

Task-set reconfiguration with predictable and unpredictable task switches

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Participants switched frequently between high/low and odd/even classification of a digit. The interval between a task cue and the next digit varied between blocks. In Experiment 1, the task switched predictably every two, four, or eight trials. In Experiment 2, switching predictably every four trials was compared with random switching. With predictable switching, the cost was limited to the first trial of a run. Random switching produced a more gradual approach to asymptotic performance. After one performance, control processes attenuate the resulting change in task-set bias if a further switch is likely, but this strategic modulation is soon overwhelmed by task-set priming through further performances. Preparation reduced switch costs but not interference from the irrelevant attribute: Control of interference appears to be reactive, not proactive. Switch costs did not increase with run length, suggesting that retrieval of the task set last associated with the stimulus did not contribute to switch costs.

A “task set” is an organization of mental resources that will accomplish a particular cognitive task, given appropriate input. To investigate how we reconfigure task set, several “task-switching” experimental paradigms have been developed. In such an experiment, a participant, pre-trained on two or more tasks, is presented on each trial with a stimulus and required to perform one of the tasks. The task changes frequently from one trial to the next. Performance on trials immediately following a task change is examined for extra processing difficulty associated with the change of tasks. The first response following a task change (the *switch trial*) is typically slower than later (*nonswitch*, or *task-repeat*) trials. This *switch cost* in RT has been attributed to time consumed by control processes that reconfigure task set and/or to carry-over of states of task-set readiness from previous trials.

With the exception of Jersild’s (1927) task-alternation paradigm, a task-switching experiment necessarily consists of *runs* of trials on Task A interspersed among runs of trials on Task B (and perhaps Tasks C, D, etc.). In the experiments reported here, we examined the way performance changes over the first few trials of a run. We will use “P” to indicate the position of a trial within a run of length r , so that the first trial of a run following a change of task (the switch trial) is P1, the next trial (the first non-switch trial) is P2, and so on, up to P_r . One aim of our ex-

periments was to compare in detail the effect of position in a run, P, between predictable and unpredictable task switching. We also examined the effects of providing time for task-set preparation and of interference from the irrelevant attribute. We also studied the effect of run length r as a manipulation of the recency of the previous performance of the task required on the switch trial.

Predictable Versus Unpredictable Switching

Task-switching paradigms fall into two broad classes. In one, task switches are *predictable*. For example, in the *alternating-runs* paradigm (Rogers & Monsell, 1995), participants know they must change tasks every r trials and are usually provided with cues to help them keep track of the sequence of trials. Such cues can be omitted, but participants then tend to lose track after errors and may have other difficulties preparing for the next task (see Koch, in press). Rogers and Monsell used spatial cues. For $r = 2$, stimuli appeared in a clockwise cycle in four locations. Two adjacent locations were associated with Task A, and the other two locations were associated with the Task B, to yield a predictable AABBA, and so on, task sequence. The assignment of locations to tasks was balanced over participants (1) to avoid confounding of task or position in run with the cue’s properties (e.g., with the direction of fixation to the next location) and (2) to equate the nature and amount of stimulus change on task switch and non-switch trials. These requirements can be achieved with other cues and generalized to any run length r , as we shall see below. Another way of doing predictable-switching experiments is to present a short sequence of trials with a prespecified task sequence (e.g., Allport, Styles, & Hsieh, 1994, Experiment 5; Mayr & Keele, 2000), but this imposes the additional load of remembering the sequence.

In other paradigms, task switching is *unpredictable*: The task required on the next trial is unknown until sig-

Experiment 1 was conducted as an undergraduate research project by P.S. and H.W. Experiment 2 was run with the assistance, gratefully acknowledged, of Sam Abdallah. The data in Figure 2 were depicted (analyzed with slightly different exclusion criteria) in a review by Monsell, Yeung, and Azuma (2000). The authors thank Nachshon Meiran, Ulrich Mayr, and an anonymous reviewer for their comments on an earlier draft. P.S. is now at Imperial College London, and H.W. is at the University of Reading. Correspondence should be addressed to S. Monsell, who is now at the School of Psychology, University of Exeter, Exeter EX4 4QG, England (e-mail: s.monsell@ex.ac.uk).

naled to the participant. In the *task-cuing* paradigm, a cue precedes or accompanies every trial (e.g., Meiran, 1996; Shaffer, 1965; Sudevan & Taylor, 1987). For example, Meuter and Allport (1999) signaled the task (the language in which a digit was to be named) by changing the color of the background on which the digit was displayed randomly between red and green. Another way of introducing unpredictable task changes is to interrupt a run of trials on one task, at an unpredictable point, with an instruction display that specifies whether the participant should, on following trials, continue with same task or switch to a different task—an *intermittent-instruction* paradigm (e.g., Gopher, Armony, & Greenspan, 2000). There is always a “restart cost” on the first trial after the instruction, but this is larger on switch trials.

