

# Bottom-Up Influences on Voluntary Task Switching: The Elusive Homunculus Escapes

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Voluntary action can be studied by giving participants free choice over which task to perform in response to each presented stimulus. In such experiments, performance costs are observed when participants choose to switch tasks from the previous trial. It has been proposed that these costs primarily index the time-consuming operation of top-down control processes that support voluntary action. The present experiments showed, contrary to this view, that greater costs were associated with voluntary switching to the easier task of a pair. These increased switch costs for the easier task were accompanied by a reliable preference of the participants for performing the other, more difficult task. Interference between tasks during response selection was identified as the critical factor driving these effects of task difficulty. Together, the findings suggest that participants' voluntary choices, and the time taken to execute those choices, may not directly index the operation of cognitive control but instead may reflect complex interactions between top-down and bottom-up influences on behavior.

*Keywords:* voluntary action, task switching, executive control, cognitive control

A long-standing challenge for experimental psychology is to provide an account of human voluntary action that does not rely on an unspecified intelligent agent—the dreaded homunculus—for its explanatory power. To this end, many theories propose the existence of dedicated mechanisms of cognitive control that are responsible for organizing the cognitive system in accordance with its current goals (e.g., Logan, 1985; Miller & Cohen, 2001; Norman & Shallice, 1986). Research within this framework attempts to specify the cognitive and neural basis of these control mechanisms in sufficient detail to “banish the homunculus” from theories once and for all (Monsell & Driver, 2000). In this context, one particularly fruitful approach has been the study of cognitive control in task switching (Allport, Styles, & Hsieh, 1994; Jersild, 1927; Rogers & Monsell, 1995).

In task switching experiments, participants are presented with stimuli associated with two or more cognitive tasks, and they are asked to switch back and forth between these tasks. Participants are typically instructed which task they are to perform for each presented stimulus. In some cases, they are asked to switch tasks in predictable order (Allport et al., 1994; Rogers & Monsell, 1995); in others, task order is unpredictable and external cues indicate which task is required on any given trial (Meiran, 1996). In both cases, however, the basic finding is the same: Switching from one task to another is associated with a performance cost in terms of increased response times (RTs) and increased error rates. These switch costs, together with their neural correlates, have been

widely studied in the hope that they will shed light on the mechanisms that support the observed flexibility of responding.

One plausible and attractive hypothesis is that switch costs reflect the time taken to perform control operations that are required when the task is switched but are not required—or, at least, are not usually required—when the task is repeated (Rogers & Monsell, 1995; Rubinstein, Meyer, & Evans, 2001). According to this hypothesis, the time course of control is further reflected in the observed reduction in switch costs when participants are given time to prepare for an upcoming task switch (Rogers & Monsell, 1995). If control operations contributed directly to observed RTs in this way, such that switch costs were amenable to additive factors logic (Sternberg, 1969) and other well-established analytic techniques, task switching methods would provide an appealingly simple way to pin down the controlling homunculus for experimental study. However, existing findings suggest that the relationship between switch costs and cognitive control is not so straightforward. For example, switch costs observed in externally cued switching designs may at least partly reflect the time taken to identify the task cues themselves, rather than indexing subsequent control operations (Logan & Bundesen, 2003).

Perhaps more problematic still, between-task interference appears to contribute substantially to switching costs regardless of whether task switches are cued or follow a predictable schedule. Between-task interference can arise from a number of related sources: from a residual tendency to perform the previously required but now irrelevant task (Allport et al., 1994), from persisting inhibition of the required task that is carried over from previous trials (Mayr & Keele, 2000), from monitoring or evaluative processes during response execution on previous trials (Philipp, Jolicoeur, Falkenstein, & Koch, 2007), and from learned associations between the presented stimulus and alternative tasks (Koch & Allport, 2006; Waszak, Hommel, & Allport, 2003). In all cases, the general notion is that interference occurs during task switching

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because the current task requirements conflict with those experienced on previous trials. Thus, switch costs may not provide a pure measure of the operation of cognitive control mechanisms but may instead reflect a consequence of a failure of these mechanisms to impose an effective task set. Neuroimaging studies have shown, consistent with this interpretation, that switch costs are increased when brain regions associated with processing of the currently irrelevant task remain active following a task switch (Yeung, Nystrom, Aronson, & Cohen, 2006) and that a major effect of task preparation is to reduce the impact of between-task interference (Wylie, Javitt, & Foxe, 2006).

The effects of between-task interference are perhaps most strikingly evident when participants switch between tasks that differ in their relative strength, such as Stroop color naming and word reading (Allport et al., 1994). Intuitively, one would expect it to be easy to switch to the familiar and well-practiced word reading task and much more time-consuming to switch to the difficult color-naming task. In fact, the opposite pattern is observed. Allport et al., for example, found that switching to the difficult color-naming task incurs little or no cost, whereas a large cost is incurred by switching to word reading. The finding of a greater cost of switching to the stronger task of a pair has been replicated in studies that used many different sets of tasks and used both cued and predictable switching designs (Allport et al., 1994; De Jong, 1995; Meuter & Allport, 1999; Shaffer, 1965; Yeung & Monsell, 2003a, 2003b). These findings are difficult to explain in terms of the hypothesis that switch costs reflect the time taken by control operations to establish the new task: One would expect these operations to take less time to complete, not more, as a task becomes familiar and practiced.

The surprising asymmetry of switch costs has instead been taken as evidence of the effects of between-task interference, an interpretation that has been formalized in computational models of task switching (Gilbert & Shallice, 2002; Yeung & Monsell, 2003a). In Gilbert and Shallice's connectionist model of Stroop switching, for example, switch costs result from carryover of control biases from one trial to the next: Following a task switch, a residual control bias toward the previously relevant task causes high levels of competition during response selection. This competition results in lengthened RTs and increased error rates. Critically, whereas little control is required when reading a word, strong control biases are required when color naming. The strength of these biases reflects the relative weakness of this task. Thus, a strong residual bias toward color naming may need to be overcome following a switch to word reading, and the result will be a large cost. In contrast, little or no control bias toward word reading will be carried over following a switch to color naming, so the cost of such switches will be low. In this way, asymmetrical switch costs are explained in terms of the asymmetrical strength of control biases required to perform color naming and word reading. Recently, Bryck and Mayr (2008) have argued that asymmetrical control biases may cause between-task interference only indirectly, by changing the strength of long-term memory representations of the competing tasks. However, regardless of whether control biases cause between-task interference directly or indirectly, these theories agree on a critical point: that switch costs are at best an indirect consequence of earlier control exertions—the fingerprints of an escaped homunculus—rather than a direct measure of control operations themselves. Thus, notwithstanding the fact that study-

ing these consequences can potentially be very informative (Yeung & Monsell, 2003a), it would be very useful if a more direct measure of cognitive control could be found.

In this context, the voluntary task switching method introduced by Arrington and Logan (2004, 2005) seems potentially very attractive. In Arrington and Logan's approach, participants are presented with stimuli associated with two simple tasks—just as in prior task switching studies—but they are instructed to choose for themselves which task to perform on each trial (specifically, as if flipping a coin decided which task to perform). This method has an obvious top-down component that distinguishes it from previous approaches in which the required task was instructed on each trial. Arrington and Logan found that, consistent with this dependence of performance on top-down control, participants' task choices were largely independent of bottom-up factors, such as associations between tasks and stimulus features. Critically, however, voluntary task switching produced a substantial performance cost that was reduced when participants were given time to prepare, and Arrington and Logan interpreted these results as indicating that top-down processes can cause switch costs. Thus, Arrington and Logan proposed that the costs associated with voluntary task switching may provide a relatively direct index of the operation of cognitive control mechanisms, as was hoped for earlier task switching methods. In this spirit, they concluded that "choice behavior and choice costs, as well as switch costs, become measures that capture the clever homunculus" (Arrington & Logan, 2005, p. 701).

However, as Arrington and Logan (2005) made explicit, even if voluntary task switching behavior primarily reflects top-down control, it is possible that bottom-up factors nevertheless exert some influence over performance. Subsequent findings have provided evidence for this possibility: Mayr and Bell (2006) have reported that participants are less likely to make voluntary task switches when the stimulus repeats from the previous trial (an effect that is amplified when stimulus repetitions are frequent); Arrington (2008; Arrington & Rhodes, *in press*) has shown that task choices are influenced by the order of presentation and relative salience of task-relevant stimuli; and Lien and Ruthruff (2008) have shown that participants are less likely to switch back to a task from which they have recently switched. Thus, even ostensibly voluntary choices appear to be influenced by bottom-up factors. However, little is currently known about the magnitude of the contribution of these bottom-up factors to voluntary switching performance. Moreover, the specific contribution of between-task interference effects—for example, as revealed through asymmetrical patterns of switch costs—remains to be established. The aim in the present study was to address these issues.

The first question was whether voluntary switching would demonstrate the same asymmetrical pattern of switch costs for tasks differing in strength that has previously been observed in instructed switching designs. *Prima facie*, there seems little reason to suppose that voluntary switch costs should be immune to between-task interference effects that infect the costs measured in instructed switching designs. However, strikingly, the only study to date that has investigated voluntary switching between tasks differing in strength—a study of bilingual language switching by Gollan and Ferreira (2009)—failed to replicate the asymmetry previously observed in instructed switching (Meuter & Allport, 1999). Gollan and Ferreira suggested that their findings might "highlight pow-

erful differences between the mechanisms underlying voluntary and cued switches" (2009, p. 660), a claim lent further credence by neuroimaging evidence that voluntary and instructed task switching engage different brain regions (Forstmann, Brass, Koch, & von Cramon, 2006). Given the significant role that asymmetrical switch costs have played in theory development in task switching research, and given the growing interest in voluntary task switching as a complement to existing methods, it seems worthwhile to attempt a direct comparison of between-task interference in instructed and voluntary switching designs.

