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To cite this article: Franziska R. Richter & Nick Yeung (2015) Corresponding influences of top-down control on task switching and long-term memory, The Quarterly Journal of Experimental Psychology, 68:6, 1124-1147, DOI: 10.1080/17470218.2014.976579

To link to this article: http://dx.doi.org/10.1080/17470218.2014.976579

Accepted author version posted online: 22 Oct 2014.
Published online: 18 Nov 2014.

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Corresponding influences of top-down control on task switching and long-term memory

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(Received 20 March 2014; accepted 25 August 2014; first published online 18 November 2014)

Three experiments investigated the impact of cognitive control on current performance and later memory in task switching. Participants first switched between object and word classification tasks, performed on picture–word stimuli that each appeared only once, then were tested for their recognition memory of these items. Each experiment replicated the recent finding that task switching results in reduced selectivity in later memory for task-relevant over task-irrelevant items. Top-down control was manipulated through varying the time available for advance task preparation (Experiment 1), the freedom of choice over which task to perform (Experiment 2), and the availability of reward incentives (Experiment 3). For each manipulation, more effective top-down control during task switching was associated with increased selectivity in memory for task-relevant information. These findings shed new light on the role of cognitive control in long-term memory encoding, in particular supporting an interactive model in which long-term memory reflects the enduring traces of perceptual and cognitive processes that operate under the selective influence of top-down control.

Keywords: Task switching; Long-term memory; Cognitive control; Attention; Episodic memory.

Interest in the interaction between cognitive control and long-term memory has grown in recent years (Chun & Johnson, 2011; Chun & Turk-Browne, 2007). This interest has been motivated in part by behavioural evidence showing that successful memory encoding depends on effective allocation of attentional control to the items to be remembered and to the accompanying encoding task (Anderson, Craik, & Naveh-Benjamin, 1998; Craik, Govoni, Naveh-Benjamin, & Anderson, 1996; Naveh-Benjamin, Craik, Gavrilcescu, & Anderson, 2000; Naveh-Benjamin, Guez, & Marom, 2003), and in part by evidence of overlap in activity in neuroimaging studies of attention and memory, in both frontal (Buckner, 2003) and parietal regions (Cabeza, Ciaramelli, Olson, & Moscovitch, 2008). However, relatively few studies to date have attempted direct comparison such that control processes and memory processes are evaluated in the same experiment. The present study attempts this kind of direct comparison, focusing in particular on the contribution of top-down control to long-term memory encoding. The experiments reported here build on our previous work suggesting an interactive relationship between cognitive control and memory (Richter...
This work combined a task-switching paradigm with a later memory test: After switching between object and word categorization tasks with trial-unique picture-word stimuli, participants were tested for their recognition memory of the items encountered during switching. We replicated the often-reported effect that task switching is associated with performance costs (referred to as switch costs), in terms of slowed reaction times (RTs) and increased error rates (Jersild, 1927; Rogers & Monsell, 1995). Crucially, task switching also had a systematic impact on later memory, where it resulted in less confident recognition of task-relevant items but actually more confident recognition of task-irrelevant items. These results suggest that selective processing is a key factor in successful task performance and later memory, with this selectivity hampered during task switching as a reflection of the increased control demand associated with such switches (cf. Meiran, 2000; Yeung, Nystrom, Aronson, & Cohen, 2006). Here we test a key prediction of this interpretation: that top-down control, when applied to improve current performance, should have a corresponding impact on later memory by increasing its selectivity for task-relevant information. That is, we predict that whereas conditions of increased control demand should be associated with decreased task performance and decreased selectivity of memory (Richter & Yeung, 2012), increased application of top-down control in these conditions should improve current performance and later memory for task-relevant information. In this regard, our logic develops and extends our interpretation of our earlier results to incorporate the notion that the extent to which control is successfully applied should result in improved performance through shielding of the current task from irrelevant distraction (cf. Dreisbach & Haider, 2008).

Our interactive model of control and memory stands in contrast to a popular alternative, which proposes instead a competitive relationship in which both processes draw on shared, capacity-limited resources (Craik et al., 1996; Otten & Rugg, 2001). Such models suggest that if cognitive control is required to conduct a task, fewer resources will be available to encode information into long-term memory. In support of this view, previous studies have shown detrimental effects on encoding when participants performed a difficult compared to an easy secondary task in a dual-task paradigm (Kensinger, Clarke, & Corkin, 2003; see also Uncapher & Rugg, 2005), and that control-demanding task switching limits the amount of information to be encoded (Otten & Rugg, 2001). Resource-limitation accounts are related to influential models of task switching which propose that control operations must be completed before task processes can begin when the task is switched, resulting in observed switch costs (Rogers & Monsell, 1995; Rubenstein, Meyer, & Evans, 2001). A key prediction of resource-limitation models is that increasing the demand for control should result in impaired memory, as resources are drawn away from the encoding process. However, our earlier results question this prediction, showing that this effect on memory is limited to task-relevant information, with task-irrelevant information actually being more confidently recognized after being encountered during control-demanding task switching (Richter & Yeung, 2012).

As such, our previous work supports the idea that between-task interference is a key source of control demands in task switching (Richter & Yeung, 2012), consistent with the conclusions of several recent reviews (Richter & Yeung, 2014; Vandierendonck, Liefooghe, & Verbruggen, 2010). Our results moreover provide evidence that the relationship between cognitive control and long-term memory is best characterized in terms of selectivity of processing, with control serving to bias processing and encoding toward information relevant to the current task and away from irrelevant distraction. However, thus far, our analyses have demonstrated this impact only in a negative fashion, providing evidence of reduced selectivity when control demands are increased (due to switching or the presence of salient distractors). In the current paper we aim to extend these findings to test the more positive prediction that systematic strengthening of applied top-down control should result in corresponding performance improvements.

Our previous results stressed the role of selective processing for control and memory. Accordingly, we
predicted that if the main benefit of attention is to increase the selectivity of processing, then more effective application of top-down control should enhance the selectivity of memory as well. Showing that this is the case is an important step in demonstrating that the same mechanisms that are known to be related to task performance and working memory (e.g., Gazzaley, Cooney, Rissman, & D’Esposito, 2005; Gazzaley & Nobre, 2012; Rutman, Clapp, Chadick, & Gazzaley, 2010; Zanto, Rubens, Thangavel, & Gazzaley, 2011) also have an effect on long-term memory encoding, a relationship that has been discussed in recent literature (cf. Bollinger, Rubens, Zanto, & Gazzaley, 2010; Khader, Jost, Ranganath, & Rösler, 2010; Meeuwissen, Takshima, Fernandez, & Jensen, 2011). Thus, our core prediction was that more effective top-down control would differentially affect task-relevant and task-irrelevant information, improving memory for the former while impairing memory for the latter.

Effective top-down control requires time, will, and motivation. For this reason, the present experiments used three experimental manipulations to induce increased top-down processing: varying the time to prepare the task (cue–stimulus interval, or CSI; Experiment 1); contrasting standard cued (or “instructed”) switching with a voluntary switch condition in which participants themselves choose which task to perform (Experiment 2); and, lastly, a manipulation of motivation via reward incentives (Experiment 3). We first give a brief overview of the background to each of these manipulations here, with more detailed reviews of relevant findings preceding each experiment.

One of the most common and well-documented top-down effects in task-switching research is that of manipulating preparation time. It has been shown that switch costs typically decrease with increased preparation time (e.g., Meiran, 1996; Monsell, 2003; but see Altmann, 2004a). This effect has been taken to indicate the successful engagement of cognitive control. As CSI manipulations have been thoroughly studied in the task-switching literature, this manipulation was used as a first method to try to systematically increase top-down control here. The effects of manipulations of preparation time were investigated in Experiment 1.

The second method with which we aimed to influence top-down control was through introducing a voluntary switching condition. In this paradigm, participants are required to choose which task to perform on each trial. Voluntary task switching was initially introduced as a more direct test of top-down control than traditional task switching, as task choice seems to require top-down processes (Arrington & Logan, 2004; 2005). However, more recent findings suggest that top-down control is actually weakened during voluntary task switching, reflecting inherent ambiguity about which task should be performed as well as bottom-up influences that infect intentions and task choice as well as impacting task performance (Demanet & Liefooghe, 2014; Millington, Poljac, & Yeung, 2013). Experiment 2 explored these ideas further to contrast the effects of voluntary and instructed task switching on task performance and memory.