The relative merits of predictable- and unpredictable-switching paradigms may be illustrated in relation to the theoretically critical issue of preparation for a task switch. With predictable switching, one can increase the time available for preparation simply by increasing the interval between the response and the next stimulus. Using alternating runs with $r = 2$, Rogers and Monsell (1995) found a substantial reduction in switch cost with an increasing response–stimulus interval (RSI). They attributed this *preparation effect* to active endogenous task-set reconfiguration in anticipation of a task switch. However, the participant can begin to prepare for the next trial as soon as the response to the previous one has been launched, and one cannot distinguish effects of passive dissipation of the control state on the previous trial from those of the time available for active preparation. Meiran (1996) and Meiran, Chorev, and Sapir (2000) used the cuing paradigm to vary the response-to-cue interval and the cue-to-stimulus interval independently. They were able to demonstrate a reduction in switch cost unambiguously attributable to active preparation, but also some passive dissipation of task-set activation.

However, unpredictable task cues also have disadvantages. The cues in the alternating-runs paradigm provide a spatiotemporal framework that helps one keep track of the sequence of trials without necessarily being the focus of attention. Cues in the unpredictable-switching paradigms require more attention. Inspecting and interpreting an informative cue can interfere with processing of the stimulus when cue and stimulus are very close in time. Interpreting an unpredictable cue may even constitute a distinct task in itself, which may be one reason for the “restart” cost seen in the intermittent-instruction paradigm even when the task does not change. An additional feature of the task-cuing paradigm, as usually administered, with one cue per task, is that there is a confound between task change and the amount of stimulus change on a trial. This will be a particularly important confound in any ERP or neuroimaging contrast of switch and nonswitch trials: Stimulus change per se is very likely to cause neural activation unrelated to reconfiguration processes or consequences.

The major phenomena of task switching identified in the last few years have been observed with both predictable-

and unpredictable-switching paradigms. In addition to the preparation effect described above, these include the *residual cost*: the asymptotic minimum, often substantial, to which the switch cost reduces with preparation (De Jong, 2000; Meiran, 1996, 2000; Rogers & Monsell, 1995). Another important phenomenon is the interaction between Stroop-like interference and switching. When both tasks use the same response set, response times (RTs) are longer for an *incongruent* stimulus (one mapped to different responses in the two tasks) than for a *congruent* stimulus. This interference is globally enhanced in a task-switching context (Wylie & Allport, 2000). It is often larger on switch trials than on nonswitch trials (Meiran, 1996; Rogers & Monsell, 1995); the now-irrelevant stimulus–response (S–R) mapping seems less suppressed on the first trial of a run than subsequently. One might expect, then, that when preparation reduces the switch cost, it would also reduce interference. Such an interaction has sometimes been reported (Goschke, 2000; Meiran, 1996), but there are also reports of no reduction in interference with preparation that is effective in reducing switch costs (Meiran et al., 2000; Rogers & Monsell, 1995, Experiment 3). Experiment 2 provided further data on this issue.

In spite of the fact that these and other major phenomena of task switching have been observed with both predictable and unpredictable task switching, there may be theoretically and methodologically important differences in the pattern of performance immediately following a task switch in the two kinds of paradigm. In an alternating-runs experiment with $r = 4$, Rogers and Monsell (1995, Experiment 6) found that the costs of a task switch were restricted to the switch trial: There was no further improvement in RT from P2 to P4. Keele and Rafal (2000), using a cuing paradigm but with predictable runs of eight trials, also observed no improvement in RT beyond P2. But Salthouse, Fristoe, McGuthry, and Hambrick (1998), using a cuing paradigm with task switches apparently unexpected by the participant (though long runs of constant length were used), found a slower approach to asymptotic performance: P2 responses were slower and less accurate than P3 responses. A similar trend can be seen in task-cuing data reported by Mayr (2001), especially in older participants. Salthouse et al. suggested that Rogers and Monsell (1995) had insufficient power to detect what they claim is the true pattern: a gradual approach to asymptotic performance. However, Meiran et al. (2000), using a task-cuing paradigm with 33% task switches, observed a small but reliable linear improvement in RT for $2 \geq P \geq 10$ rather than the improvement to asymptote over three or four trials suggested by Salthouse et al., and error rates showed no obvious trend. Finally, Altmann and Gray (2002), using an intermittent-instruction paradigm with zero RSI, found that both RT and error rate following the switch trial *increased* slowly but reliably through the run of trials following the switch trial. (They proposed an account of task switching in terms of the initial strengthening and then progressive decay of a self-

instruction memory trace—at least under conditions in which the RSI is too short for self-reinstruction.)