Moreover, the observation of asymmetrical costs in voluntary switching can potentially demonstrate more than simple comparability across paradigms, because the pattern of costs across tasks can indicate the relative contribution of top-down control and bottom-up factors. In instructed designs, switch costs are often very low (~30 ms) in conditions with little between-task interference, which suggests that top-down control processes make a rather limited contribution to observed costs (Yeung & Monsell, 2003a). Moreover, these studies suggest that task preparation reduces switch costs primarily through reducing the impact of between-task interference (Wylie et al., 2006; Yeung & Monsell, 2003b). Corresponding results in the present study might suggest that the costs of voluntary task switching likewise to a large degree reflect bottom-up factors, a conclusion that would contrast with Arrington and Logan's (2004, 2005) suggestion that choice costs might provide a relatively clear measure of top-down control.

Analysis of participants' task choices, in addition to patterns of switch costs, can provide important insight into the factors governing task performance. As described above, previous studies have shown that bottom-up factors affect participants' choices of whether to switch or repeat tasks and have in general indicated that participants exhibit preferences for less effortful choices (cf. Botvinick & Rosen, 2009). For example, they repeat more often than switch tasks and repeat tasks more often when the stimulus repeats (Arrington & Logan, 2005; Mayr & Bell, 2006). If minimizing effort is an important factor, one might expect participants to exhibit a general bias toward performing the easier of two tasks. However, the computational models of between-task interference described above suggest an intriguing alternative prediction. According to these models, asymmetrical switch costs emerge from asymmetrical task biases from earlier trials, with stronger biases associated with performing the weaker task. Thus, the weaker task can be thought of as forming a strong "attractor state" that is difficult to switch away from and results in a large cost of switching to the easier task (Gilbert & Shallice, 2002; Yeung & Monsell, 2003a). If these biases likewise influenced participants' task choices, the result would be a counterintuitive bias toward repeating the weaker task. Further effects of between-task interference might therefore be evident in participants' task choices and in this way could reveal further influences of earlier control exertions on current behavior—additional fingerprints of the elusive homunculus.

In summary, the present experiments were designed to investigate the contribution of between-task interference to voluntary task switching performance. Experiments 1a and 1b directly contrasted voluntary and instructed switching between tasks that differed in relative strength while varying the time available for task preparation. In these experiments, participants were presented with a shape in one of three locations and either indicated its location

with a spatially corresponding keypress (an easy task) or indicated its identity using a separate set of response keys (a more difficult task with no obvious compatibility between stimuli and responses). In Experiment 1a, participants were asked to make voluntary switches between the two tasks. In Experiment 1b, which acted as a control study, a more typical instructed (cued) switching design was used. To look ahead briefly, the results of both experiments demonstrated clear effects of between-task interference. Two follow-up experiments, 2a and 2b, extended these findings to investigate the mechanisms underlying the observed between-task interference effects in voluntary switching by dissociating the effects of perceptual and response factors.

## Experiments 1a and 1b

### Method

**Participants.** There were 16 participants in each experiment. In Experiment 1a there were 9 men and 7 women, 18–34 years of age. In Experiment 1b there were 5 men and 11 women, 18–33 years of age. All participants had normal or corrected-to-normal vision. Participants received payment or course credit for their participation, and they gave informed consent at the start of the session.

**Tasks and stimuli.** Participants performed two tasks that involved responding to either the shape or the location of a presented stimulus. On each trial, one of three shapes—a triangle, a square, or a circle—was presented at one location inside a grid of three adjacent boxes. The shape of the stimulus and its location within the grid varied randomly from trial to trial. In Experiment 1a, participants were responsible for choosing which task to perform on each trial, within the constraints described below. In Experiment 1b, participants were instructed which task to perform according to a cue—the word *SHAPE* or *LOCATION*—appearing prior to stimulus onset on each trial.

Half of the participants in each experiment responded to the shape of the stimulus by pressing keys with their left hand and to the location of the stimulus by pressing keys with their right hand; for the other half of the participants, this mapping was reversed. Participants responded with the index, middle, and ring fingers of the two hands. The three shapes were mapped to the three fingers of the appropriate hand as follows: circle to leftmost finger; square to middle finger; triangle to rightmost finger. The three locations were mapped compatibly to corresponding responses (i.e., left box = leftmost finger; center box = middle finger; right box = rightmost finger).

Trial blocks began with the presentation of the grid, which remained on the screen throughout. In Experiment 1a, each trial began with the presentation of the shape stimulus at one location within the grid. The stimulus remained on the screen until the participant had responded, after which time the grid cleared for a short (200 ms) or a long (1,100 ms) response–stimulus interval (RSI). In Experiment 1b, each trial began with presentation of the task cue, followed by the stimulus after either a short (100 ms) or a long (1,000 ms) cue–stimulus interval (CSI). The cue and stimulus remained on the screen until the participant responded. There followed an interval of either 1,000 ms or 100 ms, such that the RSI was fixed at 1,100 ms. At a viewing distance of approximately

1 m, the stimulus grid was 2.6° high and 7.4° wide, and the presented shape approximately filled one box within the grid.

**Procedure.** Participants were first given 30 trials of practice at each task separately. They then completed two practice switching blocks of 50 trials each, one block for each RSI/CSI. In Experiment 1a they were given the following instructions prior to the task switching practice (adapted from those used by Arrington & Logan, 2004, 2005):

For the rest of the experiment, you'll be asked to switch back and forth between the Shape and Location tasks. You only need to do one task on each trial—that is, you only need to press one button for each shape you see. In fact, you have to choose which task to perform on each trial. You should perform each task on about half the trials, and you should try to perform the tasks in a random order. For example, imagine you have a coin that said “shape” on one side and “location” on the other. Try to perform the tasks as if flipping the coin decided which task to perform. So sometimes you will be repeating tasks, and sometimes you will be switching tasks. We don't want you to count the number of times you've done each task or alternate strictly between tasks to be sure you do each one half the time. Just try to do them randomly.

In Experiment 1b, participants were instructed to perform the task indicated by the task cue appearing at the start of each trial. Participants were further instructed to use the time before the stimulus appeared on each trial to decide what task to perform (Experiment 1a) or to prepare for the instructed task (Experiment 1b).

Following practice, participants completed 16 task switching blocks of 90 trials each. They were encouraged to rest between blocks as required. At the end of each block, participants were given brief feedback about their performance that included their average response time (RT) and error rate. In Experiment 1a, the feedback additionally indicated counts of the number of times they had performed each of the two tasks and counts of the number of switch and repeat trials. This feedback was provided in order to encourage participants to respond quickly and accurately and to follow the instructions about “random” switching described above. For example, this feedback made evident whether participants were adhering to the instructions to perform both tasks and whether they were following a simple strategy of strict alternation between tasks. For each participant, RSI/CSI varied between blocks according to a repeating ABBA order. RSI/CSI in the first block was counterbalanced across participants.

For the analysis of RTs and error rates, each trial was categorized according to task, transition type, RSI/CSI, and response congruence. In Experiment 1a, the task performed on a given trial was indicated by the hand that the participant used to respond. A trial was scored as an error if the participant responded with the wrong finger of that hand. Trials were then coded as task switch or task repeat trials according to the relation between the task performed on the current and previous trials. In Experiment 1b, tasks and transitions were determined by the presented cues, and accuracy was scored accordingly.

In both experiments, response congruence was determined according to the spatial relationship between the responses associated with the shape and location of the stimulus, and the magnitude of congruence effects across tasks was used as a converging measure of relative task strength. The definition of response congruence used in this study is somewhat atypical in that the two

tasks use nonoverlapping response sets (a feature needed in order to determine which task was actually performed during voluntary task switching in Experiment 1a). It was nevertheless expected that spatial congruence effects would be observed because of the stimulus–response compatibility of the location task and because previous findings have established that bimanual responding typically makes use of shared spatial response codes (Campbell & Proctor, 1993), particularly when the stimuli have spatial features (Druey & Hubner, 2008). As will become apparent, robust spatial congruence effects were indeed observed. Thus defined, the following three stimuli were congruent: circles in the left-hand box, squares in the central box, and triangles in the right-hand box. All other stimuli—two thirds of the total—were defined as incongruent.

RT analysis excluded the first trial of each block, error trials, trials following errors, and trials with response repetitions. Exclusion of response repetitions is common in previous studies that have compared switch costs across tasks differing in strength (e.g., Bryck & Mayr, 2008; Yeung & Monsell, 2003a), because these repetitions typically produce different effects on switch and repeat trials: On task repeat trials, stimulus and response repetitions may allow bypassing of the usual response selection process (Pashler & Baylis, 1991), which could reduce the power to detect subtle effects and also artificially inflate switch costs for more difficult tasks (which benefit more from bypassing normal response selection). Nevertheless, the key findings of the present experiments do not depend on excluding response repetitions: In analyses including response repetitions, the critical patterns of results were somewhat weaker but still reliable.

The RT and error rate data were analyzed using repeated-measures analyses of variance (ANOVAs). The data were first analyzed separately for the two experiments to establish the presence of critical effects in each. Then a direct comparison was performed between experiments to assess whether switching performance differed between voluntary and cued designs. Finally, participants' task choice data in Experiment 1a were analyzed to investigate the degree to which participants' voluntary choices were influenced by task difficulty and other bottom-up factors.

## Results

**Task strength.** Mean RTs and error rates for the two experiments are given in Figure 1 and Table 1. It is first important to establish that the tasks differed in their relative strength as intended, which was assessed by comparing their overall performance and response congruence effects. The analyses below collapsed data from switch and repeat trials; analyses including only repeat trials produced equivalent results.