Whereas voluntary task switching draws on internal motivation, an extrinsic motivational factor that has been widely researched is reward. The promise of reward has been shown to produce robust performance improvements (Padmala & Pessoa, 2011; Zedelius, Veling, Bijleveld, & Aarts, 2012). For example, decreased RTs and error rates have been observed in response to incongruent stimuli in a reward compared to a no-reward condition (Locke & Braver, 2008). Reward has also been associated with performance enhancement such as a reduction in switch costs in task switching (Kleinsorge & Rinkenauer, 2012). Of interest here was the impact of reward on task switching and later memory, assessed in Experiment 3.

For each of these manipulations of top-down control, we make some general predictions. Because increases in control demand (e.g., on switch trials) seem to limit the selectivity with which we process information, we predicted that effective application of top-down control would counteract these effects: Enhanced top-down control should result in better focusing on task-relevant information and reduced processing of
task-irrelevant information, which should be evident in the task-switching data as faster RTs and reduced error rates, as well as a reduction of switch costs. In memory, the effects of this selective processing should be evident in more selective encoding (Uncapher & Rugg, 2009). Thus, we predicted that manipulations of top-down control would affect performance and memory in a similar way, by increasing the selectivity of processing.

An alternative prediction could be that top-down control will bias the allocation of resources away from memory encoding, thus resulting in a global decrement in memory (i.e., one affecting both task-relevant and irrelevant information; Broadbent, 1958; Norman & Bobrow, 1975). It could also be predicted, however, that more effectively applied control will result in an overall benefit to memory, because control processes can be employed proactively (Braver, 2012), thereby reducing competition with memory encoding after the stimulus appears. This prediction would be consistent with models of task switching that posit control processes that must be completed before task processing can begin (Rogers & Monsell, 1995; Rubinstein et al., 2001). Although these resource-competition model predictions differ in whether effective top-down control will benefit or harm later memory, they agree that corresponding effects should be observed for both task-relevant and task-irrelevant items. As such, their predictions differ critically from those of our proposed interactive model of memory and cognitive control, which holds that effective top-down control will have opposing effects on memory for task-relevant and task-irrelevant information—improving the former and impairing the latter.

The alternative predictions outlined above were tested in three experiments that built on methods developed in our previous work, in which task switching and recognition memory are combined (Richter & Yeung, 2012). Participants first conducted a task-switching phase in which they switched between object and word classification tasks, performed on stimuli that appeared only once each during the task-switching phase. Subjects then completed a recognition memory test on the words and objects presented during task switching. During the task-switching phase, top-down control was manipulated either between blocks (Experiment 1) or in short trial sequences within the block (Experiment 2 and 3). Of interest was the impact of these manipulations of top-down control on later recognition memory ratings for attended and unattended items from the task-switching phase.

**EXPERIMENT 1**

The effect of task preparation is one of the most thoroughly investigated top-down effects reported in the task-switching literature (Grange & Houghton, 2014; Monsell, 2003; Vandierendonck et al., 2010). An overall reduction in RTs and error rates is typically observed as the time available for preparation is increased, alongside a reduction in the switch cost (but see Altmann, 2004a, 2004b, for notable exceptions). The effect of preparation in cued task-switching designs has been argued to reflect two processes: active preparation and the passive decay of the previous task set (e.g., Koch & Allport, 2006; Meiran, 1996). Evidence for active preparation stems from the finding that RTs tend to decrease when the time between a task cue and the stimulus increases, even if the overall interval between the trials is held constant (Meiran, Chorev, & Sapir, 2000; but see Horoufchin, Philipp, & Koch, 2011a, 2011b, for contrasting evidence and interpretation). For this reason, designs investigating task preparation need to control for passive decay by keeping the RSI constant while varying the CSI, so that passive decay can be assumed to be comparable between different preparation times.
Experiment 1 compared a condition in which the CSI was short (5 ms), giving participants almost no time to prepare the task indicated by the cue, with a condition in which the CSI was long (1000 ms), giving them ample time to prepare (Rogers & Monsell, 1995). On the basis of previous research, we expected that longer preparation times should lead to improved RTs and error rates, and importantly also to reduced costs of switching between tasks (Meiran et al., 2000), as participants would be expected to apply control more effectively in this condition. Critically, these performance improvements during task switching should be associated with higher memory ratings for attended and lower memory ratings for unattended information in trials with long preparation time. That is, we predict that preparation time will improve focusing on the relevant material rather than creating a generic “favourable state of mind” for encoding (cf. Chun & Turk-Browne, 2007) that should benefit all information regardless of relevance.

Method

Participants
There were 16 paid participants, five male and 11 female, aged between 18 and 27 years (mean = 20.6, SD = 2.4). All of them were native English speakers and gave informed consent.

Material
Stimuli included in this experiment were words and pictures of objects. Stimuli were presented on a black background with the words superimposed on the pictures in brown font colour. The pictures were photo-realistic objects drawn from the Hemera Photo-Objects Collections (Hemera Photo Objects, Hull, Quebec, Canada). The words were a subset taken from the stimulus set reported by Poldrack et al. (1999), which consisted of a mix of abstract and concrete nouns that were 1, 2, or 3 syllables long. Words and objects were assigned randomly to the experimental conditions, separately for each participant, such that pairings of objects and words were unique to each trial. Thus, pairings were rarely, if ever, repeated across participants, making it unlikely that potential semantic associations between these pairs could be driving any experimental effects observed.

Procedure
Participants first performed task-switching blocks in which trial-unique words and pictures were presented. Following these task-switching blocks, subjects were tested for their recognition memory of the words and pictures they had seen.

In task-switching blocks, participants saw a series of compound picture–word stimuli and were asked to indicate either whether the pictured object was natural or man-made, or whether the word was abstract or concrete. At the beginning of each trial, a coloured frame cue appeared for either 5 ms (short CSI) or 1000 ms (long CSI), indicating which task should be performed. To enhance ease of interpretability, the colour of the cue frame matched the colour of the stimuli: A brown frame signified that they should attend to the word; a grey frame indicated that they should attend to the object. After this CSI, a compound object–word stimulus appeared inside the cue frame for 300 ms before it disappeared again (Figure 1). There was no time limit on the responses, but participants were instructed to respond as quickly as possible while being accurate. Participants responded by pressing one of four keys on a standard computer keyboard (the “x” and “n”
keys were used for the object task, and the “z” and “m” keys for the word task; the index fingers were used for the object task, and the middle fingers for the word task). The screen cleared after the participant’s response, followed by the cue for the next trial.

CSI length varied blockwise, as previous research has indicated that varying CSI blockwise rather than on a trial-by-trial level might increase participants’ effort to prepare in the long CSI condition, as no uncertainty exists about whether or not preparation could be completed (cf. Rogers & Monsell, 1995). The response–cue interval was set to 1500 ms in the short CSI condition and 505 ms in the long CSI condition, resulting in a constant overall response–stimulus interval (RSI) of 1505 ms (due to synchronization with the monitor screen refresh, the intervals were in practice slightly variable, with an average approximately 10 ms longer delays than stated above).

Participants first conducted practice blocks for each task separately, then two practice blocks of task switching. Each block comprised 30 trials, with the first three blocks having short CSIs and the last block having long CSIs, so participants could get accustomed to both conditions. After practice, participants completed eight task-switching blocks of 30 trials each in the main experiment. The order of CSI length in the blocks was counterbalanced between participants and was either SLLSSLLS or LSSLLSSL (with S indicating a short CSI and L indicating a long CSI). There were explicit instructions about preparation time: Participants were told that “The frame will appear before the picture and the word are shown” and were instructed to “use this additional time to prepare for the task, so that you can respond quickly and accurately”.