We hypothesized, for reasons we elaborate below, that the pattern of performance after a task switch might depend on whether task switches were predictable or random. In Experiment 2, we therefore developed a way to compare the effect of position in run between the alternating-runs paradigm (with predictable task switches) and the cuing paradigm (with unpredictable task switches), keeping all other things as equal as possible. We also compared across paradigms the effects of preparation and Stroop-like interference from the irrelevant attribute. As a prelude to this, in Experiment 1, we established more securely the pattern of switch costs with predictable switching demonstrated by Rogers and Monsell (1995), and we examined the effects of run length. We now develop some theoretical motives for these comparisons.

Strategic Modulation of Control Input

If a task switch occurs predictably every r trials, and $r > 1$ (i.e., alternating runs), the participant knows that, having reconfigured task set on a switch trial, he/she will not have to reconfigure it again immediately. But if switches are random, the next trial may require reinstatement of the task set just abandoned. Hence, we might expect a greater degree of commitment to the new task set after the first trial of a run—and, hence, a more effective “recovery” from the task change—with predictable runs of trials.

Some theorists see the voluntary control of task-set readiness as adjusting a continuously varying level of activation or inhibition. An example is Norman and Shallice’s (1986) framework, ancestor of a number of current theories. The readiness of a procedural *schema*, in their terms, varies over continua of long-term strength and short-term activation and is a function of (1) *endogenous* control input, (2) the prior availability or readiness of task sets consequent on their recency and frequency of *use* (we will term this *autogenous*¹ priming), and (3) the presence of stimulus attributes or context associated with the task sets (*exogenous* driving, or triggering). Given the requirement to change tasks, a supervisory attention system applies control input to increase the activation of the appropriate task set and/or diminish that of competitors. This endogenous modulation of relative task readiness should be conservative: just enough to get the appropriate task performed rather than its competitors (on most occasions). This is partly because endogenous control requires effort and partly because excessive endogenous input is maladaptive; it results in cognitive inflexibility, compromising the ability to change rapidly to another task if an unexpected threat or opportunity arises (Goschke, 2000). The graded application of just enough endogenous input to get the appropriate task reliably performed is a feature of recent models of task switching (Gilbert & Shallice, 2002; Yeung & Monsell, in press).

Other theorists see the reinstatement of a task set as a discrete process (e.g., De Jong, Berendsen, & Cools,

1999; Mayr & Kliegl, 2000; Rubinstein, Meyer, & Evans, 2001). In support, it has been found that the distribution of RTs on prepared switch trials is well fit by a mixture of the distributions on prepared nonswitch and unprepared switch trials (De Jong, 2000; De Jong et al., 1999; Nieuwenhuis & Monsell, 2002). Mayr and Kliegl (2000) suggest that discreteness makes sense if intention activation is interpreted as the success/failure of retrieval of the task set from memory. Under a discrete-state model of preparation, it is the probability of a successful preparation attempt that mediates deliberate modulation of task readiness. De Jong et al. (1999) suppose, for example, that effort and motivation are critical determinants of whether the participant will “fail to engage” a successful intention activation. However, Nieuwenhuis and Monsell (2002) found that incentive manipulations had only modest effects, and, even for maximally motivated participants, the estimated probability of preparation fell well short of unity.

Whether endogenous control input is conceptualized as having continuous or discrete effects on task readiness, it seems likely to be actively modulated, following a switch trial, in the light of the probability of a further immediate task switch. This should generate different patterns of performance after a task switch when task switches are unpredictable and when they occur only after a predictable run of trials. Our first experiment was run in part to replicate and extend Rogers and Monsell’s (1995) disputed demonstration that, with alternating runs, one trial is enough for complete recovery from a task switch and to examine position-in-run effects through a longer run. We then proceeded in Experiment 2 to a direct comparison of position-in-run effects in the alternating-runs and task-cuing paradigms, all other things being held equal. In both experiments, we also varied preparation interval, in order to separate components of the switch cost that are and are not eliminable by voluntary preparation.

Run Length and Recency

In Experiment 1, we also varied the length of the alternating runs between 2 and 8 (between blocks). This manipulates the recency with which the task required on the switch trial was last performed. Recency is of interest because of the proposal that transient priming of task set carries over from the previous trial or trials. Allport et al. (1994) attributed the residual switch cost entirely to “task-set inertia” (TSI)—persisting activation of the competing task set and/or inhibition of the current task set. More recent authors have seen TSI as just one source of switch costs (e.g., Monsell, Yeung, & Azuma, 2000; Ruthruff, Remington, & Johnston, 2001; Sohn & Anderson, 2001). Although Allport and colleagues initially saw TSI as lasting several minutes, in their recent work (Allport & Wylie, 2000; Waszak, Hommel, & Allport, in press; Wylie & Allport, 2000), they attribute long-term effects of task priming on switch costs to associative *retrieval* of task goals and responses previously associated with individual stimuli. This is additional to any transient TSI.