**Voluntary switching (Experiment 1a).** Consistent with our expectation that the location task would be the stronger of the two, participants were faster,  $F(1, 15) = 166.7, p < .01, \eta_p^2 = .92$ , and more accurate,  $F(1, 15) = 9.1, p < .01, \eta_p^2 = .38$ , when responding to the location of the stimulus than to its shape. Analyses of response congruence effects add further evidence that the tasks differed in relative strength. Overall, participants were slower,  $F(1, 15) = 37.4, p < .01, \eta_p^2 = .71$ , and less accurate,  $F(1, 15) = 94.7, p < .01, \eta_p^2 = .86$ , when responding to incongruent stimuli than when responding to congruent stimuli. This provides evidence that participants experienced interference from the response associated

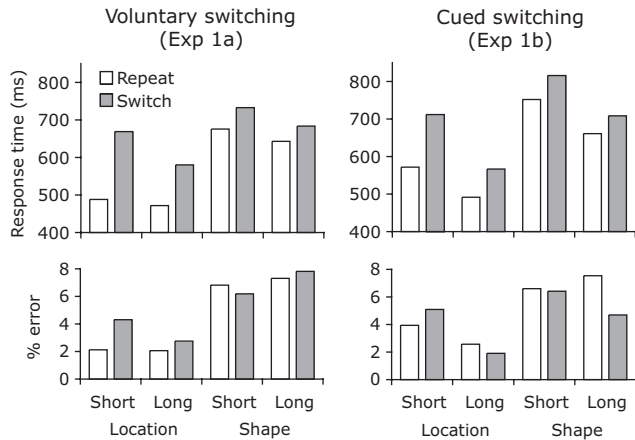


Figure 1. Mean response times and error rates for the location and shape tasks in Experiments 1a and 1b as a function of trial type (switch or repeat) and response-stimulus interval/cue-stimulus interval (short or long).

with the irrelevant stimulus attribute. Critically, this effect of response congruence was greater for the shape task than for the location task: The RT difference between congruent and incongruent trials in the shape task was 63 ms, compared with 20 ms for the location task, a reliable difference,  $F(1, 15) = 17.3, p < .01, \eta_p^2 = .54$ . Corresponding patterns were apparent in the error rate data, where response congruence effects were again larger for the shape task (7.3%) than for the location task (1.8%),  $F(1, 15) = 11.6, p < .01, \eta_p^2 = .44$ .

**Cued switching (Experiment 1b).** The results of Experiment 1b mirror those of 1a. The location task was performed more quickly,  $F(1, 15) = 56.8, p < .01, \eta_p^2 = .79$ , and more accurately,  $F(1, 15) = 9.2, p < .01, \eta_p^2 = .38$ , than the shape task. In addition, response congruence effects were smaller for the location task than the shape task, both for RTs (47 ms vs. 10 ms),  $F(1, 15) = 28.5, p < .01, \eta_p^2 = .66$ , and for error rates (4.6% vs. 1.2%),  $F(1, 15) = 26.9, p < .01, \eta_p^2 = .64$ .

Thus, the location task was performed more quickly, more accurately, and with less interference on incongruent trials than was the shape task. Although RT and error rates, and to a lesser degree response congruence effects, are an imperfect guide to relative strength, the confluence of these three effects—particularly when considered in the context of the vast literature on the compatibility between spatial codes in perception and action (e.g., Kornblum, Hasbroucq, & Osman, 1990)—supports the notion that the location task was the dominant task of the pair. Of interest then are the corresponding switch costs for the two tasks.

**Task strength and task switching.**

**Voluntary switching (Experiment 1a).** The main effect of transition type (switch vs. repeat) was reliable for RTs,  $F(1, 15) = 19.0, p < .01, \eta_p^2 = .56$ , but not for error rates,  $F(1, 15) = 2.5, p > .1, \eta_p^2 = .14$ . Thus, overall there were significant costs of a voluntary task switch. Critically, as shown in Figure 1, the cost of a voluntary switch to the easier location task (144 ms) was substantially greater than the cost of a voluntary switch to the more difficult shape task (49 ms),  $F(1, 15) = 32.4, p < .01, \eta_p^2 = .68$ . A corresponding pattern was evident in the error data, with a numerically larger switch cost for the location task (1.4%) than for

the shape task (−0.1%),  $F(1, 15) = 2.8, p > .1, \eta_p^2 = .16$ . Therefore, as has previously been observed in predictable and cued switching designs, the cost of task switching was greater when switching to the stronger task of a pair.

These findings suggest that the cost of a voluntary task switch is influenced by between-task interference effects. Consistent with this interpretation, a reliable interaction in the RT data was found among task, transition type, and stimulus congruence,  $F(1, 15) = 6.3, p < .05, \eta_p^2 = .30$ . For the location task, the interfering effects of an incongruent stimulus were greater on switch trials (29 ms) than on repeat trials (11 ms); for the shape task, the effects of stimulus congruence were, if anything, slightly reduced on switch trials (55 ms) relative to repeat trials (71 ms). Corresponding patterns were evident in the error rate data, but the effects were not statistically reliable,  $F(1, 15) = 1.4, p > .1, \eta_p^2 = .09$ . Thus, differential effects of response-specific interference across tasks contributed to the asymmetrical pattern of switch costs observed. Nonetheless, interference at the level of whole tasks, independent of specific response interference, also seems to have contributed to the observed pattern of results, as the asymmetry of switch costs was still apparent, albeit to a reduced degree, in analyses focusing selectively on congruent trials for which there is no response-specific interference: for RTs,  $F(1, 15) = 15.5, p < .01, \eta_p^2 = .51$ , and for errors,  $F(1, 15) = 1.1, p > .1, \eta_p^2 = .07$ .

**Cued switching (Experiment 1b).** A corresponding pattern of asymmetrical switch costs was apparent in Experiment 1b, with location task switch costs exceeding shape task switch costs, both for RTs (106 ms vs. 58 ms),  $F(1, 15) = 10.0, p < .01, \eta_p^2 = .40$ , and for errors (0.2% vs. −1.5%),  $F(1, 15) = 9.8, p < .01, \eta_p^2 = .39$ . As in Experiment 1a, the asymmetry was numerically larger on incongruent trials than on congruent trials, but the interaction among task, transition type, and stimulus congruence was not reliable for RTs,  $F(1, 15) = 1.1, p > .1, \eta_p^2 = .07$ , or for errors ( $F < 1$ ). Once again, the asymmetrical pattern was

Table 1  
Behavioral Data From Experiments 1a and 1b, Showing Mean RTs (in Ms) and Error Percentages in Parentheses for the Factorial Combination of Task, Response-Stimulus Interval/Cue-Stimulus Interval, Transition Type, and Response Congruence

	Short		Long	
	Repeat	Switch	Repeat	Switch
Voluntary switching (Experiment 1a)				
Location				
Congruent	479 (1.4)	648 (1.8)	466 (1.4)	562 (0.9)
Incongruent	492 (2.4)	681 (5.7)	476 (2.2)	590 (3.6)
Shape				
Congruent	620 (2.4)	705 (2.1)	602 (1.4)	640 (2.3)
Incongruent	704 (8.8)	746 (7.9)	663 (10.4)	709 (10.5)
Cued switching (Experiment 1b)				
Location				
Congruent	567 (2.4)	705 (2.6)	486 (3.2)	557 (1.3)
Incongruent	575 (4.0)	715 (5.3)	494 (3.3)	570 (1.8)
Shape				
Congruent	716 (4.9)	796 (3.7)	627 (3.1)	676 (1.9)
Incongruent	771 (8.1)	827 (8.7)	678 (8.8)	725 (6.4)

apparent, but to a reduced degree, in analyses focusing selectively on congruent trials: for RTs,  $F(1, 15) = 3.7$ ,  $p < .08$ ,  $\eta_p^2 = .20$ , and for errors ( $F < 1$ ).

**Effects of task preparation.** Switch costs are typically found to be reduced when participants are given time to prepare for an upcoming switch (Meiran, 1996; Rogers & Monsell, 1995); this effect has also been observed in prior studies of voluntary task switching (Arrington & Logan, 2004, 2005; Liefvooghe, Demanet, & Vandierendonck, 2009). Reductions in switch costs with increasing preparation interval are sometimes interpreted as evidence that the cost directly indexes the operation of control operations (e.g., Arrington & Logan, 2005; Rogers & Monsell, 1995). However, preparation effects might also be mediated via reductions in between-task interference: It seems intuitively plausible that effective task preparation should reduce competition from task-irrelevant information (Allport & Wylie, 1999; Yeung & Monsell, 2003b). If asymmetrical switch costs reflect between-task interference, and if preparation tends to reduce this interference, then it follows that preparation should reduce the asymmetrical pattern of switch costs. The relevant data are presented in Figure 1 and Table 1.

**Voluntary switching (Experiment 1a).** As shown in Figure 1, increasing the RSI led to a reduction in overall RTs,  $F(1, 15) = 6.4$ ,  $p < .05$ ,  $\eta_p^2 = .30$ , and RT switch costs,  $F(1, 15) = 7.8$ ,  $p < .05$ ,  $\eta_p^2 = .34$ . Critically, a reliable three-way interaction among task, transition, and RSI,  $F(1, 15) = 4.8$ ,  $p < .05$ ,  $\eta_p^2 = .24$ , indicated that increasing preparation time led to a greater reduction in switch costs for the location task (from 180 ms to 109 ms) than for the shape task (from 57 ms to 41 ms). Subsequent pairwise comparisons revealed that only the former difference was statistically reliable: for the location task,  $t(15) = 2.90$ ,  $p < .05$ ; for the shape task,  $t(15) = 1.15$ ,  $p > .25$ . A corresponding pattern was apparent in the error data, where increasing the RSI led to a numerical reduction of error costs for the location task (from 2.2% to 0.7%) but to a slight increase in error costs for the shape task (from -0.6% to 0.5%),  $F(1, 15) = 2.8$ ,  $p > .1$ ,  $\eta_p^2 = .16$ . These results suggest that the observed reduction in voluntary switch costs with preparation was primarily driven by a reduction in between-task interference effects, as indexed by a reduction in the asymmetrical pattern of switch costs.

**Cued switching (Experiment 1b).** The results of Experiment 1b once again replicated key features of the voluntary switching data. Thus, the cost of instructed switching was reliably reduced as CSI increased,  $F(1, 15) = 14.6$ ,  $p < .01$ ,  $\eta_p^2 = .49$ , and this reduction with preparation was greater for the location task (from 140 ms to 64 ms) than for the shape task (from 75 to 47 ms), although the three-way interaction in the RT data was only marginally reliable,  $F(1, 15) = 4.4$ ,  $p < .06$ ,  $\eta_p^2 = .23$  (for errors,  $F < 1$ ). Subsequent pairwise comparisons revealed a reliable effect of preparation for the location task,  $t(15) = 3.67$ ,  $p < .01$ , but not for the shape task,  $t(15) = 1.23$ ,  $p > .2$ .