After this task-switching part of the study, which critically served as an encoding phase, participants completed a surprise memory test. Participants were presented with a single stimulus (either an object or a word) in each trial, which could be either old (i.e., presented during task switching; 480 items, ~80% of all memory test items) or new (i.e., not presented either during training or task switching; 112 items, ~20% of all items). They rated each stimulus on a 1–6 scale, with 1 indicating a sure judgement that the item was new and 6 indicating a sure judgement that the item was old. Participants were instructed to only use the 6 response when they were able to recall specific detail about having seen this item in the task-switching phase. We take these ratings as an index of the quality of retrieved memories—in common with much prior research (Yonelinas, Aly, Wang, & Koen, 2010), where subjective ratings are typically found to be predictive of objective accuracy (Dunlosky & Metcalfe, 2008; Koriat & Goldsmith, 1996)—while acknowledging that higher confidence is an imperfect index of better memory (e.g., Roediger & DeSoto, 2014; Schacter, Norman, & Koutstaal, 1998). Ratings between extreme values of 1 and 6 were used for less confident answers. Participants used the number keys on the main keyboard and responded with both hands. Answers to the memory test were time-limited to 2500 ms, otherwise the word “LATE!” appeared in red letters for 1000 ms. Following a response or after the “LATE!” feedback, a 500-ms intertrial interval (ITI) elapsed before the next trial started.

The memory test consisted of a total of 602 trials. The first 10 trials were excluded from subsequent analysis because they were included in a training block to explain the task. After this training, participants conducted eight blocks of the memory test with 74 trials each. The blocks were divided into object blocks (O, only objects were presented) and word blocks (W, only words were presented) and were delivered in WOOOWWOOW or OWOOOWWO order, counterbalanced across participants. The order in which the stimuli were presented within the blocks was randomized. After each block, participants received feedback on their performance.

For analysis of the task-switching data, RT outliers (3 SDs above the mean) were excluded. This cut-off of 3 standard deviations resulted in 2.6% and 3.8% of the trials being rejected in the short and long CSI conditions, respectively (3.1% of switch trials and 3.6% of repeat trials). Data were also screened for very short RTs (<100 ms), but no additional trials were excluded with this
criterion. Additionally, posterror trials were excluded. Trials answered incorrectly during task switching and trials with late (i.e., missing) responses in the memory test were excluded from analysis of the memory data.

Results

Task switching
To assess the effect of preparation time on task performance and switch costs, an analysis of variance (ANOVA) with variables transition type (switch vs. repeat) and CSI (short vs. long) was conducted (see Table 1). The ANOVA revealed main effects of transition in the RTs, $F(1, 15) = 53.91, p < .01, \eta_p^2 = .782$, and error rates, $F(1, 15) = 5.21, p < .05, \eta_p^2 = .258$, with longer RTs and higher error rates in switch than in repeat trials (1287 ms vs. 1068 ms, and 6.9% vs. 4.8%, respectively). Furthermore, the main effect of CSI was significant for RTs, $F(1, 15) = 91.11, p < .01, \eta_p^2 = .859$, with slower RTs in the short than in the long CSI condition (1333 ms vs. 1022 ms), and for error rates, $F(1, 15) = 8.57, p < .01, \eta_p^2 = .364$, with more errors in the short than in the long CSI condition (7.0% vs. 4.6%).

There was, however, no reliable interaction between transition and CSI ($F_3 < 1$ for both RTs and error rates). Numerically, there was a larger cost of switching in the short than the long CSI condition for RTs (241 ms vs. 196 ms) and error rates (2.5% vs. 1.8%), but this effect was inconsistent across participants. This lack of effect is surprising given the wide replication in task-switching studies (cf. Karayanidis et al., 2010; Vandierendonck et al., 2010). Possible reasons for the lack of this effect are considered in the discussion; for now we only note that we failed to replicate the effect of CSI on the switch cost in several pilot studies that preceded the present design. Nevertheless, a robust main effect of CSI on overall task performance was observed. This effect is of interest, as it enables the investigation of possible effects of CSI on later memory.

Memory
Preliminary comparison between memory ratings for old and new items revealed a reliable difference, with old items receiving on average higher ratings than new items (3.90 vs. 2.81, respectively), $t(15) = 16.81, p < .01, d = 4.07$, indicating that participants performed the memory task as instructed. Subsequent analysis focused on memory ratings for old items. Specifically, to assess whether the same variables as those that affect performance during task switching also affect memory, we conducted an ANOVA on item recognition ratings with factors of transition type, CSI, and attention, which were defined according to how each memory-test item was presented during earlier task switching. This analysis revealed a main effect of transition, $F(1, 15) = 7.89, p < .05, \eta_p^2 = .345$, with higher memory ratings for items presented in repeat than in switch trials (mean memory ratings of 3.84 vs. 3.76), as well as a main effect of attention, $F(1, 15) = 143.30, p < .01$, for now we only note that we failed to replicate the effect of CSI on the switch cost in several pilot studies that preceded the present design. Nevertheless, a robust main effect of CSI on overall task performance was observed. This effect is of interest, as it enables the investigation of possible effects of CSI on later memory.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Transition type</th>
<th>Experiment 1</th>
<th>Experiment 2</th>
<th>Experiment 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Short</td>
<td>Long</td>
<td>Instructed</td>
<td>Voluntary</td>
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<tr>
<td>RT (ms)</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Switch</td>
<td>1453</td>
<td>1220</td>
<td>1091</td>
<td>1161</td>
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<tr>
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<td>924</td>
<td>865</td>
<td>972</td>
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<tr>
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<td>226</td>
<td>89</td>
</tr>
<tr>
<td>Error rate (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Switch</td>
<td>8.3</td>
<td>5.8</td>
<td>8.6</td>
<td>8.2</td>
</tr>
<tr>
<td>Repeat</td>
<td>5.8</td>
<td>3.7</td>
<td>6.4</td>
<td>8</td>
</tr>
<tr>
<td>Switch cost</td>
<td>2.5</td>
<td>2.1</td>
<td>2.2</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Note: RT = reaction time.
\( \eta^2_p = .905 \), with higher memory ratings for attended than unattended items (mean memory ratings 4.49 vs. 3.11). The main effect of CSI did not reach significance, \( F(1, 15) = 1.06, p = .320 \) (mean memory ratings of 3.78 for the short CSI condition and 3.82 for the long CSI condition).

The main effects were qualified by several interactions. Reliable interactions were observed between transition and attention, \( F(1, 15) = 55.72, p < .01, \eta^2_p = .788 \), transition and CSI, \( F(1, 15) = 9.95, p < .01, \eta^2_p = .399 \), and between CSI and attention, \( F(1, 15) = 10.36, p < .01, \eta^2_p = .409 \) (see Figure 2). The interaction between attention and transition indicated that the difference in memory ratings for attended and unattended items (i.e., memory selectivity) was reduced on switch trials. Pairwise comparisons revealed a significant decrease in ratings between attended repeat and switch trials, \( t(15) = 5.74, p < .01, d = 0.68 \) and a significant increase in ratings between unattended repeat and switch trials, \( t(15) = 2.51, p < .05, d = 0.21 \). These results replicate key findings from our first study using the combined switching and memory paradigm (Richter & Yeung, 2012).

The interaction between transition and CSI reflected the fact that memory ratings for repeat-trial items increased when CSI was long compared to when CSI was short, \( t(15) = 2.62, p < .05, d = 0.49 \), whereas a corresponding effect was not observed for items seen on switch trials, \( t(15) = 1.09, p = .293 \). Lastly, the interaction between CSI and attention indicated a larger difference between attended and unattended items—that is, greater memory selectivity—in long than in short CSI trials (see Figure 3). Memory ratings for unattended items were numerically higher when CSI was short (3.14) than when CSI was long (3.07), but the difference was not reliable, \( t(15) = 1.60, p = .130 \). There was a significant increase in memory scores for attended items from the short CSI condition (mean memory rating of 4.41) to the long CSI condition (mean memory rating of 4.56), \( t(15) = 2.90, p < .05, d = 0.43 \). Thus, the long CSI condition improved allocation of attention to the relevant stimulus. This effect was consistent with the effect of CSI in the task-switching data, where a longer...
preparation interval was associated with better performance for both switch and repeat trials. The three-way interaction between transition, attention, and CSI did not reach significance, \(F(1, 15) = 2.96, p = .106\). Numerically, the familiar transition by attention interaction (Richter & Yeung, 2012) was seen in the short CSI condition, but was weaker in the long CSI condition. Here, unattended items did not display an increase in memory ratings on switch trials compared to repeat trials. Thus, memory selectivity for attended information was somewhat less impaired by task switching when CSI was long. However, this effect was not statistically reliable, perhaps not surprisingly given a similar lack of interaction between transition type and CSI in task-switching performance.