How transient might TSI be? Using the cuing paradigm, Meiran et al. (2000) found a modest negatively accelerated decline in switch cost as they increased the response–cue interval up to 3 sec, which they attributed to dissipation of task-set activation. In Sohn and Anderson's (2001) model, much of the reduction in switch cost observed as RSI was increased to 5 sec was attributed to exponential decay of activation of the S–R rules (in ACT-R's declarative memory). Goschke (2000) attributed the larger switch cost immediately following an incongruent stimulus to transient persistence of extra inhibition needed to overcome crosstalk. Others have detected effects that, though transient, span intervening trials. Ruthruff et al. (2001) found that RT increased linearly with the log of the lag in trials since the previous performance of a task, an effect additive with the effect of task expectancy. Mayr and Keele (2000; also Mayr, 2002) attributed longer RTs on the final trial of an ABA task sequence than those on the final trial of a CBA task sequence to inhibition needed to disengage from Task A on the first trial; the inhibition must persist through at least one intervening trial to be detectable.

If decay of TSI happens over several trials, it should be harder to switch to Task X, the more trials have elapsed since the previous performance of Task X (i.e., the longer the run length). This tendency would be enhanced by any cumulation, during the intervening Task Y trials, of activation of Task-Set Y or of inhibition of Task-Set X. We should also see continuing improvement of RT beyond P1. The absence of such trends would imply either that TSI decays so fast or is so labile that one trial is sufficient to erase TSI from previous trials or that decay of TSI is too slow to produce a detectable difference between lags of 2 and 8 trials.

The run-length manipulation is also of interest in relation to the proposal of associative binding between specific stimuli, task goals, and responses (Allport & Wylie, 2000; Waszak et al., in press; Wylie & Allport, 2000). In Experiment 1, there were only eight stimuli (digits) that could occur in either task. With $r = 2$, the most recent encounters with a given digit were roughly evenly divided, by chance, between the two tasks. But with $r = 8$, all or most of the eight digits occurred during each run; thus, it is highly probable that, on a switch trial, the most recent previous encounter with a digit was in the context of the competing task. As the run length increases, we might therefore expect more task-level associative interference of the type proposed by Allport and colleagues. If no increase in switch cost is observed, then either associative binding is too persistent for its effects to be dominated by the most recent encounter (which would imply that it does not contribute to switch costs in experiments with small stimulus sets) or it persists for no longer than the shortest run.

EXPERIMENT 1

On each trial, the participants saw a digit chosen from the set {1–4, 6–9}. The tasks were to classify each digit

as low/high or as even/odd. The task was externally cued and changed predictably every r trials, with r constant for a block. The variables of interest are position in run, run length (2, 4, and 8), and RSI (100, 600, and 1,100 msec). RSI was varied between blocks to examine the interaction between preparation and the other variables.

Method

Participants. Twelve participants (6 men and 6 women), between the ages of 20 and 22 years, with normal or corrected-to-normal vision and normal color vision, were paid the going rate for two sessions each.

Procedure. The experiment was run using SuperLab on a Macintosh IIfx with a screen refresh rate of 66.6 Hz and displays synchronized to the refresh cycle. During each block of trials, a background, consisting of eight equally spaced radii of a circle 50 mm in diameter, was displayed continuously in the center of the screen so as to define eight loci arranged in a circle (Figure 1). On each trial, a colored disk 20 mm in diameter (the cue) was presented in one locus immediately after the response to the previous trial. A digit from the set {1–4, 6–9} was then displayed in 24-pt Geneva font in the center of the disk. As soon as the participant responded by pressing a key, the colored disk in the next locus clockwise was presented. The task was indicated by the color of the disk: green for odd/even, and red for high/low. The color switched predictably every 2, 4, or 8 trials, constant for a block. In addition, one, two, or four radii of the background were thickened to indicate the location of task switches. Thus, task switches were completely predictable, task being cued by both the color of the disk and the location on the screen, the latter also indicating position in a run.

To classify as odd/even, the participants used the left middle or index finger to press the "Z" key or the "X" key on a standard computer keyboard. To classify as low/high, they used their right index or middle finger to press the "M" key or the ";" key. If the correct key was pressed, the cue circle and digit disappeared, and the next cue circle appeared in the next position clockwise. The delay between cue onset and the next digit was constant within a block at 100, 600, or 1,100 msec. If the wrong key was pressed, an error message was displayed for 2 sec before the onset of the next cue circle.