**Between-experiment comparison.** The preceding analyses were run in parallel for the two experiments. Next, the results of these experiments were directly compared in ANOVAs that included experiment as a between-participants factor. This analysis revealed that the asymmetry in switch costs between the two tasks was somewhat greater in voluntary (Experiment 1a) than cued (Experiment 1b) switching, for RTs,  $F(1, 30) = 2.9$ ,  $p = .1$ ,  $\eta_p^2 = .09$ , but not for errors ( $F < 1$ ), perhaps indicating that

participants experienced greater between-task interference when there were no explicit cues about which task to perform. Consistent with this interpretation, response congruence effects were also larger during voluntary switching, at the trend level for RTs,  $F(1, 30) = 2.7$ ,  $p = .1$ ,  $\eta_p^2 = .08$ , and reliably so for errors,  $F(1, 30) = 5.1$ ,  $p < .05$ ,  $\eta_p^2 = .11$ . This analysis also revealed reliable interactions between experiment and RSI/CSI, for RTs,  $F(1, 30) = 8.3$ ,  $p < .01$ ,  $\eta_p^2 = .22$ , and for error rates,  $F(1, 30) = 6.6$ ,  $p < .05$ ,  $\eta_p^2 = .18$ . These interactions reflect an increase in RTs and error rates at the short CSI during cued switching (Experiment 1b), presumably caused by the difficulty of processing task cues and stimuli appearing close together in time. No other between-experiment differences were significant.

**Task choices in Experiment 1a.** Participants in Experiment 1a were instructed to decide randomly (“as if flipping a coin”) which task to perform on each trial. If their behavior was truly random, they would produce equal numbers of trials of each task and equal numbers of switch and repeat trials. In fact, their behavior exhibited systematic biases away from randomness that provide further insights into interactions between bottom-up and top-down factors in voluntary task switching.

**Choosing to switch or repeat.** Figure 2 plots the average probability that participants would produce runs of tasks of a particular length before switching to the alternative task. With truly random task choice, the probability of each particular run length  $N$  would be equal to  $0.5^N$  (the pattern inevitably seen in Experiment 1b). However, participants’ behavior in Experiment 1a departed substantially from this expected distribution. In particular, as has been observed in previous studies of voluntary task switching (Arrington & Logan, 2004, 2005; Mayr & Bell, 2006), participants produced fewer very short runs of trials than would be expected if they had switched tasks randomly. As a consequence, participants repeated tasks (on 62.5% of trials) more often than would be expected given truly random behavior (50%),  $t(15) = 12.9$ ,  $p < .01$ . The preponderance of task repeat trials was more marked in blocks with a short RSI (65%) than in blocks with a long RSI (60%),  $t(15) = 3.1$ ,  $p < .01$ . Chi-square tests performed on data from individual participants revealed that the performance of 15 of the 16 participants differed from expected values in both tasks at both RSIs; the remaining participant differed from expected values only when performing the shape task.

**Task choice.** Of particular interest in the present context is whether participants exhibited a preference for one of the two

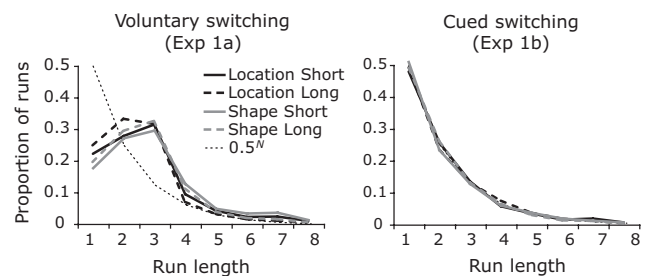


Figure 2. Distribution of run lengths for the two tasks in Experiments 1a and 1b, separately for the short and long response–stimulus intervals, plotted against the expected distribution given a truly random sequence of tasks.

tasks. As described above, previous studies have noted a tendency for participants to choose the easier option (e.g., repeating tasks more often than they switch and avoiding difficult switches back to tasks recently switched away from). It is therefore striking that participants in Experiment 1a exhibited a small but consistent bias toward performing the more difficult shape task,  $t(15) = 3.9, p < .01$ , performing this task on an average of 52.5% of trials across participants (range = 47%–58%). This preference did not reliably differ as a function of RSI,  $t(15) = 1.2, p > .1$ . As shown in Figure 2, the preference was manifested as a tendency to perform longer runs of the shape task than of the location task (mean run lengths of 2.81 vs. 2.55 trials, respectively,  $t(15) = 4.26, p < .01$ ). A tendency to produce longer runs is in fact the only way for a preference to be expressed in voluntary switching between two tasks, because the overall numbers of switches and runs when there are only two tasks must necessarily be roughly equivalent.

Subsequent analyses further investigated this bias toward performing the shape task. As noted above, this bias might reflect the influence of between-task interference, which should increase the difficulty of switching to the stronger (location) task. However, a simple alternative account of this finding might be in terms of stimulus repetition effects. It seems plausible that the effect of stimulus repetition might be greater for a more difficult task, given that performance on this task would particularly benefit from the speedup associated with repeating a response. However, although stimulus repetition did indeed increase the probability of task repetition (cf. Mayr & Bell, 2006), this effect did not differ across tasks (see Table 2). The probability of task repetitions was greater for the shape task than the location task,  $F(1, 15) = 18.8, p < .01, \eta_p^2 = .56$ , and was greater when there was a repetition of the location,  $F(1, 15) = 13.8, p < .01, \eta_p^2 = .48$ , or of the presented shape,  $F(1, 15) = 7.1, p < .05, \eta_p^2 = .32$ . However, task choice did not interact with either shape or location repetition effects or their interaction ( $F_s < 1$ ). A pairwise comparison revealed that task repetitions were more likely for the shape task than the location task even when only trials without stimulus feature repetitions were included in the analysis,  $t(15) = 2.62, p < .05$ .

To follow a brief tangent, the data in Table 2 reveal patterns that extend Mayr and Bell’s (2006) earlier analysis of stimulus repeti-

tion effects. In particular, voluntary task switching behavior was influenced by repetitions not only of the attended stimulus feature but also of the unattended feature. Thus, if participants performed the shape task on trial N, they were more likely to stay with this task on trial N + 1 if there was a repetition of stimulus location,  $F(1, 15) = 12.4, p < .01, \eta_p^2 = .45$ . Similarly, location task repetitions were more likely when the shape repeated,  $F(1, 15) = 4.4, p = .05, \eta_p^2 = .28$ . This effect was partly driven by a tendency to repeat tasks most frequently when there was an exact stimulus repetition, although the interaction between location and shape repetition effects was not reliable,  $F(1, 15) = 2.0, p > .15, \eta_p^2 = .12$ . However, the tendency to stay with the shape task when the location repeated was reliable in an analysis focusing solely on trials in which the shape itself changed,  $t(15) = 2.86, p < .05$ . A corresponding trend was apparent for the location task, but the difference was not reliable,  $t(15) = 1.2, p > .2$ . These findings demonstrate further the sensitivity of participants’ voluntary task choices to bottom-up factors.

Returning to the task choice bias, the next analysis investigated whether participants’ preference for the shape task changed over time or as a function of response congruence. If the shape task bias was a strategic choice to avoid the effort associated with switching to the easier location task, it might be expected that the bias would increase over time, as participants became fatigued toward the end of experimental blocks or sessions, or would increase on difficult incongruent trials. However, the percentage of shape task trials was very similar in the first half (52.5%) and second half (52.6%) of blocks ( $t < 1$ ); was if anything slightly greater in the first half (53.0%) than the second half (52.0%) of the experimental session,  $t(15) = 1.7, p > .1$ ; and was fractionally larger on congruent (52.8%) than on incongruent (52.4%) trials ( $t < 1$ ). Thus, although these analyses do rule out the notion that the shape task bias was a strategic choice to avoid the effort of switching to the location task, they certainly do not provide any direct support for this idea.

**Performance preceding voluntary switching.** A final analysis focused on performance differences associated with switching and repeating tasks. Arrington and Logan (2004) have previously reported that RTs increase on the trial prior to a voluntary task switch, suggesting that a decrease in efficiency of task performance might be a precursor to a switch of task. This idea is intriguing in the context of the hypothesis that switching behavior is strongly influenced by (asymmetrical) biases carried over from trial to trial. In Gilbert and Shallice’s (2002) connectionist model, for example, a strong control bias is required in order to perform the more difficult task, which makes this task a strong attractor state of the network and therefore difficult to switch away from. In contrast, weak control biases are required when performing easy tasks, such that these tasks are less stable attractor states of the network. Applied to the present experiment, this theory suggests that performance of the easier location task should be less stable than performance of the shape task. It might therefore be predicted that the location task should be more prone to performance decrements prior to task switches, as participants effectively “fall out” of the location task in a way that they should not for the more difficult shape task.

Table 3 presents the relevant data. Averaged across tasks, there was a reliable RT increase prior to voluntary task switches,  $F(1, 15) = 9.9, p < .01, \eta_p^2 = .40$ , an effect that was absent in Experiment 1b, in which switching was instructed ( $F < 1$ ). Crit-

Table 2  
Proportion of Task Repetitions for Each Task in the Voluntary Task Switching Experiments 1a, 2a, and 2b as a Function of Whether the Location and Shape Repeated From the Previous Trial

Variable	Location changes		Location repeats	
	Shape changes	Shape repeats	Shape changes	Shape repeats
Experiment 1a				
Just performed location	0.59	0.60	0.61	0.65
Just performed shape	0.62	0.63	0.66	0.69
Experiment 2a				
Just performed compatible	0.46	0.49	0.55	0.60
Just performed incompatible	0.50	0.53	0.56	0.59
Experiment 2b				
Just performed location	0.55	0.58	0.57	0.66
Just performed shape	0.49	0.54	0.58	0.62

Table 3  
Performance on Trials Prior to Task Repeats and Task Switches in Each Experiment, Showing Mean RTs (in Ms) and Error Percentages in Parentheses

Experiment	Location (Compatible)		Shape (or Incompatible)	
	Before repeat	Before switch	Before repeat	Before switch
1a	458 (2.4)	496 (1.3)	606 (7.7)	610 (4.9)
1b	533 (3.9)	524 (3.8)	666 (5.3)	672 (6.3)
2a <sup>a</sup>	525 (1.3)	577 (0.6)	728 (5.3)	718 (3.9)
2b	451 (2.0)	480 (0.4)	674 (0.0)	716 (0.1)

Note. To remove the confounding effects of differing run lengths between tasks, the analysis included only trials in which the prior trial was itself a task repetition.

