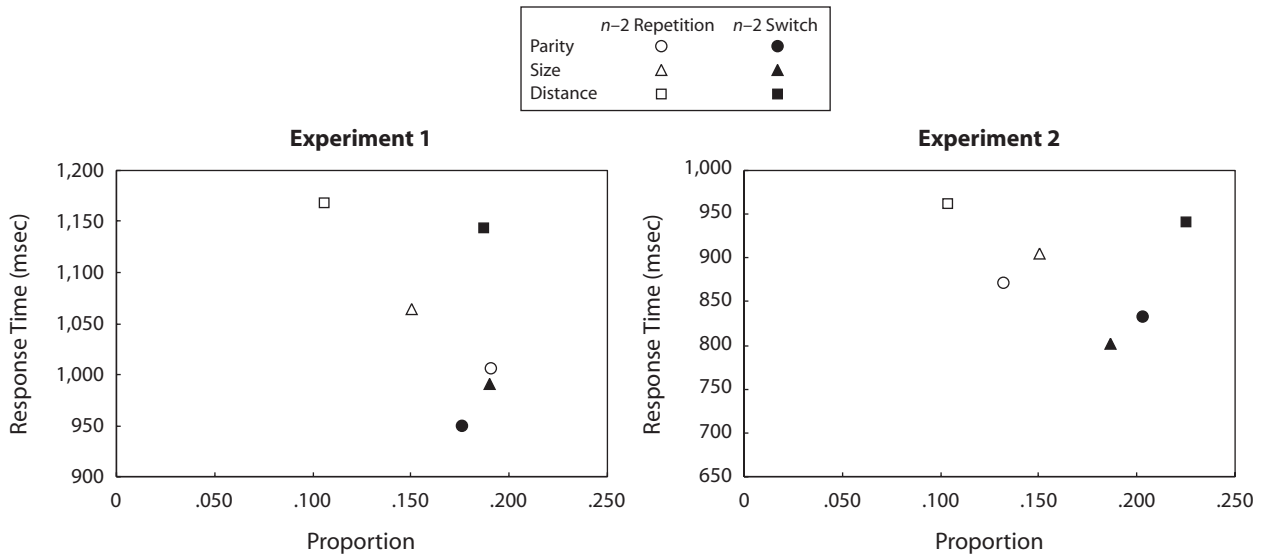
Figure 1. Mean response time for each condition, plotted against the proportion of trials for that condition, in Experiments 1 and 2.

Apparatus, Stimuli, and Procedure. Relative to Experiment 1, the only change was that participants were allowed to repeat the task.

Results and Discussion

As in Experiment 1, we first considered whether participants tended to respond in a fixed sequence. The probability of repeating a three-task sequence (ABCABC) by chance is .037. Three of the 34 participants produced repetitions more frequently than .037 (range = .102 to .228), and, thus, their data were excluded. Averaged across the remaining 31 participants, the probability of repeating a three-task sequence was only .030. No participants consistently used a repeating two-task sequence (e.g., ABABAB).

Before assessing task-set inhibition, we first examined the proportions of $n-1$ switches and repetitions. The mean proportion of $n-1$ switches was .639±.042 (95% confidence interval), whereas the proportion of $n-1$ repetitions was .361±.042. This proportion of $n-1$ repetitions is slightly (but not significantly) higher than would be found in a truly random sequence of the three tasks (.333), consistent with a preference to repeat tasks. The proportions were of $n-1$ repetitions slightly higher for the parity and distance tasks than for the size task [$F(2,60) = 4.59, p < .05, \eta_p^2 = .13$]. As in Experiment 1, this pattern is consistent with the differences in overall RTs between tasks.[2] An $n-2$ repetition is especially unlikely for the most difficult task (i.e., the distance task) when the competitor is both inherently easier and there is (by hypothesis) less inhibition.

Our main goal in the analyses of task choice was to assess task-set inhibition. Thus, as in Experiment 1, we excluded $n-1$ repetitions and trials following a task repetition. Application of RT cutoffs (only for the RT and PE analyses) eliminated an additional 3% of trials. Tables 1 and 2 show the resulting task choice proportions, RTs, and PE.

To look for evidence of task-set inhibition, we examined the proportion of $n-2$ repetitions. There were two task choices (having already excluded $n-1$ repetition trials from further analysis), so the proportion of $n-2$ repetitions in a random task sequence would be .500. The results generally resembled those of Experiment 1, in that participants strongly avoided repeating the $n-2$ task. The proportion of $n-2$ switches was .614±.038 (95% confidence interval), whereas the proportion of $n-2$ repetitions was only .386±.038. Further analyses on the mean proportion of $n-2$ repetitions as a function of task type showed that the proportions of $n-2$ repetitions were higher for the parity and size tasks than for the distance task [$F(2,60) = 6.68, p < .01, \eta_p^2 = .18$] (see Table 1).