At the beginning of the first session, the participants were given 32 trials per task in separate blocks, so that they could learn the S–R mappings, and then nine short blocks, each containing four runs per task, so that they could practice the switching manipulation, one block for each combination of RSI and run length. The participants were encouraged to use the RSI to prepare for the upcoming task, and they were encouraged to respond as fast as possible while

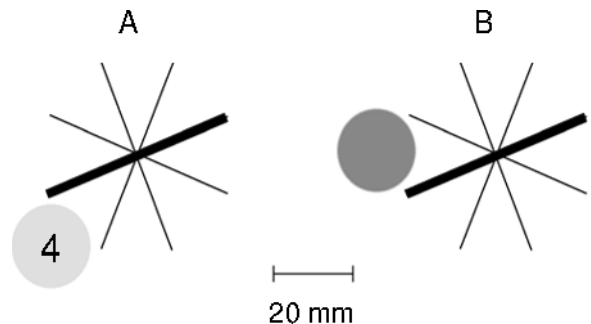


Figure 1. Examples of displays, for run lengths of 4 in Experiment 1. (A) Digit stimulus displayed on colored disk cue for last position in run. (B) Disk cue displayed for the immediately following trial, with both the thickened radius and the change in the color of the disk signaling a change of task.

avoiding errors. After practice, there were two experimental sequences, each containing nine longer blocks, with a 5-min break between sequences. On the second day, there were two more such sequences following a brief familiarization sequence. Each sequence contained one block for each combination of RSI and run length. A display at the beginning of each block specified the combination of interval and run length to be tested. A card indicating the response mappings was visible throughout the experiment.

Design. Each experimental block comprised a warm-up run on the odd/even task, followed by eight runs of each task. There were thus more trials in blocks with longer runs, yielding a total of 756 experimental trials per sequence. Within each sequence of nine blocks, three blocks at one preparation interval were run before three at the next, repeating the order of run lengths. Order of preparation intervals and of run lengths were counterbalanced over participants, and, as far as possible, over sequences within participants. The order of each day's second sequence reversed the order of the first. The starting position on the display (north, south, east, or west) was constant within a sequence but was balanced over sequences within participant and participants within sequence, in order to control for systematic effects of display location or saccade direction. Digits were sampled randomly, but with each digit used equally often for each combination of task, r , and RSI.

Results and Discussion

The effects of position in run and run length are shown in Figure 2. There was a substantial drop in RT between the first trial and the second trial of a run of about the same size for different run lengths. There was no further reduction in RT on later trials ($P > 2$): Recovery from a task switch appears complete after one trial.

We excluded from analysis warm-up trials, trials following errors, and trials with correct RT > 2,000 msec (0.03% of correct responses). We conducted analyses of variance (ANOVAs) on mean correct RTs and error percentages for the two positions (P1 vs. P2) common to all run lengths, with the additional factors of task, practice (Days 1 and 2), run length ($r = 2, 4, 8$), and RSI (100, 600, 1,100 msec). To assess trends in performance beyond the second trial of a run, we also conducted separate ANOVAs for $r = 4$ and $r = 8$, with the factors RSI and position in run. These analyses included only trials following three (for $r = 4$) or seven (for $r = 8$) correct responses, in order to ensure that errors did not cause a mismatch between nominal and actual position in a run. Cell mean and median correct RTs were analyzed; since the patterns were very similar, we report analyses only on means.

Position in run. The drop in mean RT from the first trial to the second trial of a run (the RT switch cost) was a reliable 137 msec [$F(1,11) = 65.6$, $MS_e = 61,538$, $p < .001$]. The corresponding decrease in errors was not reliable [$F(1,11) = 1.76$, $MS_e = 104.5$]. However, of the errors on switch trials, 9.5% were task errors (responses with the wrong hand), but, on the second trial, there were no task errors at all [$t(11) = 2.36$, $p < .05$].

As Figure 2 indicates, there was a slight increase in RT over trials following P2. The linear trend was reliable both for $r = 4$ [$F(1,11) = 7.38$, $MS_e = 3,046$, $p = .02$] and