<sup>a</sup> Two participants in Experiment 2a had very few trials in one or more cells of the factorial design and were therefore excluded from this analysis.

ically, the preswitch RT increase in Experiment 1a was apparent only for the location task and not for the shape task, as reflected in a reliable RT interaction between task and subsequent transition type,  $F(1, 15) = 10.0$ ,  $p < .01$ ,  $\eta_p^2 = .40$ . Pairwise comparisons revealed that this interaction was driven by a robust preswitch RT increase for the location task ( $p < .01$ ). Another way to look at this effect is in terms of the probability that participants would switch task on the next trial as a function of RT on the current trial. To this end, switch probability was calculated for each task after dividing trials in quartile bins on the basis of RT. This analysis revealed that for the location task, participants were much more likely to make a voluntary task switch after a trial in the slowest RT quartile than after a trial in the fastest RT quartile (59% vs. 45%,  $p < .01$ ). No corresponding effect was apparent for the shape task (48% vs. 47%,  $p > .1$ ).

These findings are therefore consistent with the view that performance of the easier location task was less stable than performance of the shape task, being more prone to performance decrements as a precursor to switching to the other task. The error data provide only qualified support for this hypothesis, however, because error rates tended to decrease prior to task switches for both tasks,  $F(1, 15) = 5.7$ ,  $p < .05$ ,  $\eta_p^2 = .28$ . This effect was numerically larger for the shape task than the location task but not consistently so across participants,  $F(1, 15) = 2.8$ ,  $p > .1$ ,  $\eta_p^2 = .16$ . Pairwise comparisons revealed that the preswitch increase in accuracy was present for both the location ( $p < .07$ ) and shape ( $p < .05$ ) tasks. One interpretation of this effect is that participants tend to avoid switching after they make an error, perhaps because of increased cognitive demands associated with detecting and compensating for errors (Jentsch & Dudschig, 2009).

In summary, the choice data provide clear evidence that participants' voluntary choices are influenced by bottom-up factors. Replicating previous findings, the data show that participants in the present study were biased to repeat rather than switch tasks and were more likely to repeat tasks when attended stimulus features repeated across trials. Extending prior findings, the present data suggest that participants' choices are also affected by repetition of currently unattended stimulus features and, critically, by the relative difficulty of the two tasks. Perhaps surprisingly, the task bias

observed in the present study was toward the more difficult task of the pair.

## Discussion

The results of Experiment 1a demonstrate that in voluntary task switching, the relative difficulty of tasks being switched between affects both the choice of which task to perform and the time taken to implement that choice. The finding of asymmetrical switch costs, with a greater cost of switching to the easier task of a pair, has previously been observed in studies using instructed switching designs, where such an asymmetry has been taken as a diagnostic marker of the effects of between-task interference (Allport et al., 1994; Meuter & Allport, 1999; Yeung & Monsell, 2003a, 2003b). The present findings demonstrate that between-task interference likewise makes a substantial contribution to task switching performance even under conditions in which behavior is notionally under complete voluntary control.

The results demonstrate further that between-task interference also influences participants' voluntary choices. Surprisingly, participants exhibited a small but consistent bias toward performing the more difficult of the two tasks. This preference was particularly striking given that, in terms of overall RT and error rate, participants found it easier to switch to the (easy) location task than to repeat performance of the (more difficult) shape task. Thus, even when participants were already performing the more difficult task, it should have been more effortful for them to continue with this task than to switch to the easier location task, yet they tended to choose the former option. As described above, these findings can be interpreted in terms of the asymmetrical task biases associated with the two tasks. This interpretation is discussed below pending replication of this novel finding in Experiments 2a and 2b.

The present data also permit a direct comparison between voluntary and instructed (cued) switching. Perhaps the most striking aspect of this comparison is the close similarity between the results of the two experiments: Both studies found asymmetrical switch costs that were reduced as a function of preparation interval, and overall costs were of a similar magnitude in the two studies. However, the asymmetry in switch costs was larger during voluntary switching (95 ms) than cued switching (52 ms), perhaps indicating that between-task interference is amplified in the absence of explicit task cues. This interpretation is consistent with the increase in response congruence effects also observed during voluntary switching.

The results of Experiment 1b also help inform the interpretation of the effects of RSI on voluntary task switching performance in Experiment 1a. Manipulations of RSI confound the effects of passive task-set decay and of active task preparation (Meiran, 1996). These effects can be deconfounded in cued switching designs by varying CSI (and, hence, the time available for active preparation) while holding constant the total amount of time between trials (and, hence, the amount of time over which passive task decay can occur). It is therefore of interest that the magnitude of the RSI effect on voluntary switch costs in Experiment 1a (44 ms) was comparable to the reduction of cued switch costs with CSI in Experiment 1b (41 ms). The reduction in the switch cost asymmetry with RSI/CSI was likewise similar across experiments (55 ms and 48 ms). Although caution must be taken when interpreting the results of studies with different methods, the similarity

between the effects of RSI in Experiment 1a and CSI in Experiment 1b suggests that the combined CSI/RSI effects primarily reflect active preparation rather than passive decay of tasks between trials.

Together, the results of Experiments 1a and 1b provide evidence that between-task interference exerts a substantial influence over participants' switching behavior in voluntary as well as instructed task switching. However, these results leave open the mechanisms underlying the observed between-task interference effects. On the basis of previous empirical and computational modeling work (Gilbert & Shallice, 2002; Yeung & Monsell, 2003a), one might assume that interference occurs at the level of response selection. However, the tasks used in the present experiments confounded response selection difficulty (easy vs. hard) with the nature of the relevant perceptual attribute (location vs. shape). It is possible that perceptual switching requirements differed between tasks, contributing to the observed results. For example, it could plausibly be more difficult to switch attention to an incidental feature of an object (its location) than to an integral feature of that object (its identity). Experiments 2a and 2b were therefore designed to identify whether the presence of response interference or the perceptual switching requirement was the critical factor driving the pattern of results observed in Experiments 1a and 1b.

### Experiments 2a and 2b

Experiments 2a and 2b both involved voluntary switching using the same stimuli as Experiment 1a. However, in Experiment 2a participants no longer responded to stimulus shape in one of the tasks. Instead, they switched between two location tasks, one compatibly mapped—as in the location task of Experiment 1a—and the other incompatibly mapped (cf. De Jong, 1995; Shaffer, 1965, for reports of asymmetrical switch costs for such tasks in instructed switching designs). In Experiment 2b, participants switched between location and shape tasks as in Experiment 1a, but now the shape task involved a simple compatible mapping—naming the presented shape—that was associated with distinct response codes (shape names) and a different response modality (vocal) from the location task. If the results of Experiment 1a reflected effects of response-level interference, one would expect corresponding results in Experiment 2a (which involved a pair of tasks that differed in relative strength and response interference) and a different set of results in Experiment 2b (which involved two compatible tasks that differed in the relevant perceptual attribute). If perceptual factors were critical, one would expect the opposite pattern of results.

### Method

**Participants.** There were 16 participants in each experiment. In Experiment 2a there were 5 men and 11 women, 18–34 years of age. Three additional participants were excluded from this study. One had performed at chance in the incompatibly mapped task, and two had failed to follow instructions to switch between tasks in experimental blocks. In Experiment 2b there were 4 men and 12 women, 18–35 years of age. All participants had normal or corrected-to-normal vision. Participants received payment or course credit for their participation, and they gave informed consent at the start of the session.

**Tasks, stimuli, and procedure.** The presentation and timing of stimulus events were identical to those in Experiment 1a. In Experiment 2a, participants performed two tasks that involved responding to the location of the presented shape within the three-box grid. In the “matching” task, the locations were compatibly mapped to the index, middle, and ring fingers of one hand. In the “crossed” task, the locations were incompatibly mapped to the fingers of the other hand as follows: left box = middle finger; center box = rightmost finger; right box = leftmost finger. The assignment of tasks to the left and right hands was counterbalanced across participants. In Experiment 2b, participants switched between a compatibly mapped location task (as in Experiment 1a) and a vocal version of the shape task in which they named the presented shape. Participants responded with their right hand for the location task and spoke their shape task responses into a microphone that triggered a voice key interfaced to the computer. The experimenter monitored these vocal responses and operation of the voice key, marking response errors and trials on which the voice key failed to trigger or triggered before the spoken response. Trials with these microphone errors, and immediately subsequent trials, were excluded from data analysis. The experimental procedures were otherwise the same as in Experiment 1a, except that participants performed 12 rather than 16 blocks of 90 trials in the main experiment to ensure an experimental session less than 1 hr in length. The data analysis procedures were also the same as in Experiment 1a, except that trials were not coded according to response congruence because there were no congruent stimuli in the tasks used.