Discussion
This experiment investigated whether manipulation of preparation time affects task-switching performance and later memory in related ways. The results indicated that the long CSI condition led to an improvement in performance in the task-switching phase, evident as a main effect of CSI. Importantly, the results of the memory test suggested that manipulation of top-down control during task switching also affected later memory: There was a greater difference between memory for attended and unattended items—that is, greater memory selectivity—when the CSI was long than when it was short.

These results indicate that variation in top-down control influences not only the efficiency of current information processing, but also that of later memory (cf. Chun & Johnson, 2011). Specifically, advance preparation led to increased recognition memory ratings for attended information, whereas memory ratings for unattended information were if anything somewhat lower when the CSI was long. This latter result presents a challenge to any theory proposing that control processes compete with memory for limited processing resources (because this competition should affect memory for attended and unattended items alike). Furthermore, by the same reasoning, our findings cannot be explained in terms of fluctuations in the availability of general attentional resources, or more-or-less effective creation of favourable states of mind for encoding. We found no global effect of preparation on memory, but rather evidence that effective top-down control results in increased selectivity of memory for attended, task-relevant information.

Surprisingly, though, we failed to replicate the reduction in switch costs that is typically observed as preparation time is increased (Meiran, 1996; Monsell & Mizon, 2006). This failure was not an isolated occurrence: The present design was determined based on several pilot studies in which weak effects of CSI on switch costs were consistently found. In the course of these pilots, we tried different preparation interval lengths and different cue types, and varied CSI both trial- and block-wise. Pilot data for the design reported here showed the strongest evidence of effects of CSI on switch costs, but again failed to show a reliable effect in the final full sample. Whereas this finding is in contrast to the vast majority of published studies that find a reduction of switch costs with increasing preparation time, several factors might have contributed to the lack of a reliable effect here. For example, it has been suggested that for complex tasks, preparation can be equally beneficial for switch and repeat trials (Dreisbach, Haider, & Kluwe, 2002), or even occur on repetition trials only (Horoufchin et al., 2011a, 2011b). Similarly, it has been shown that there may not be a difference between switch and repeat trials when complex or abstract task cues are used (Monsell & Mizon, 2006). Moreover, it has been suggested that preparation can only counteract switch costs to a limited amount if conflict arises with stimulus presentation (Hakun & Ravizza, 2012), and that limited preparation effects may be found when stimulus–response mappings of the different tasks do not overlap (e.g., Poljac & Bekkering, 2009), or when task switches are frequent (Dreisbach et al., 2002; Koch, 2005). Lastly, several papers have suggested that CSI effects may be weakened by the blocking of CSIs (Horoufchin et al., 2011a, 2011b) contrary to what we found in our pilot data. In fact, the effect of CSI on the switch cost may be less reliable than initially thought, depending on several factors such as within-subject variation of the CSI (e.g.,...
Instead, as described above, CSI exhibited a robust main effect on task-switching performance. This main effect of CSI might be attributed to unspecified factors such as increased arousal, greater predictability of stimulus timing (cf. Sanders, 1972), or advance processing of the task cue before stimulus onset (Logan & Bundesen, 2003; Schneider & Logan, 2005) at long CSIs, rather than specific improvements in cognitive control. However, our finding of increased memory selectivity at the long CSI suggests otherwise, indicating that increasing the time available for preparation led to improved performance at least in part through more effective top-down control that benefited switch and repeat trials alike (see also Koch & Philipp, 2005, who show that cue-based temporal preparation alone cannot explain the effects of CSI on task performance).

To conclude, manipulating preparation time had effects on task performance and corresponding impact on later memory. Contrary to expectation, task switch costs were not reduced as CSI increased. The effect of CSI on later memory ratings consistently did not differ across switch and repeat trials. Instead, task performance and memory ratings for attended information improved when the CSI was long to a similar degree for both switch and repeat trials. Task switching and memory encoding were thus affected by changes in top-down control in a consistent manner, suggesting that common processes support successful task performance and memory encoding.

EXPERIMENT 2

The results of Experiment 1 provide initial support for the hypothesis that top-down control affects task switching and memory in a similar way, by increasing the selectivity of processing. Experiment 2 implemented a different manipulation of top-down control, with the aim of extending the earlier findings and generalizing the conclusions drawn. The current experiment additionally addressed an ongoing debate in the task-switching literature: the question of the nature of control processes in the voluntary task-switching design. In this experiment, participants again completed a task-switching phase followed by a memory test. The task-switching phase in the current experiment consisted of some trial sequences in which participants chose the task themselves (voluntary task switching) and some sequences in which the task required was indicated by a cue (instructed task switching, as in Experiment 1).

Voluntary task switching has received considerable scrutiny in recent years (e.g., Arrington & Yates, 2009; Liefooghe, Demanet, & Vandierendonck, 2010; Orr, Carp, & Weissman, 2012; Orr & Weissman, 2011; Yeung, 2010), as it arguably targets top-down control-related processes more directly (Arrington & Logan, 2005): Arrington and Logan (2005) proposed that the fact that participants are required to choose the task themselves in the voluntary task-switching design ensures that an act of top-down control is involved in the task-switching procedure, which may not be the case in instructed task switching (although this view is not universally held, and the influence of bottom-up factors on voluntary task choice has in recent years been acknowledged, Arrington, 2008). Moreover, if participants choose the task themselves, they might be more committed to perform well, which should increase top-down control, as intrinsic motivation has been shown to increase performance (e.g., Robinson et al., 2012). According to this view, voluntary task switching should be more efficient than instructed task switching.

There are, however, compelling reasons to predict otherwise. First, choosing a task is in itself a demanding process because there is ambiguity about which task to choose (Arrington & Logan, 2005). In addition to (or as a result of) this ambiguity, participants might not have formed a strong decision, and thus a strong task set, for the task to perform. This could impair their performance on the task. In comparison, an instructed task might not involve the participants’ own decision, but clearly indicates a required task (Arrington & Logan, 2005). Thus, the very characteristics of
the voluntary task-switching paradigm that have been argued to make it a superior measure of top-down control might actually result in impaired control and increased conflict in this condition compared to instructed switching. Accordingly, while initial ideas about voluntary task switching would lead us to expect better top-down control in this condition than in instructed switching, recent work strongly suggests otherwise. According to this work, it seems that switch costs in voluntary task switching may in fact be strongly associated with bottom-up, rather than top-down control (Demanet & Liefooghe, 2014; Millington et al., 2013). Therefore, there are good reasons to expect a performance decline rather than benefit for voluntary task switching compared to the instructed condition. For this reason, the current experiment aimed to address the question of control processes in voluntary compared to instructed switching paradigms.

To this end the experiment used a “double registration” procedure in which participants on each trial first indicated their task choice and then shortly after were presented with the stimulus on which they were to perform the task (cf. Arrington & Logan, 2005). This method provides an additional measure to the task-switching RTs and error rates typically studied: the choice RT to cues that invite participants to choose a task in a voluntary switching condition, or to indicate the relevant task in the instructed condition (see details below, cf. Arrington & Logan, 2005; Orr et al., 2012; Poljac, Poljac, & Yeung, 2012). Differences in speed of responding to the instructed cue (indicating which task they ought to perform) and the voluntary cue (indicating that a task choice is required) might indicate differential involvement of control processes in the two conditions. Taken alone, however, these choice RTs are ambiguous, because fast choice RTs could equally well be associated with hasty, ill-formed choices (i.e., weakly applied control) as with clear and decisive decisions (i.e., strongly applied control). However, we can use the combination of choice RT and subsequent task performance to infer whether participants exerted control more or less successfully in the voluntary versus the instructed task switching conditions (Millington et al., 2013): Fast choice RTs that are associated with poor subsequent performance are indicative of weakly applied control, whereas fast choice RTs paired with good subsequent performance are indicative of effectively applied top-down control.