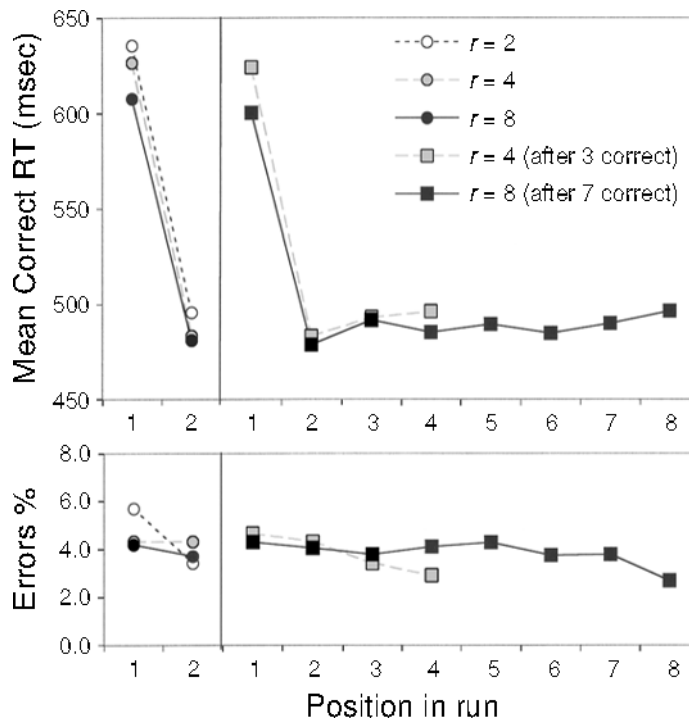


Figure 2. Mean correct RT and error rate as a function of run length and position in run in Experiment 1. For comparison across run lengths, data in the left panels exclude only trials following an error. For examination of the effect of position in run, data in the right panels include only trials following three correct responses, for $r = 4$, or seven correct responses, for $r = 8$.

for $r = 8$ [$F(1,11) = 5.66, MS_e = 3,167, p = .04$]. However, these increases in RT were accompanied by slight decreases in error rate, with linear trends approaching reliability for $r = 4$ [$F(1,11) = 3.64, MS_e = 10.14, p = .08$], but not for $r = 8$ [$F(1,11) = 2.37, MS_e = 10.67$]. Slopes are given in Table 1. We mentioned above Altmann and Gray's (2002) claim that, with an RSI too short to refresh the memory trace of the last task-set "instruction," it progressively weakens over the course of a run, leading to a steady increase in both RTs and errors. As Table 1 shows, this is not quite what we observed in our short RSI conditions: The RT slopes were positive, as predicted by Altmann and Gray, but the error rate slopes were negative; neither were reliably different from zero. Nor was this pattern notably different from what happened with longer RSIs.

The dramatic reduction in RT from the first trial to the second trial of a run following a change of task, with no further reduction thereafter, confirms and extends the observation of Rogers and Monsell (1995). With predictable alternating runs, one trial was enough for full recovery from a task switch. Inasmuch as there was any change in performance subsequent to P2, it was a small but reliable upward trend in RT accompanied by a small but unreliable downward drift in error rate. This suggests a gradual drift over a run of trials toward a more cautious speed-accuracy tradeoff.

Preparation. The reduction in RT switch cost (P1 - P2) with increasing RSI (Figure 3) was highly reliable [$F(2,22) = 10.98, MS_e = 3,334, p < .001$], with switch costs of 163, 125, and 123 msec for RSI = 100, 600, and 1,100 msec, respectively. The equivalent interaction for error rates was not reliable ($F < 1$). This reduction in switch cost to a high asymptote with preparation is similar to that observed by Rogers and Monsell (1995, Experiment 3) and other studies, though the residual cost here is a larger fraction (75%) of the unprepared switch cost than often seen. An analysis restricted to nonswitch RTs ($P \geq 2$) indicated no effect of RSI on mean RT or

error rate for nonswitch trials ($p > .1$) in all cases except for $r = 2$, where the error rate was (inexplicably) higher for the middle interval than for the other two [$F(2,22) = 10.1, MS_e = 2.34, p < .001$].

Run length. Either a suitably transient priming of task set or retrieval of the task set most recently associated with the current stimulus would predict greater difficulty following a longer run, especially on the switch trial. If anything, the opposite trend was seen: The (P1 - P2) costs of switching for RT (errors) were 140 msec (2.3%), 144 msec (0.0%), and 127 msec (0.5%) for $r = 2, 4$, and 8, respectively. But this interaction between run length and switching was not reliable for RT [$F(2,22) = 1.96, MS_e = 2,898$] or for error rate [$F(2,22) = 2.35, MS_e = 42.94$]. Overall mean RT also reduced slightly with increasing run length [$F(2,22) = 4.96, MS_e = 6,508, p < .05$], and error rate was unaffected ($F < 1$).

The clean outcome was slightly marred by a statistically reliable three-way interaction between switching (P1, P2), run length, and RSI for both RT [$F(4,44) = 3.23, MS_e = 1,721, p = .02$] and error rate [$F(4,44) = 3.08, MS_e = 20.02, p = .03$]. The relevant values, available in Table 1, do not suggest a coherent pattern. The RT interaction arises from an anomalously high RT on the switch trials for the medium RSI at Run Length 4, but the error interaction arises largely from the disappearance of the error cost at the medium RSI for runs of two trials.