### Results

**Task strength.** Mean RTs and error rates for Experiments 2a and 2b are presented in Figure 3.

**Response switching (Experiment 2a).** This experiment paired compatible and incompatible location tasks. An extensive literature has documented the difference in strength and automaticity between such tasks, and the present results are in line with this

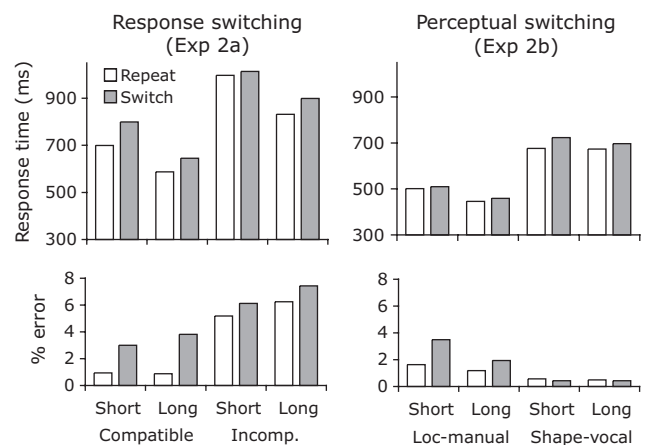


Figure 3. Mean response times and error rates for the compatible and incompatible spatial tasks in Experiment 2a and the manual location and vocal shape tasks in Experiment 2b, as a function of trial type (switch or repeat) and response-stimulus interval (short or long). Incomp. = incompatible; Loc = location.

prior work: The compatible location task was performed more quickly,  $F(1, 15) = 109.4, p < .01, \eta_p^2 = .88$ , and more accurately,  $F(1, 15) = 21.0, p < .01, \eta_p^2 = .58$ , than the incompatible task. Although RT and error rate measures do not provide an unambiguous guide to relative strength, as noted above, the data certainly provide little reason to doubt the expected dominance of the compatible task.

**Perceptual switching (Experiment 2b).** In this experiment the two tasks differed in the relevant perceptual attribute, but both were compatibly mapped. As expected, the dominance of one or other task was much less clear. Thus, although the manual location task was performed more quickly than the shape task,  $F(1, 15) = 93.4, p < .01, \eta_p^2 = .86$ , it was also performed significantly less accurately,  $F(1, 15) = 34.7, p < .01, \eta_p^2 = .70$ . Vocal responses are typically slower than manual ones—it takes longer to vibrate vocal chords than to twitch a finger—and here this difference was exacerbated by a speed–accuracy trade-off, such that neither task was obviously the dominant one of the pair.

#### Task strength and task switching.

**Response switching (Experiment 2a).** The main effect of transition type (switch vs. repeat) was reliable both for RTs,  $F(1, 15) = 10.1, p < .01, \eta_p^2 = .40$ , and for error rates,  $F(1, 15) = 10.5, p < .01, \eta_p^2 = .41$ . As shown in Figure 3 (left panel), the cost of voluntary task switching was larger for the compatible than the incompatible location task. The two-way interaction between task and transition type was not reliable for RTs,  $F(1, 15) = 2.7, p > .1, \eta_p^2 = .15$ , or for errors ( $F < 1$ ), but the three-way interaction involving RSI was reliable for RTs,  $F(1, 15) = 15.9, p < .01, \eta_p^2 = .51$  (for errors,  $F < 1$ ). Separate ANOVAs for the two RSI conditions revealed that RT switch costs were reliably greater for the compatible task than the incompatible task at the short RSI,  $F(1, 15) = 7.8, p < .05, \eta_p^2 = .34$ , but did not differ for the two tasks at the long RSI ( $F < 1$ ). Separate ANOVAs for the two tasks indicated that switch costs were reduced as the preparation interval increased for the compatible task,  $F(1, 15) = 5.1, p < .05, \eta_p^2 = .25$ , but (surprisingly) increased with RSI for the incompatible task,  $F(1, 15) = 5.6, p < .05, \eta_p^2 = .27$ . Aside from this unexpected effect of RSI for the incompatible task, the findings of this study replicate key results from Experiment 1a: Voluntary switch costs showed an asymmetric pattern, with greater costs for the dominant task of the pair, and this pattern diminished as the time available for preparation was increased.

**Perceptual switching (Experiment 2b).** Voluntary task switching costs were generally smaller in this experiment, averaging 23 ms across tasks, but were statistically reliable both for RTs,  $F(1, 15) = 5.2, p < .05, \eta_p^2 = .26$ , and for errors,  $F(1, 15) = 11.0, p < .01, \eta_p^2 = .42$ . The RT and error data exhibited contrasting between-task differences in switch costs. In the RT data, switch costs were generally larger for the vocal shape task than the manual location task, particularly so at the short RSI, as reflected in a reliable three-way interaction involving task, transition type, and RSI,  $F(1, 15) = 5.2, p < .05, \eta_p^2 = .26$ , although the two-way interaction between task and transition was not itself reliable,  $F(1, 15) = 2.0, p > .1, \eta_p^2 = .12$ . In contrast, the error data exhibited greater switch costs for the manual location task,  $F(1, 15) = 9.8, p < .01, \eta_p^2 = .39$ , an effect that was somewhat greater at the short RSI,  $F(1, 15) = 2.4, p > .1, \eta_p^2 = .14$ . Overall, therefore, both tasks exhibited reliable switch costs that were reduced with RSI, but these effects were expressed differentially for the tasks in

terms of RT slowing or increased error rates. There was no consistent pattern for greater costs for either of the two tasks.

**Between-experiment comparison.** Next, the results of the two experiments were directly compared in ANOVAs that included experiment as a between-participants factor. The analysis focused in particular on performance of the compatible location task: The same compatible task was used in both experiments, but this task was expected to suffer much greater between-task interference during response switching (Experiment 2a) than during perceptual switching (Experiment 2b). Consistent with this expectation, this task was performed much more slowly in Experiment 2a (mean RT = 697 ms) than in Experiment 2b (mean RT = 479 ms), a reliable between-experiment difference,  $F(1, 30) = 15.1, p < .01, \eta_p^2 = .34$ . Correspondingly, switch costs for this task were reliably greater in Experiment 2a (84 ms) than in Experiment 2b (11 ms),  $F(1, 30) = 9.2, p < .01, \eta_p^2 = .23$ . These findings provide further evidence that between-task interference—specifically, interference at the level of response selection—is a strong determinant of the cost associated with voluntary task switching.

A second between-experiment comparison contrasted the results of Experiments 1a and 2b: These two experiments had identical perceptual switching requirements, but in Experiment 2b separable, compatible response mappings were used to reduce the level of between-task interference. The analysis revealed that this reduction in interference led to an overall reduction in switch costs in Experiment 2b relative to Experiment 1a,  $F(1, 30) = 9.3, p < .01, \eta_p^2 = .23$ , and a corresponding reduction in the switch cost asymmetry,  $F(1, 30) = 25.2, p < .01, \eta_p^2 = .46$ . The sharp differences in patterns of switch costs between experiments suggest that the switch cost asymmetry observed in Experiment 1a is very unlikely to reflect perceptual factors: The same perceptual switching requirement was present in Experiment 2b, but no corresponding asymmetry of switch costs was observed.

Collectively, the present results provide clear evidence that interference at the level of response selection is the most likely cause of the asymmetrical pattern of switch costs observed in Experiment 1a. Relative to Experiment 1a, Experiment 2a removed the need to switch between perceptual attributes (both tasks involved responding to locations) but retained the feature that the tasks should interfere with one another during response selection. The results of this study demonstrated a consistent pattern of greater costs of switching to the dominant, compatible task. In contrast, Experiment 2b retained the need to switch between perceptual attributes but reduced the scope for response-level interference by separating the response codes (locations vs. shape names) and response modalities (manual vs. vocal) of the two tasks. The results of this experiment showed no obvious dominance of one task over the other and no consistent asymmetry in switch costs.

**Choice data: Transition probabilities.** Figure 4 plots averaged probabilities for particular run lengths of each task for the two experiments. Relative to the results of Experiment 1a, participants' choice performance in these experiments more closely approached the proportions of run lengths that would be expected given random task choices on each trial. Participants in Experiment 2a repeated tasks on 52% of trials and switched tasks on 48% of trials; this result was not significantly different from truly random behavior ( $t < 1$ ). Chi-square tests on the data from individual participants revealed that the behavior of 13 of 16

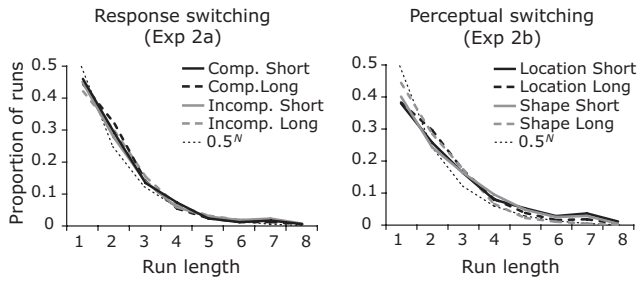


Figure 4. Distribution of run lengths for the pairs of tasks in Experiments 2a and 2b, separately for the short and long response–stimulus intervals, plotted against the expected distribution given a truly random sequence of tasks.

participants deviated from expected values (for data pooled across tasks and RSIs). Of the 13, four participants exhibited a consistent tendency to perform shorter runs of tasks than expected, whereas nine participants exhibited the opposite tendency (sign test,  $p > .1$ ). Participants in Experiment 2b repeated tasks more often (on 56% of trials) than would be expected given truly random task choices,  $t(15) = 3.4$ ,  $p < .01$ , a bias that was particularly marked at short RSIs,  $t(15) = 3.3$ ,  $p < .01$ . Chi-square analyses revealed that the choices of 12 of 16 participants deviated reliably from expected values. Of the 12, one participant performed more short runs of trials than expected, whereas 11 participants exhibited the opposite tendency (sign test,  $p < .01$ ). Overall, therefore, participants in Experiments 2a and 2b exhibited less of a tendency to produce task repetitions than did participants in Experiment 1a or previous studies (Arrington & Logan, 2005; Mayr & Bell, 2006). These unexpected results perhaps provide evidence of the susceptibility of voluntary task switching performance to subtle experimental factors: In the present experiments, the importance of performing the tasks randomly was explicitly emphasized to the participants, after two early participants in Experiment 2a had to be excluded for ignoring these instructions (as noted above).<sup>1</sup>

**Task choice.** Of more relevance to the theoretical issues at hand are participants' choices of which task to perform. Again, consistent biases were demonstrated in both experiments. Broadly, the results during response switching (Experiment 2a) replicated the patterns apparent in Experiment 1a, with participants exhibiting a small but consistent bias toward performing the more difficult (in this case, spatially incompatible) task. In contrast, participants in Experiment 2b exhibited a preference for performing the location task over the shape task—a preference opposite to that apparent in Experiment 1a.