Method

Participants
Participants in this study were six male and 10 female undergraduate students from the University of Oxford. Their ages ranged from 20 to 22 years with a mean of 20.5 and a standard deviation of 0.9. All participants were native English speakers, were right-handed, and had normal or corrected-to-normal vision. They gave informed consent.

Procedure
This experiment compared voluntary with instructed task switching. Overall, the procedure was similar to that used in the previous experiment, with a task-switching encoding phase followed by a surprise memory test. There were five experimental task-switching blocks overall. Each 40-trial block of the task-switching phase was divided into four sequences of 10 trials of either instructed or voluntary task switching. The cue type (instructed vs. voluntary) was varied between sequences. In voluntary task-switching sequences, participants were instructed to try to choose the task randomly (as if they were “tossing a coin” to decide) and to try to perform roughly equal numbers of trials of each task as well as of task switches and repetitions. At the end of each block, they received feedback about how often they switched and how often they performed the object and word task.

In the voluntary task-switching procedure, participants chose the task by button press while the cue was on the screen (i.e., prior to stimulus presentation). This method ensures that participants did not see the stimulus before they made their choice, thus eliminating stimulus-driven influences known to affect task choice, such as stimulus repetitions, priming effects, and associations between stimuli and tasks (Arrington, 2008; Arrington, Weaver, & Pauker, 2010; Demanet, Verbruggen, Liefooghe,
A similar double-registration procedure was used in instructed task-switching sequences. Here participants pressed a key to indicate the instructed task. In the voluntary-switching sequences, a purple cue indicated that participants should choose which task to perform; in the instructed task-switching sequences a red cue indicated the object task and the blue cue the word task. When the cue appeared, participants indicated their task choice (in the voluntary condition) or which task was instructed (in the instructed condition). After this response to the cue, the screen cleared briefly (250 ms) before the stimulus appeared within the cue frame.

In this study, the mapping of the keys to responses differed from that in the other studies. Participants used the “z” key to indicate that they chose the word task and the “m” key to indicate that they chose the object task. After this response to the cue, the screen cleared briefly (250 ms) before the stimulus appeared within the cue frame. Following the participant’s response to this imperative stimulus, there followed an ITI of 500 ms. The total interval between the participant’s response on trial N and the appearance of the imperative stimulus on trial N+1 (i.e., the RSI) thus depended on the time taken to indicate task choice, which averaged 479 ms across participants, for a total RSI of 1229 ms. Following the imperative stimulus, participants used the “x” (“abstract”) and “c” (“concrete”) keys to respond to words, and the “b” (“man-made”) and “n” (“natural”) keys to respond to objects. Task choice was indicated with the ring fingers, and the task responses were given with index and middle fingers. The different mapping of the keys in this study compared to previous experiments was employed to ensure that the same hand was used for the task choice as well as the task, to make it easier for the participants to remember the relevant mappings.

Participants first completed two single-task practice blocks (32 trials each), as well as two mixed-task practice blocks (20 trials each), before completing a voluntary task-switching practice block (20 trials). This was done to familiarize participants with the task and how to balance the choice of switching/repeating and object/word task. The memory test was the same as that in Experiment 1.

Results

Task switching

Task choice and choice speed. An important feature of the double registration design is that it permits analysis of task choices (in voluntary switching conditions) and task choice RTs (for both voluntary and instructed conditions), complementing traditional measures of RTs and error rates in task performance. Our first analyses focused on these cue-related responses. The first analysis assessed whether participants followed the task instructions to perform both tasks, as well as task switches and repetitions, equally often. No significant difference was evident in the frequency with which participants chose the object and word tasks (50.8% vs. 49.2%, SD = 5.23, t(15) = 1.56, p = .14, nor in how often they switched or repeated tasks (49.5% vs. 50.5%, SD = 10.39, t < 1). These results suggest that participants broadly followed instructions to perform both tasks, as well as task switches and repetitions, equally often.

We next analysed whether there were systematic differences in the time taken to decide on a task versus that to indicate the instructed task. If differences in the RTs to the cue are observed between voluntary and instructed conditions, this could indicate that participants used different strategies to respond to the cue, were more or less thoughtful in their response, or found the decision to the cue more or less difficult. An ANOVA with factors transition (switch vs. repeat) and cueing type (voluntary vs. instructed) revealed main effects for both transition, F(1, 15) = 33.07, p < .01, η² = .688, and cueing type, F(1, 15) = 87.65, p < .01, η² = .545, as well as an interaction between these factors, F(1, 15) = 6.89, p < .05, η² = .315. Participants were faster to indicate task choice in repeat than in switch trials (431 ms vs. 518 ms), as well as being faster to indicate task choice in voluntary than in instructed trials (393 ms vs. 565 ms). The difference between switch and repeat trials was larger in the instructed (614 ms vs. 497 ms) than in the voluntary (422 ms vs. 497 ms).
364 ms) condition. Thus, participants overall made faster responses to voluntary than to instructed trials, and their response time did not seem to differ as much between switch and repeat trials in the voluntary condition. This finding could indicate increased motivation and more effective application of top-down control in voluntary task-switching trials, in that the cost of a choice to switch tasks is reduced. However, it could also indicate that participants did not commit to their choice and made a “hasty” decision (cf. Millington et al., 2013). Given these two alternative interpretations, it was important to assess how these differences relate to task performance in response to the imperative stimulus.

**Task performance.** To examine performance in response to the stimulus, RTs and error rates were entered into ANOVAs with variables transition and cueing type (see Table 1). A main effect of transition in the RT data, $F(1, 15) = 52.59, p < .01, \eta^2_p = .778$, indicated slower responses in switch trials than in repeat trials (1244 ms vs. 1047 ms). The effect of transition was only marginally significant in the error rates, $F(1, 15) = 4.14, p = .06, \eta^2_p = .216$ (8.4% in switch vs. 7.2% in repeat trials). Furthermore, the analysis revealed a main effect cueing type in the RT data, $F(1, 15) = 6.93, p < .05, \eta^2_p = .316$, which was not significant in the error rate data, $F < 1$. In contrast to the RT to the cue, responses to the stimulus in the voluntary condition were slower than those in the instructed condition (1066 ms vs. 978 ms). No interaction between transition and cueing type was found in the RTs, $F < 1$, or error rates, $F < 1$, indicating similar switch costs overall across voluntary and instructed switching conditions.

The discussion considers these performance differences between voluntary and instructed task switching in more detail. For now, the key point is that the combination of faster RTs to the cue and worse performance in response to the stimulus during voluntary task switching suggests that participants tended to make premature responses in the cue phase in these trials—that is, before they had fully settled on and prepared their task choice—a tendency that has been noted in previous voluntary switching studies (e.g., Millington et al., 2013). Thus, collectively these findings suggest that proactive top-down preparation was applied less effectively in voluntary than in instructed trials.

**Memory**

As in Experiment 1, old items received significantly higher memory ratings than new items (3.96 vs. 2.79), $t(15) = 12.87, p < .001, d = 3.04$, indicating that participants followed task instructions. The subsequent analyses focus on old items only. As indicated above, there was a significant difference in performance between voluntary and instructed trials in the task-switching phase. The key question next was whether a corresponding effect of cueing type (voluntary versus instructed) could also be found in the memory data. Given that performance was worse, not better, in the voluntary task-switching condition, we expected that selectivity of memory would similarly be reduced in the voluntary condition.