Other effects. Average RT for the high/low tasks was 45 msec shorter than that for the odd/even task, but this difference between tasks was confounded with response hand; there was no difference in error rate. The switch cost for the high/low task (116 msec) was lower than that for the odd/even task (157 msec) [$F(1,11) = 4.61, MS_e = 19,615, p = .06$], and a difference in the same direction was seen for errors (-1.0% vs. 2.6%) [$F(1,11) = 7.87, MS_e = 84.76, p < .05$]. Practice (Day 2 vs. Day 1) reduced RT [$F(1,11) = 53.3, MS_e = 17,605, p < .001$] but had no reliable effect on error rate ($F < 1$). Practice reduced the

Table 1
Effects of Run Length (r), Position in Run (P), and Response-Stimulus Interval (RSI) on Mean Correct RT (in Milliseconds) and Percent Error (PE)

RSI	Switch Cost (P1 - P2)		Position in Run												Slope (for $P \geq 2$)							
			P1		P2		P3		P4		P5		P6		P7		P8		M		SE	
	RT	PE	RT	PE	RT	PE	RT	PE	RT	PE	RT	PE	RT	PE	RT	PE	RT	PE	RT	PE		
$r = 2$																						
100	174	2.6	672	5.6	498	3.0																
600	111	-1.8	605	4.8	494	4.9																
1,100	134	4.4	629	6.6	495	2.2																
$r = 4$																						
100	157	-0.6	642	3.0	491	3.3	508	3.2	504	2.4									6.8	-0.43	3.5	0.55
600	150	0.22	630	5.4	479	5.1	487	3.0	494	3.2									7.4	-0.96	3.2	0.72
1,100	123	0.52	600	5.5	479	4.6	484	4.0	490	3.0									5.3	-0.76	3.5	0.68
$r = 8$																						
100	157	1.0	626	3.0	481	2.8	499	2.8	489	5.8	505	4.4	494	3.0	496	3.3	499	2.1	1.8	-0.14	0.9	0.13
600	113	0.8	584	4.1	466	3.5	480	3.9	478	3.5	484	3.0	479	4.4	480	4.5	493	3.7	2.9	0.09	1.1	0.19
1,100	112	-0.5	590	5.7	488	5.8	497	4.6	488	3.0	479	5.4	482	3.8	494	3.5	498	2.2	0.61	-0.43	1.1	0.13

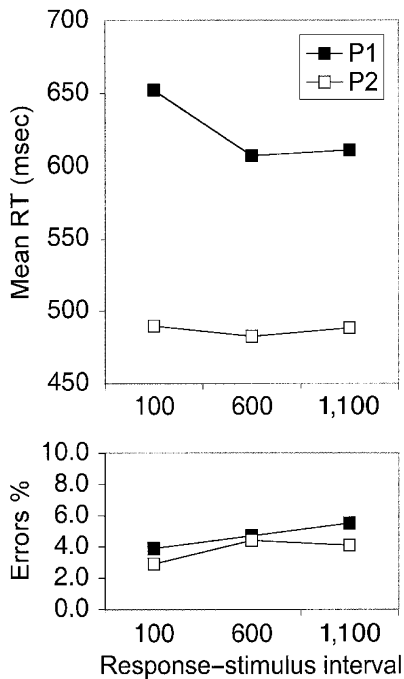


Figure 3. Mean correct RT and error rate as a function of preparation interval (the response-stimulus interval) for the first (P1) and second (P2) trials of a run in Experiment 1.

RT switch cost [$F(1,11) = 15.70$, $MS_e = 6,994$, $p < .01$], but not the error cost ($F < 1$). There was still a robust switch cost of 114 msec on the second day, but the switch cost was more reduced by practice (28%) than was the nonswitch RT (8%). Task and practice interacted with no other effects of interest.

RT distributions. Figure 4 presents cumulative RT distribution functions obtained by averaging 19 equally spaced percentiles estimated for each combination of participant, day, task, run position ($P = 1$ and 2 only), and RSI, pooling over run length and response. As has been reported by De Jong (2000) and Nieuwenhuis and Monsell (2002), the opportunity for preparation prior to a task switch increases the variance of the RT distribution by bringing its minimum closer to that of the nonswitch distribution, while having little effect on the maximum. (It can also be seen that, on nonswitch trials, the RT variance was somewhat smaller at the shortest RSI.) According to De Jong's discrete-state preparation model, preparation enables a proportion of switch trial (P1) responses to be made as fast as nonswitch (P2) responses, whereas others remain as slow as on unprepared switch trials. The RT distributions do not necessarily require such a discrete-state process, but they do imply that preparation is much more effective on some trials than on others. A general question for the De Jong "failure to engage" model is why the residual cost is asymptotic: Why does an extra half-second for preparation not help on trials for which an intention-activation attempt was ineffective in the

first half-second? Considerable refractoriness in the intention-activation process must be posited.