**Response switching (Experiment 2a).** Participants in Experiment 2a performed the incompatible location task more frequently than the easier compatible task, on an average of 51.7% of trials (range = 47%–58%),  $t(15) = 2.5$ ,  $p < .05$ , thus mirroring the results of Experiment 1a. This preference was evident as a tendency to perform longer runs of the incompatible task ( $M = 2.32$ ) than the compatible task ( $M = 2.03$ ),  $t(15) = 3.34$ ,  $p < .01$ . As shown in Table 2, this task bias was not driven by a disproportionate tendency to repeat the incompatible task when stimulus features repeated: Repetition of location did increase the probability of task repetitions,  $F(1, 15) = 7.9$ ,  $p < .05$ ,  $\eta_p^2 = .34$ , but if anything this effect tended to be greater for the compatible

task than the incompatible task,  $F(1, 15) = 2.7$ ,  $p > .1$ ,  $\eta_p^2 = .15$ . As in Experiment 1a, the bias toward the more difficult task did not reliably differ in the first versus second half of experimental blocks ( $t < 1$ ) or first versus second half of the experimental session ( $t < 1$ ).

The results of Experiment 2a also provide further insight into the sensitivity of participants' task choices to stimulus-driven factors. In this experiment, shape identity was irrelevant to both of the tasks performed. Nevertheless, as shown in Table 2, participants were more likely to repeat the task when the same shape appeared on consecutive trials,  $F(1, 15) = 14.1$ ,  $p < .01$ ,  $\eta_p^2 = .49$ . This effect was seen even when trials with location repetitions were excluded from the analysis,  $t(15) = 2.8$ ,  $p < .05$ , indicating that the effect was not solely due to an increased tendency to repeat tasks when identical stimuli appeared on successive trials. The magnitude of the shape repetition effect, a 2.9% increase in the percentage of task repetitions, was comparable to that seen for the location task in Experiment 1a (2.7%). Together, these findings demonstrate that participants' voluntary choices are influenced not only by stimulus features that are irrelevant in the current task (as in Experiments 1a and 2b) but also by features that are irrelevant in the experiment as a whole.

**Perceptual switching (Experiment 2b).** Participants in Experiment 2b performed the location task more frequently than the shape task, on an average of 52.2% of trials (range = 47%–62%),  $t(15) = 2.0$ ,  $p < .05$ . This preference was also evident as a somewhat greater mean run length for this location task (2.42 vs. 2.23),  $t(15) = 1.70$ ,  $p > .1$ . These findings demonstrate that participants do not have a simple preference for responding to stimulus shape over stimulus location, which helps to rule out this simple explanation of the task bias exhibited by participants in Experiment 1a. In Experiment 2b, repetitions of both tasks were more likely with repetitions of the location,  $F(1, 15) = 6.4$ ,  $p < .05$ ,  $\eta_p^2 = .30$ , or of the presented shape,  $F(1, 15) = 20.8$ ,  $p < .01$ ,  $\eta_p^2 = .58$ , and they were especially likely when both stimulus features repeated, as reflected in a reliable interaction between location and shape repetition effects,  $F(1, 15) = 5.2$ ,  $p < .05$ ,  $\eta_p^2 = .26$ . The effect of exact stimulus repetitions was particularly marked for the location task,  $F(1, 15) = 4.7$ ,  $p < .05$ ,  $\eta_p^2 = .24$ . Nevertheless, participants' preference for the location task was apparent even when trials with repetitions of stimulus features were excluded from the analysis,  $t(15) = 2.3$ ,  $p < .05$ .

#### Performance preceding voluntary task switches.

**Response switching (Experiment 2a).** A final analysis focused on performance prior to voluntary repetitions and switches of tasks (see Table 3). The results of Experiment 2a resembled those of Experiment 1a, showing a preswitch RT increase that was

<sup>1</sup> An alternative account of the high switch rates in Experiments 2a and 2b is that the tasks used nonarbitrary response rules: Perhaps the low switch costs associated with these tasks led participants to switch more frequently than they do when switching between tasks with arbitrary mappings. However, this hypothesis predicts that switch rates should be highest in Experiment 2b (which paired two compatibly mapped tasks) and should be lower in—and similar between—Experiments 1a and 2a (both of which paired one compatibly mapped task with a second task with an arbitrary mapping). In contrast to this prediction, switch rates were highest in Experiment 2a, lower in Experiment 2b, and lowest in Experiment 1a (which had switch rates comparable to those observed in prior studies).

restricted to the easier (compatible) location task. This was reflected in a reliable interaction between task and subsequent transition type,  $F(1, 13) = 12.1, p < .01, \eta_p^2 = .48$ , that was driven by a large preswitch RT increase for the compatible location task ( $p < .01$ ). This effect was also apparent in a parallel analysis of switch probability as a function of RT: Participants were more likely to switch away from the location task after a slow RT trial than after a fast RT trial (62% vs. 48% switch rate, respectively, for trials in the slowest and fastest RT quartiles,  $p < .01$ ). In contrast, the incompatible task showed small effects in the opposite direction, with slightly faster RTs prior to task switches ( $p > .1$ ) and, correspondingly, a slightly reduced tendency to switch after slower RT trials (48% vs. 52%,  $p > .1$ ). Error rates were again somewhat lower on preswitch trials,  $F(1, 13) = 1.5, p > .1, \eta_p^2 = .11$ , an effect that was numerically larger for the incompatible location task ( $F < 1$ ).

**Perceptual switching (Experiment 2b).** As shown in Table 3, a robust preswitch RT increase,  $F(1, 15) = 16.8, p < .01, \eta_p^2 = .53$ , was apparent for both tasks in Experiment 2b (pairwise comparison  $ps < 0.01$ ). Correspondingly, participants exhibited a tendency to switch away from both tasks after a slow RT trial: Participants switched from the location task 55% of the time after trials in the slowest RT quartile, compared with 42% of the time after trials in the fastest RT quartile ( $p < .01$ ). A similar effect was apparent for the shape task (55% vs. 43% switch rates, respectively, for trials in the slowest and fastest RT quartiles,  $p < .05$ ). Accuracy was at ceiling in the shape task, but an analysis of error rates for the location task indicated that accuracy again tended to increase prior to task switches,  $t(15) = 3.1, p < .01$ .

## Discussion

The results of Experiments 2a and 2b were clear cut. Experiment 2a paired compatible and incompatible location tasks that would be expected to produce between-task interference during response selection. The results of this experiment replicated the findings of Experiment 1a, with a larger cost associated with voluntary switching to the easier of the two tasks and with participants exhibiting a small but reliable bias toward performing the other, more difficult task. Experiment 2b paired a compatible manual location task with a compatible shape task, such that the tasks differed in perceptual requirements but would be expected to produce much less interference during response selection. No consistent asymmetry in voluntary task switching costs was observed in this experiment, and participants exhibited a small bias toward responding to the location rather than shape of the stimulus (a bias opposite to that observed in Experiment 1a). During debriefing, participants in Experiment 2b reported that they found the vocal shape task very slow, relative to the manual task, but not difficult (as reflected in their very low error rates for this task). These reports suggest that in the absence of bottom-up effects favoring one task over the other, participants' biases tend toward minimizing effort (or, equivalently here, maximizing speed). Taken together, these results suggest that the critical factor determining the results of Experiment 1a (and 2a) is the presence of between-task interference, specifically at the level of response selection.

## General Discussion

The present findings demonstrate that between-task interference has a significant impact on task switching performance even when behavior is notionally under voluntary, top-down control. These results suggest that voluntary task switching performance does not directly index the contribution of top-down control to observed behavior—the workings of the elusive homunculus. Between-task interference effects were evident both in patterns of switch costs, as an increased cost of switching to the stronger task of a pair, and in patterns of task choices, as a surprising bias toward performing the weaker task on a greater proportion of trials. Experiments 2a and 2b provided a systematic investigation of the mechanisms underlying these interference effects. Asymmetrical patterns of switch costs and task choices were replicated in conditions with response overlap but were not observed when perceptual switching occurred without such overlap, demonstrating that between-task interference occurs critically during the response selection process. In the following discussion the implications of these findings are considered, first regarding the contribution of between-task interference to the costs of voluntary task switching, second regarding the influence of bottom-up factors on task choices, and finally regarding the relationship between task performance and task choice measures in voluntary switching.

## Between-Task Interference and Task Performance

Our findings demonstrate that the effects of between-task competition, previously observed in instructed switching designs (Allport et al., 1994; Wylie & Allport, 2000; Yeung & Monsell, 2003b; Yeung et al., 2006), are also observed when task choice is voluntary. A positive, but perhaps rather circumscribed, implication of these findings is that key task switching phenomena are not tightly bound to the particular experimental methods used but are instead robustly observed across studies with quite different requirements. This generalization is reassuring, not least because current theories of cognitive control in task switching provide little ground to expect that the costs seen in voluntary switching should differ fundamentally from those seen in instructed switching designs (e.g., Allport et al., 1994; Altmann, 2007; De Jong, 2000; Meiran, 2000; Rogers & Monsell, 1995; Rubinstein et al., 2001; Ruthruff, Remington, & Johnston, 2001; Sohn & Anderson, 2001; Yeung et al., 2006). However, this generalization was far from inevitable, given recent evidence of dissociations between voluntary and instructed task switching in both behavioral studies (Gollan & Ferreira, 2009) and neuroimaging studies (Forstmann et al., 2006).