An ANOVA on the recognition memory scores including transition, cueing type, and attention as variables revealed the following effects (see Figure 4). The main effect of attention reached significance, $F(1, 15) = 188.79, p < .01, \eta^2_p = .926$, with items that were attended during task switching receiving higher memory ratings than unattended items (mean memory ratings of 4.74 vs. 3.20), as did the interaction between attention and transition, $F(1, 15) = 14.92, p < .01, \eta^2_p = .499$, which indicated the usual pattern of reduced selectivity of memory for items seen in switch compared to repeat trials. To investigate the nature of this interaction, we performed follow-up $t$-tests, which indicated that there was a significant increase in memory ratings for unattended items from repeat to switch trials, $t(15) = 2.64, p < .05, d = 0.60$, whereas the numerically opposite trend was observed for

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1. In light of the large difference in baseline repeat trial RT between conditions, we analysed whether between-condition switch cost differences would still be apparent if those costs were scaled in proportion to baseline RT. Though preserved numerically—23.9% versus 20.9% switch cost for instructed versus voluntary trials—the difference was not statistically significant, $t < 1$. 
attended, although the effect was only marginally reliable, $t(15) = 1.85$, $p = .084$, $d = 0.25$. No significant main effect of transition was observed, $F < 1$, indicating that there was no evidence for an effect of transition on overall memory.

The interaction between cueing type and attention also reached significance, $F(1, 15) = 12.74$, $p < .01$, $\eta^2_p = .459$. The memory difference between attended and unattended items was greater for items presented during instructed than voluntary-switching trials (see Figure 3). That is, memory was more selective for items presented during instructed switching. Pairwise comparisons revealed that attended items in instructed trials received higher memory ratings than attended items in voluntary trials, $t(15) = 2.31$, $p < .05$, $d = 0.27$. Descriptively, there was a trend in the opposite direction for unattended items, but it did not reach significance, $t(15) = 1.70$, $p = .11$. Thus, cueing type modulated how well relevant items were attended and later remembered. Consistent with the task-switching data, instructed attended items received higher memory ratings than voluntary attended items. No reliable main effect of the cueing type was found, $F < 1$ (mean memory rating instructed 3.98, mean memory rating voluntary 3.96), indicating that whether the task was chosen voluntarily or whether the task was instructed did not significantly affect the overall rated strength of memory across all encountered items. The three-way interaction between transition type, attention, and cueing type was not reliable, $F < 1$.

Discussion
There were two main objectives of this study. The first was to test whether performance differences between two cueing-type conditions (instructed vs. voluntary) during task switching would be reflected in corresponding differences in later memory. Evidence consistent with this prediction would replicate and generalize the findings of Experiment 1 and thereby provide further support for the hypothesis that similar processes are involved in successful task performance and memory encoding. A second aim of this study was to investigate the nature of control processes in voluntary task switching compared to instructed task switching, to address the debate on whether voluntary task switching is associated with less or more effective top-down control than instructed task switching (Arrington & Logan, 2005; Yeung, 2010).

Consistent with the predictions made with regard to the first research question, performance differences between voluntary and instructed trials in the task-switching phase were mirrored in the memory data: The task-switching data indicated that task performance was slower in voluntary task-switching trials than in instructed trials, suggesting less successful application of cognitive control. Correspondingly, in the memory data, instructed trials led to higher memory ratings for attended items than voluntary trials, with a numerical trend in the opposite direction for the unattended items. Thus, enhancement of top-down control (here in instructed switching) does not impair memory, as one might expect if control and memory competed for limited cognitive resources. Rather, enhanced top-down control again led to increased selectivity of processing and later memory for task-relevant information. In relation to the second aim of this study, our findings suggest that voluntary task switching—which was originally proposed as a manipulation of enhanced top-down control—in fact leads to less effective application of top-down control, because there is inherent ambiguity about which task to perform and also because it is possible to make a task choice without committing to a decision—the very
process originally suggested by Arrington and Logan (2004, 2005) to involve top-down control.

EXPERIMENT 3

Experiment 3 focused on a widely researched extrinsic motivational factor: the influence of reward. The effect of reward on task performance and memory is well documented (e.g., Chiew & Braver, 2011). For example, the prospect of reward has been shown to significantly reduce RTs and error rates in flanker tasks (Hubner & Schlosser, 2010), and high compared to low reward incentives during encoding increases performance in a later memory test (Halsband, Ferdinand, Bridger, & Mecklinger, 2012). Moreover, reward has also been demonstrated to reduce switch costs in the task-switching paradigm (Kleinsorge & Rinkenauer, 2012), where it has been argued to lead to a more stable mode of cognitive control, at least when the achievement of reward is perceived to be effortful (e.g., Mueller et al., 2007). Somewhat in contrast, in research by Shen and Chun (2011), reward incentives led participants to prepare flexibly, evident in a reduction of switch costs, only when reward increased from the previous to the current trial. One potential factor that might mediate the effect of reward on performance is emotional processing. However, the exact distinction between reward and positive emotionality and their potential interactions are complex and not yet fully understood (e.g., Chiew & Braver, 2011).

One mechanism by which reward might influence performance is by encouraging effective advance preparation (cf. Kleinsorge & Rinkenauer, 2012). In task-switching studies, reward incentives contingent upon performance (no errors in a specified numbers of trials) have been shown to reduce switch costs, and trials in which reward could be obtained exhibited a larger contingent negative variation, a measure of preparation processes (Capa, Bouquet, Dreher, & Dufour, 2013). Moreover, increased top-down control associated with reward has been shown to bias the processing of relevant versus irrelevant information in visual cortex (Padmala & Pessoa, 2011).

In the current experiment, we contrasted a reward condition with a standard task-switching condition. We predicted that reward should increase the effort to focus attention on relevant material, thereby leading to better task-switching performance and more selective memory for items presented in reward trials. Confirmation of these predictions would provide further support for the importance of top-down control supporting selective processing in both task performance and memory.

Method

Participants

Participants in this study were three male and 13 female undergraduate students of the University of Oxford. Their ages ranged from 18 to 26 years (mean = 21.8, SD = 2.8). Participants were paid for their participation. Furthermore, participants were able to gain monetary reward (between £0 and £6) during the experiment, as detailed below. All participants were native English speakers and had normal or corrected-to-normal vision. They gave informed consent to take part in the study. One participant was excluded due to failure to comply to task instructions to always respond as quickly as possible with substantially greater switch costs (>2 SDs above the mean of all subjects), particularly in the no reward versus the reward condition.

Procedure

The design was similar to that of Experiment 2, in which two conditions were intermixed across sequences of 10 trials in each block; here, the sequences were part of either a reward or a no reward condition. Participants again began with practice blocks of the word and object tasks separately (32 trials each), as well as two task-switching blocks. Participants were then instructed that different trial sequences could either be reward or no-reward sequences in the main experiment, and that good performance (accuracy and speed) in reward sequences would result in monetary reward. At the beginning of each 10-trial sequence they were instructed whether good performance in
this trial sequence would be rewarded or not. In each reward sequence they were able to gain 50p. Reward sequences were marked with yellow stars in the corners of the cue frames.

There were five blocks of 40 trials in the task-switching phase. Each block comprised four sequences of 10 trials, two of which were reward sequences and two of which were no-reward sequences. The order of the sequences within each block was randomized. Within each sequence there were equal numbers of switch and repeat trials. At the end of each reward sequence, feedback was given on the RT, error rate, and whether or not participants received reward in this sequence. Specifically the feedback was “Well done! So far you have gained £[amount]” if they received reward, and “Sorry, no reward!—Too many errors!”, “Sorry, no reward!—Too slow!”, or “Sorry, no reward!—Too many errors and too slow!” if they did not meet the criteria for reward. Participants received the “Well done!” feedback if their error rate was below or equal to 10% errors, and their RT was 10% faster than in the previous reward sequence. For the first reward sequence, the RT of the last training block minus 10% was used as a cut-off. Note that at this stage participants did not know about the reward condition and how it was calculated, so they could not use strategies to maximize reward such as intentionally trying to be slow in this block. If the sequence they completed was not a reward sequence, the feedback included their RT and error rate together with the sentence “This was not a reward sequence”. On average, participants gained £1.90 (minimum: £0, maximum: £3.50, SD = 0.8). The same response keys as those in Experiment 1 were used. The ITI was set to 500 ms (as in Experiment 2), and the cue was displayed for 500 ms on each trial, for a total RSI of 1000 ms. The memory test was the same as that in Experiments 1 and 2.