RT and PE data were again analyzed as a function of task type and $n-2$ task transition. Mean RTs were shorter for the parity and size tasks than for the distance task [$F(2,60) = 13.11, p < .0001, \eta_p^2 = .30$]. These numbers again are consistent with the proportion of $n-2$ repetitions for each task, on the assumption that people prefer to perform tasks that take less time (see Figure 1). Participants performed $n-2$ repetitions (913 msec) more slowly than $n-2$ switches (858 msec) [$F(1,30) = 7.30, p < .05, \eta_p^2 = .20$]. This $n-2$ repetition cost of 54 msec is similar to the 52-msec cost obtained in Experiment 1. Although the $n-2$ repetition cost was largest for the size task (102 msec), intermediate for the parity task (39 msec), and smallest for the distance task (22 msec), the difference was not statistically significant [$F(2,60) = 2.28, p = .1141, \eta_p^2 = .07$].

As in Experiment 1, the PE data analyses revealed a significant effect only of task type [$F(2,60) = 11.14, p < .0001, \eta_p^2 = .27$]. Mean PEs were .058, .035, and .111 for the parity, size, and distance tasks, respectively.

In sum, Experiment 2 allowed immediate task repetition (i.e., $n-1$ repetition), and in fact, participants tended to prefer performing such task repetitions. Nevertheless, partici-

pants still avoided performing $n-2$ repetitions, a result that replicates the findings of Experiment 1. There was also a substantial $n-2$ repetition cost of 54 msec on RT, providing converging evidence that people inhibit task sets.

GENERAL DISCUSSION

The present study looked for converging evidence of task-set inhibition in voluntary task selection. On each trial, participants were free to decide which task to perform. Previous studies have shown that participants favor repeating the task that they had performed on the previous trial (over .600; Arrington & Logan, 2004), presumably because it was the most active. The question addressed here was whether participants would also prefer the task that they had performed on the $n-2$ trial or whether they would avoid it due to lingering inhibition.

Random task selection would produce $n-2$ repetitions on half of the trials (after excluding $n-1$ repetitions). As task-set inhibition theory predicts, however, the proportion of $n-2$ repetitions was substantially less than .500, whether participants were required to always switch tasks (.447 in Experiment 1) or not (.386 in Experiment 2). Further supporting task-set inhibition theory, substantial $n-2$ repetition costs on RT were obtained in both Experiments 1 and 2 (52 and 54 msec, respectively).

The present study also demonstrated that task-set inhibition occurs not just with explicit task cues, as in almost all previous studies supporting task-set inhibition, but also when people voluntarily switch tasks (see also Mayr & Bell, 2006). We sometimes use task cues in the real world (as when following instructions or responding to an alarm) but, arguably, real-world tasks are usually chosen voluntarily. It is reassuring to know that task-set inhibition applies broadly. Furthermore, there is some evidence that task switching in the voluntary task-switching paradigm is qualitatively different from task switching in the traditional cuing paradigm. A recent fMRI study by Forstmann, Brass, Koch, and von Cramon (2006) suggested that the brain areas utilized in voluntary task selection are different from those engaged by explicit task cues. Nevertheless, task sets are inhibited in both cases.

The participants' avoidance of $n-2$ repetition and the interaction of $n-2$ repetition with task type are consistent with task-set inhibition. One could argue, however, that $n-2$ repetitions are infrequent simply because participants think that an ABA sequence is less random than an ABC sequence. However, it is questionable whether, in a demanding experiment, participants keep track of the previous task sequence (beyond the $n-1$ task). Furthermore, Mayr and Bell (2006) argued that people tend to use a discrete-event strategy—treating trials individually rather than keeping track of previous tasks—in the voluntary task-switching paradigm. They found that participants who switched more frequently tended to produce a larger elevation in RT for $n-1$ repetitions than for single-task blocks. They argued that task inhibition makes it easier to switch tasks but slows performance if the task is repeated.

Inspired by their findings, we predicted that in Experiment 2, in which task repetitions were allowed, participants with the strongest inhibition should have the highest frequency of $n-1$ switches and the strongest avoidance of $n-2$ repetitions. Indeed, these variables were significantly correlated across participants ($r = -.357, p < .05$). This finding strengthens the case that the avoidance of $n-2$ repetitions is specifically due to inhibition, rather than to some other influence.

In summary, we have provided a new line of evidence for task-set inhibition, based on task choice within a voluntary task-switching procedure. We propose that inhibition is applied when one is switching away from a task, to reduce its accessibility relative to the new task. This is especially important when the tasks use the same stimuli and the same responses. Inhibition appears to linger over time and cannot easily be undone via deliberate task preparation. Thus, people tend to avoid switching back to that task until the inhibition has passively subsided. If a person does perform the inhibited task (due to choice or to an explicit instruction), it will take extra time because of the need to overcome the inhibition.

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NOTES

1. Similar predictions would follow if, instead of being applied proactively (in anticipation of a switch), inhibition is applied reactively, in response to competition encountered during the trial following the switch (e.g., Schuch & Koch, 2003; but see Lien et al., 2006, for evidence favoring proactive inhibition over reactive inhibition).

2. As a reviewer noted, the repetition trials of Experiment 2 provide a relatively clean assessment of differences in task difficulty (unconfounded with task-switching difficulty). As it turns out, the effects of task type on RT are nearly identical for repetition and switch trials ($F < 1$). Mean RTs for the parity, size, and distance tasks were 787, 798, and 904 msec, respectively, on repetition trials and 826, 818, and 946 msec, respectively, on switch trials.