Beyond this basic conclusion, the present findings give an indication of the relative contribution of top-down and bottom-up factors to voluntary task switching costs. In particular, the results suggest that the direct contribution of top-down control processes to observed switch costs is, at most, rather small: This contribution should be particularly evident in the cost of switching to weaker tasks, which presumably require a high level of top-down support, yet these costs were very modest—57 ms for the difficult shape task in Experiment 1a and just 17 ms for the incompatible location task in Experiment 2a—as compared with those seen for the easier location task (180 ms and 99 ms in Experiments 1a and 2a, respectively) and in prior studies of voluntary task switching (typically exceeding 200 ms). Moreover, switch costs for the

weaker task were very little affected by increasing the available preparation time; they showed a numerical reduction of just 16 ms at the long RSI in Experiment 1a and an unexpected increase in Experiment 2a. In contrast, much greater switch costs—and much larger reductions in these costs with preparation—were observed for the easier, spatially compatible task in Experiments 1a and 2a. To the extent that switch costs for this easy task reflect the effects of between-task competition, the present findings suggest that bottom-up factors may be a primary determinant of the costs associated with voluntary task switching. According to this interpretation, the switch cost does not directly index the time consumed by the process of activating or enabling new task-level representations. Rather, the cost reflects a relative failure to activate such representations following a change of task, resulting in increased between-task competition and hence impaired performance.

As noted above, the asymmetrical costs observed here contrast with the recent findings of Gollan and Ferreira (2009), who failed to find a corresponding asymmetry in a study of voluntary bilingual language switching. This discrepancy might reflect the massive overtraining that bilingual speakers have in voluntary switching between languages, an interpretation suggesting that cognitive control processes are susceptible to improvement with practice. However, Gollan and Ferreira's (2009) results might also reflect the strategies used by their participants, who were instructed to "say whichever name comes to mind most quickly" (p. 643), and who were found to use their weaker language more often for high-frequency, easily pronounced words. One characterization of these results is that the participants used a strategy of tonically inhibiting their dominant language to such an extent that their two languages were roughly equipotent, then passively allowed the two languages to compete (or race) to produce the picture-naming response on each trial, so that second language responses would occur particularly for familiar or easily pronounced words in that language.

This strategy is very different from the one required in the present study—and in previous studies of voluntary task switching—in which participants were instructed to make top-down voluntary task choices in advance of stimulus presentation. A straightforward test of this interpretation would be to study voluntary language switching in an experiment in which participants were instructed to choose the specific language in advance of stimulus presentation. This study would be expected to replicate the asymmetrical pattern of costs seen in previous studies of instructed language switching (Meuter & Allport, 1999) and in the present study of voluntary switching. Confirmation of this prediction would suggest that asymmetrical switch costs are specifically diagnostic of a cognitive control strategy in which tasks are selected proactively and irrespective of the specific stimulus presented. Such a result would have the broader theoretical implication that patterns of switch costs may be informative about the strategic application of cognitive control even if, as argued here, the operation of control is reflected only indirectly in those costs (cf. Yeung & Monsell, 2003a).

### Between-Task Interference and Task Choice

The influence of bottom-up factors on voluntary switching performance was evident not only in the time participants took to implement task choices but also in the choices they made. Participants were instructed to switch randomly, but their behavior exhibited consistent biases away from true randomness. Replicat-

ing previous findings, participants in this study were found to generally favor task repetitions over task switches and to favor these repetitions more often when stimulus attributes repeated (Mayr & Bell, 2006). Extending these findings, it was found that the probability of task repetition was increased by repetition of stimulus features irrelevant to the current task, even for stimulus features that were never relevant in the experiment. Most strikingly, it was found that participants exhibited a bias toward performing the more difficult task of a pair when, as in Experiments 1a and 2a, the tasks differed in relative strength. Thus, whereas most reported biases in task choice can be broadly explained in terms of participants' preference for minimizing effort (Arrington, 2008; Arrington & Yates, 2009; Lien & Ruthruff, 2008; Mayr & Bell, 2006), participants in the present study exhibited a choice bias toward a more difficult option, a bias that does not seem to indicate simple laziness.

Further analysis of the choice data revealed that the task bias was independent of stimulus repetition effects. Also, no evidence was found that the effect reflected strategic avoidance of the extra effort associated with switching to the easier task. Another possible strategic account of the observed task bias is that participants recognized that they preferred performing the easier task and then overcompensated in the direction of performing the difficult task more frequently. Although initially plausible, this account struggles to provide a coherent explanation of the range of present findings. First, it is unclear on this account why participants should be sensitive to (and overcompensate for) a bias toward one task over the other, yet should be insensitive to (and unable to compensate for) a bias toward repeating over switching tasks, particularly given that they were given feedback on both aspects of their performance. Second, if switching to the weaker task was a strategic overcompensation in the face of an underlying bias toward performing the easier task, one would expect these switches to be particularly effortful and time consuming, yet the RT and error rate data suggest the opposite. Finally, this hypothesis does not provide a ready account of the finding that switches from the easier to the more difficult task were preceded by an RT increase but that no corresponding effect was observed for switches in the opposite direction.

In contrast, between-task interference effects provide a coherent account of the combined findings of our task choice data. According to this interpretation, persisting biases toward the weaker task increase the difficulty of switching away from this task to the stronger task, leading participants to exhibit a surprising preference for performing the weaker task. This hypothesis provides a consistent account of differences between tasks seen in the choice and RT data: Both are explained in terms of asymmetrical task biases causing between-task interference that hinders switching to the stronger task of a pair. Led by this hypothesis, subsequent analyses investigated possible performance differences on trials preceding voluntary task switches. Arrington and Logan (2004) have previously reported that RTs tend to increase prior to voluntary task switches; this finding is suggestive of a weakening of task performance as a precursor to switching. Our prediction was that this effect would be more marked for the stronger task: Weak control biases are required for this task, which should render the task relatively less stable. In contrast, the strong biases required for the weaker task create a strong attractor state that is less likely to decay over time. Consistent with this interpretation, preswitch RT increases were observed only for the stronger task of the pair in Experiments 1a and 2a. These task-related asymmetries in preswitch RTs were absent in

Experiment 2b, in which separation of response codes and response modalities of the two tasks minimized response interference. Therefore, as with the switch cost data, the contrasting task choice results across experiments suggest that conflict at the level of responses is the critical factor determining the expression of between-task interference in voluntary task switching.

### Relating Task Performance and Task Choice

An important advantage of the voluntary switching method is that participants' task choices provide an additional measure with which to capture the elusive controlling homunculus (Arrington & Logan, 2005), which thereby complement and extend the typical focus on performance measures (primarily the switch cost) in instructed switching designs. Emerging evidence suggests that these performance and choice measures may index at least partly separable aspects of cognitive control. For example, although the difficulty of task switching is reflected both in a performance cost and in participants' choice preference for repeating tasks, the magnitudes of these effects appear to be, at best, weakly correlated across participants (Arrington & Yates, 2009; Mayr & Bell, 2006). The present data add further nuance to this picture. Thus, it was found that switch costs and task choices were both sensitive to the influence of between-task interference, but no reliable individual difference correlations were observed between these measures: No consistent positive correlation between the switch cost and task choice asymmetries was seen in Experiments 1a and 2a, and pooling the data from the two experiments revealed even a slight negative correlation,  $r(31) = -.16, p > .1$ .

Nevertheless, the present findings do suggest some links between task performance and task choices. In particular, it was found that participants were consistently more likely to switch tasks after a trial with a slow RT than after a trial with a fast RT (at least for the dominant task of the pair). These findings suggest that inefficiency of task performance, perhaps reflecting a weakening of the current task set, is an important factor influencing participants' task choices. On a more methodological note, the reliability of this preswitch slowing effect—which was seen in all three of our voluntary switching experiments and was reflected in a 12%–14% increase in switch probability after slow RT trials—suggests that within-participant comparisons might provide more robust evidence of links between performance and choice measures than do individual difference correlations. One reason for this could be that within-participant measures of this kind are less sensitive to variation in participants' strategies. For example, although between-task interference effects might create an overall bias toward performing the weaker task—as was observed—participants who find the weaker task particularly difficult might exhibit a countervailing strategic (or simply lazy) bias toward the easier task (cf. Lien & Ruthruff, 2008) that would disrupt the individual differences correlation between task performance and task choice. Thus, future investigations of the relationship between choice and performance measures might usefully consider within-participant manipulations as well as between-participants correlation approaches.

In relation to this issue, a potentially fruitful approach will be the use of methods that allow separation between task choice and task performance, such as the “double-registration” procedure introduced by Arrington and Logan (2005, Experiment 6). In this

procedure, participants indicate their voluntary task choices with an overt keypress prior to the presentation of the imperative stimulus on each trial. This procedure was not ideally suited to the present aims, because its requirements are quite different from those used in typical instructed switching designs (which the present research compared directly with voluntary switching) and because the requirement to make two separate responses could potentially introduce a “restart cost” (cf. Bryck & Mayr, 2008) after each cue selection. However, now that the present study has established the influence of between-task interference in voluntary task switching, the double-registration design provides opportunities for further investigation of these effects. Using this approach, for example, one could investigate whether interference persists to influence performance even after a task has been chosen and whether the bias observed toward performing the weaker task affects task choice directly (in which case the effect should be replicated in the double-registration design) or rather indirectly by increasing interference during response selection (in which case the effect should be reduced or absent). In this way, future research might extend the present findings to provide further insight into the nature of bottom-up influences on voluntary task switching.

### Conclusion

Collectively, the present findings demonstrate the pervasive influence of bottom-up factors—specifically, the influence of between-task interference—on voluntary task switching performance. The replication of switch cost asymmetries between tasks differing in relative strength provides grounds for optimism that findings from prior studies of instructed task switching are relevant for understanding the voluntary control of action more widely. This is a reassuring conclusion given recent demonstrations of discrepancies in results between instructed and voluntary switching paradigms. More broadly, the current analyses of switch costs and task choices converge to suggest that the organizing functions of cognitive control—the workings of the elusive homunculus—are reflected rather indirectly in voluntary switching performance. This conclusion is consistent with theoretical frameworks that view cognitive control as operating via the biasing of competitive interactions among tasks and that view task switching performance as emerging from the dynamics of those interactions. Nonetheless, even if the operation of cognitive control is reflected only indirectly in performance measures, these findings suggest that the measures provide useful insights because they vary systematically with participants' control strategies and thus may bear the identifying fingerprints of the controlling homunculus.

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