Results

Task switching
We first examined the effect of reward on task-switching performance to determine whether reward led to the expected performance improvements (see Table 1). An ANOVA with variables transition and reward revealed a significant main effect of transition in the RT data, $F(1, 14) = 130.25, p < .01, \eta^2_p = .903$, with lower RTs for repeat than for switch trials (791 ms vs. 978 ms), and in the error data, $F(1, 14) = 6.00, p < .05, \eta^2_p = .300$, with lower error rates for repeat than for switch trials (7.6% vs. 10.1%). There was a main effect of reward only in the RT data, $F(1, 14) = 13.58, p < .01, \eta^2_p = .492$, with faster responses in reward sequences than in no-reward trials (844 ms vs. 925 ms), but not in the error rate data, $F < 1$ (reward 9.0% and no reward 8.6%). Furthermore, the transition by reward interaction reached significance in the RT data, $F(1, 14) = 6.88, p < .05, \eta^2_p = .330$, and was marginally significant in the error rate data, $F(1, 14) = 3.34, p = .09, \eta^2_p = .193$. There was a smaller switch cost in the RTs in the reward than in the no-reward condition, with a similar trend for errors. Thus, in contrast to the CSI and voluntary task-switching experiments, the reward condition affected the switch cost as well as overall performance during task switching.

Memory
Old items received significantly higher memory ratings than new items (3.78 vs. 2.82), $t(15) = 15.80, p < .001, d = 2.92$, consistent with the results of Experiments 1 and 2, again indicating that participants followed task instructions. All subsequent analyses of the memory data focused on old items. To assess the effect of reward-influenced top-down control on later memory, an ANOVA with attention, transition type, and reward as variables was conducted on the recognition memory ratings for items seen during task switching. As in Experiments 1 and 2, the critical question here was whether memory would be affected by transition in the same way as task-switching performance. Therefore, here we might expect the effect of reward on later memory to be modulated by whether or not the item was presented in a switch or repeat trial during task switching, because the effect of reward was modulated by transition type during task switching.
The main effect of reward was not significant, $F < 1$ (mean memory rating on no-reward trials of 3.83 vs. reward trials of 3.78). There was a significant effect of attention, $F(1, 14) = 139.81, p < .01, \eta_p^2 = .909$, with attended items receiving higher memory ratings than unattended items (mean ratings of 4.44 vs. 3.17), and a significant interaction between transition and attention, $F(1, 14) = 8.67, p < .05, \eta_p^2 = .382$, with more similar ratings to attended and unattended items in switch than in repeat trials, replicating the findings of Experiments 1 and 2 and Richter and Yeung (2012). The interaction between transition, attention, and reward descriptively showed the pattern that would be predicted based on the task-switching results—that is, a stronger interaction between transition and attention in no-reward than reward trials (Figure 5), but this effect did not reach significance ($p = .130$).

Inspection of the separate participants’ data indicated that one participant had a transition–reward interaction effect in the opposite direction (i.e., this participant showed larger switch costs in reward trials) that was more than 2 standard deviations away from the mean of all participants. Reanalysis of the data excluding this participant did not substantially change the task-switching data results: The main effect of reward was again significant in the RT data, $F(1, 13) = 14.78, p < .01, \eta_p^2 = .532$, with a reliable interaction between reward and transition type, $F(1, 13) = 10.46, p < .01, \eta_p^2 = .446$. However, after excluding this outlying participant, the ANOVA on the memory data revealed a main effect of attention, $F(1, 13) = 121.23, p < .01, \eta_p^2 = .903$, and an interaction between transition and attention $F(1, 13) = 6.86, p < .05, \eta_p^2 = .345$. The main effect of reward was not reliable, $F < 1$, but critically there was a reliable interaction between transition, attention, and reward, $F(1, 13) = 5.94, p < .05, \eta_p^2 = .314$. Separate follow-up ANOVAs for items seen in reward and no-reward sequences revealed that there was a significant interaction between transition and attention for items seen in no-reward sequences, $F(1, 13) = 13.61, p < .01, \eta_p^2 = .511$, but not for those seen in reward sequences, $F < 1$. Thus, the usual decrease in selectivity of memory in switch compared to repeat trials was observed for the no-reward condition but not for the reward condition. Follow-up $t$-tests on the no-reward trials indicated that there was a significant decrease of memory ratings for attended items appearing in switch compared to repeat trials (4.34 vs. 4.57), $t(13) = 3.32, p < .01, d = 0.28$, coupled with a significant increase in memory ratings for unattended items (3.24 vs. 3.11), $t(13) = 2.19, p < .05, d = 0.54$. In the reward condition, memory rating differences between items appearing on switch versus repeat trials were numerically small and not statistically reliable, both for attended items (4.39 vs. 4.42) and for unattended items (3.15 vs. 3.14).

These results are in accordance with the prediction that enhanced top-down control during task switching not only should improve performance but should also result in greater selectivity in later memory for attended information. The results must, however, be interpreted with caution, because the three-way interaction between reward, transition, and attention only reached significance once an outlying participant was excluded. Also unexpected, switch versus repeat memory selectivity differences across conditions were at least as strongly driven by reward-related reductions in selectivity on repeat trials as by the predicted increase in selectivity on switch trials. We have no ready account of this effect, but speculate that it relates to the fact that RTs were very low.
and error rates relatively high on these trials during task switching. This pattern could be indicative of speeded and perhaps relatively superficial stimulus processing in this condition (perhaps the subjects’ effort to meet the strict reward criterion), which would be expected to have a negative impact on later memory.

Discussion

The reward manipulation was successful in this experiment in leading to improved performance overall and decreased costs of task switching. Critically, the successful manipulation of the switch cost was also reflected in the memory data, where reward counteracted the decrease in selectivity typically seen in switch trials (an effect that was significant after exclusion of an outlying participant). This interaction indicated that reward incentives improved the effective use of control in switch trials and decreased the switch-related reduction in selectivity found in other experiments. This finding is consistent with the notion that reward incentives enhance the recruitment of cognitive control processes to bias processing toward task-relevant stimuli (e.g., Padmala & Pessoa, 2011). In contrast to Experiments 1 and 2, the manipulation of top-down control via reward affected switch and repeat trials differentially, both during task switching and in the later recognition memory test (see Figure 3).

GENERAL DISCUSSION

The three experiments reported here investigated whether systematic manipulation of top-down control affects task performance and memory encoding in corresponding ways. Overall, the manipulations of top-down control successfully induced performance improvements in task switching, and, crucially, these improvements were accompanied by increased selectivity in later recognition memory for attended over unattended items (see Figure 3): Where conditions exhibited reliable performance improvements during task switching, this effect was accompanied by reliable between-condition differences in memory selectivity. These effects did not differ reliably for switch and repeat trials in Experiments 1 and 2, where enhanced top-down control improved task performance and memory selectivity to a similar degree for both transition types. In Experiment 3, however, more effective application of top-down control in the reward condition was associated with a decrease in switch costs during task switching and increased memory selectivity specifically for switch trials. Collectively, these results suggest that task performance and encoding are similarly reliant on effective top-down control—reflected in parallel effects of control (increased selectivity of processing) on task performance and memory.

The present findings provide further evidence that cognitive control and memory interact in a manner that is symbiotic rather than competitive (Richter & Yeung, 2012): If control and memory competed for limited processing resources (Craik et al., 1996; Liefooghe, Barrouillet, Vandierendonck, & Camos, 2008; Otten & Rugg, 2001; Reynolds, Donaldson, Wagner, & Braver, 2004), one would expect manipulation of control to influence memory for attended and unattended items in similar ways (reflecting the availability, or otherwise, of resources according to current control demands). However, all three experiments replicated our previous finding that task switching impairs memory for attended information but actually improves memory for unattended items. Extending this analysis, the observed effects on memory of our three manipulations of top-down control—varying preparation interval (Experiment 1), allowing voluntary choice over the current task (Experiment 2), and varying motivation via reward (Experiment 3)—were all similarly evident as modulations of memory selectivity rather than global improvement or impairment in memory across items regardless of task relevance. It remains possible, of course, that other manipulations of cognitive control might affect attended and unattended items in the same way. For example, a concurrent demand to attend (overtly or covertly) to a spatial location distant from the compound word–picture stimulus would be likely to impair memory for both items. Impaired
memory for both items would plausibly also be observed in situations with extremely high concurrent working memory demand. Nevertheless, in our experiments here and elsewhere, in which we have manipulated the demand for control and application of control using a wide variety of methods, we have found no reliable evidence of global memory deficits in conditions of increased control demand. Rather, we consistently observe that control demand impairs memory selectivity, and successful application of control effectively counteracts this impairment.

In Experiment 2, the requirement to choose tasks should increase control demands (Arrington & Logan, 2005), which we find to have a negative impact on task-switching performance. However, the consequent memory impairment for items seen during voluntary switching was limited to task-relevant, attended information. Memory for unattended information was, if anything, improved during voluntary switching. In Experiment 3, we expected reward to result in increased recruitment of control (Kleinsorge & Rinkenauer, 2012; Padmala & Pessoa, 2011), reflecting the high demand of continually improving performance over time. Thus, effective application of top-down control was necessary for successful task performance, rather than merely encouraged. Resource limitation theories might therefore predict limited encoding success in this situation, with high control demands meaning that “fewer resources were available for encoding” (cf. Otten & Rugg, 2001). However, memory ratings for task-relevant items in fact increased under reward incentive, particularly when the task switched, with little effect apparent on memory for unattended items. Taken together, these results make little sense in terms of resource competition between control and memory, but follow naturally from the view that top-down control imposes selective memory encoding that is impaired in voluntary task switching (because of ambiguity about the task to be performed) and enhanced by reward (because of incentive to focus effectively on the task at hand).

As such, our findings are consistent with the proposal that memory can be characterized as “enduring traces of attention”—that is, as “the persisting consequence of cognitive activities initiated by and/or focused on external information from the environment . . . or internal mental representations” (Chun & Johnson, 2011, p. 520). Our results follow naturally from this perspective, with increased strength of top-down attentional focus leading directly to stronger, longer lasting “persisting consequences”. Refining this broad perspective, our findings favour a model in which the relevant feature of attention in relation to memory encoding is its selectivity, rather than attention in the sense of general arousal or motivation. For example, whereas effects of advance preparation on memory could be interpreted as creating generally “favorable states of mind” for memory encoding (cf. Chun & Turk-Browne, 2007, p. 179), our findings suggest that the states of mind established by top-down control are favourable only to task-relevant information, with task-irrelevant information not favoured, or even suppressed.

By linking control and memory so tightly, the present findings add support to the conclusion that memory can be used as a useful new index of previous cognitive control (cf. Richter & Yeung, 2012). The value of this approach is evident, for example, in interpreting the results of Experiment 1. Here, we failed to replicate the often-reported reduction in switch cost with increased time for advanced preparation, but did observe that performance benefited overall from increased CSI. The memory data indicate that this main effect of CSI is more relevant to the study of top-down control than might be evident from the task-switching data alone, which could otherwise be interpreted as reflecting a general alerting effect or reduction in temporal uncertainty following advance cues (Rogers & Monsell, 1995). However, the observed increase in memory selectivity for task-relevant information suggests that the main effect of CSI reflects, at least in part, effective preparation for the upcoming task. Thus, top-down control may be necessary for efficient performance even when the task repeats across trials—a challenge to theories proposing the existence of switch-specific control processes (cf. Ruge, Jamadar, Zimmermann, & Karayanidis, 2013, for converging conclusions from neuroimaging data).
Along similar lines, the drop in performance in voluntary switching compared to instructed switching seen in Experiment 2 is ambiguous when taken alone: The most straightforward interpretation is that the performance drop reflects weaker top-down control. However, it could also be that top-down control is equally strong, or even stronger, when task choice is voluntary than when the task is cued—for example, because the alternative compound-stimulus strategy is unavailable (Arrington & Logan, 2005; Logan & Bundesen, 2003)—but responding is slower because of the concurrent demand of keeping track of previous task choices. The data on choice speed could be taken to support this view of enhanced top-down control, because faster (more definitive?) responses to cues were seen in voluntary than in instructed switching. However, the memory data suggest otherwise: Memory selectivity for attended items was reduced in voluntary switching, indicating less effective control—contrary to proposals from early research on this topic (Arrington & Logan, 2005). As such, fast responses to the cue perhaps indicate that participants did not complete the choice process or were not fully committed to a task choice at the time of the response to the cue (Millington et al., 2013). In this regard, the present findings converge with other evidence questioning the idea that voluntary task switching provides a relatively pure and direct measure of top-down control processes (Arrington, 2008; Arrington et al., 2010; Demanet et al., 2010; Lien & Ruthruff, 2008; Mayr & Bell, 2006; Orr & Weissman, 2011; Yeung, 2010).

The combined task-switching and memory data from Experiment 3 provide new insight into the impact of reward on cognitive control. Overall, the results were in line with previous evidence that reward encourages successful recruitment of cognitive control (Hubner & Schlosser, 2010; Kleinsorge & Rinkenauer, 2012; Mueller et al., 2007), apparent here as increased selectivity of attentional processing. Some previous research has suggested that consistent levels of reward increase the stability of cognitive control (versus the flexibility; Mueller et al., 2007) and therefore specifically improve performance in repeat trials. However, reward-related improvements in Experiment 3 were largely restricted to switch trials (similar to the results obtained by Shen & Chun, 2011), evident as a reduction of the switch cost and increased memory selectivity for items appearing on those trials, which suggests that the effect of reward on cognitive control might be more complex and situation dependent: The fact that reward benefited switch trials more than repeat trials could suggest that repeat-trial performance was already at a peak, even without reward, and that reward increased performance especially in switch trials.

Two features of the reported results were more surprising. As already noted, the design of Experiment 1 was honed through several pilot studies to optimize task preparation effects, yet no reduction in switch cost with CSI was apparent. It has been suggested that preparation can be equally beneficial for switch and repeat trials when the task is complex (Dreisbach et al., 2002) and when abstract task cues are used (Monsell & Mizon, 2006). Moreover, preparation effects tend to be reduced when stimulus–response mappings of the different tasks do not overlap (e.g., Poljac & Bekkering, 2009). Some combination of any or all of these factors might explain the null effect of CSI on switch costs in Experiment 1. However, it was not the aim of this study to explore CSI effects per se: For our purposes, it was sufficient that CSI had a main effect on task performance that could then be assessed for its impact on later memory. Nonetheless, given the centrality of preparation effects to theories of cognitive control in task switching (Altmann, 2004a), the task-switching data of Experiment 1 might usefully constrain future theorizing about the boundary conditions of CSI effects on task switching performance.

Second, and on a related note, we did not expect variability across our three manipulations of top-down control in terms of their differential effect on switch and repeat trials: All three manipulations might reasonably be expected to interact with switching, yet this interaction was only observed with reward incentives in Experiment 3. It is perhaps relevant that the reward condition was our only manipulation of top-down control in which participants needed to increase their efforts to obtain good results, with the reward criterion
becoming increasingly strict as participants’ performance improved. Increasing effort to perform well might have been particularly effective on switch trials, with performance on repeat trials already close to optimal. In contrast, the manipulations in Experiments 1 and 2 were less stringent, in that poor performance was not associated with a negative outcome (loss of available reward). It is possible that in these conditions participants did not try to improve performance to the same degree as they did in the reward condition, which could result in less effective preparation on switch trials as well as leaving greater scope for an influence of control on repeat trials. This conclusion highlights the context dependency of top-down control effects, with seemingly similar manipulations having different impact on task performance and later memory.

In conclusion, the present findings provide consistent evidence that the requirement to exert top-down control on task performance does not limit the amount of information that is encoded in long-term memory, but instead affects the selectivity of the encoding process. When controlled processing is enhanced, this enhancement is reflected in more selective memory for relevant than for irrelevant information. Taken together, our results demonstrate the dependence of long-term memory on the establishment of an appropriate cognitive set in processing presented information. More broadly, they point to the interdependence of core cognitive processes—memory and control—that are often dealt with separately but which are demonstrably intertwined.

REFERENCES