Conclusions. Like Rogers and Monsell (1995), we found that one trial is enough for complete recovery after a task switch. The data depicted in Figure 2, based on about 2,500 trials per participant, do not support Salthouse et al.'s (1998) contention that Rogers and Monsell failed to detect a more gradual recovery from a task switch through low power. We suggest, instead, that the more gradual recovery observed by Salthouse et al. and by Mayr (2001) may be attributable to the difference in expectation of a further switch between predictable and unpredictable-switching paradigms. This suggestion was tested in Experiment 2.

Opportunity for preparation, as manipulated via RSI, had its impact largely on the RT on the first trial of a run and replicated previous findings of approach to an asymptotic residual cost after about half a second of preparation. We cannot rule out some contribution to the RSI effect of passive dissipation of activation of the competing task set between trials (Meiran et al., 2000). But if this is a major factor, we might also expect to see an opposite effect of RSI on nonswitch trials, reflecting dissipation of activation of the repeated task set; there was no sign of this.

There was no hint of any increase in switch costs with longer run lengths. This and the abrupt recovery from a task switch seem incompatible with TSI decaying over just a few trials. They do not rule out either a TSI that lasts for one trial only (which could contribute to switch costs) or a TSI that is stable over many intervening trials (which would not). The absence of a run-length effect also rejects as a contributor to switch cost competition due to associative "binding" to the stimulus of the last task set (or response) associated with it, unless this lasts for just one trial. If it lasted two or three, that should have been reflected in continued improvement beyond the second trial of a run. An associative binding that is long-lived, and, hence, not dominated by the most recent encounter with a stimulus, is not ruled out (see Waszak et al., in press). But, by the same token, it should not be a significant source of switch costs in experiments with small stimulus sets (i.e., most task-switching experiments), since all stimuli should rapidly become asymptotically associated with both tasks.

EXPERIMENT 2

Our aim was to compare the effects of position in run, of preparation, and of stimulus congruence between the alternating-runs and task-cuing paradigms, keeping all other aspects of the situation identical. To achieve this, each trial began with a cue: a colored background shape (pink or blue, diamond or square; see Figure 5). For half of the participants, the color of the background served as the cue; for the other half, the shape of the background served as the cue. (For one participant, a blue background might signal the odd/even task and a pink back-

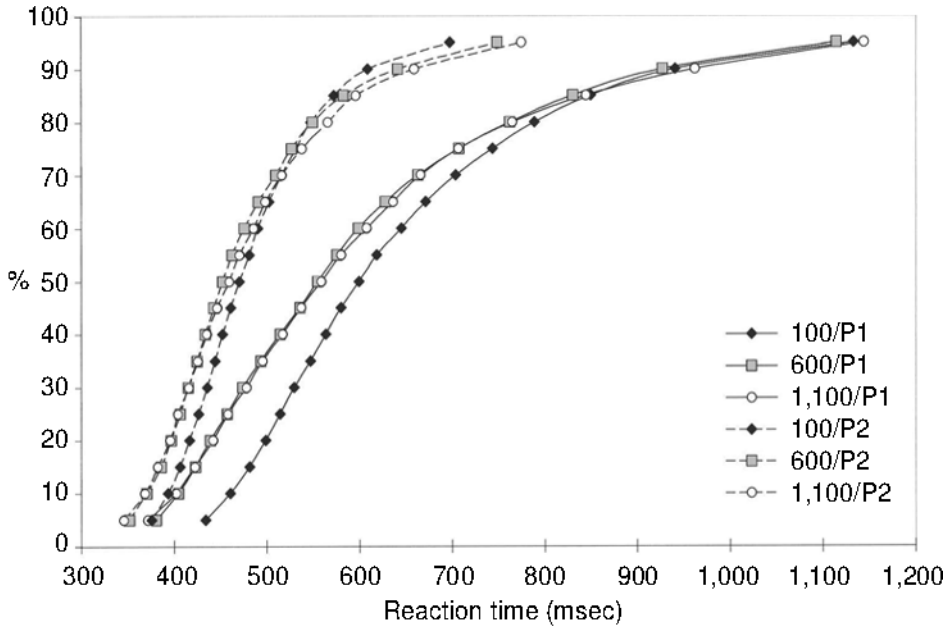


Figure 4. Average cumulative RT distributions plotted as the average over participants of 19 percentiles of the correct RTs, for the first two positions in a run and for each preparation interval, pooling over run length and response and averaging over days in Experiment 1.

ground the high/low task, whereas for another participant, the odd/even task might be signaled by a square background and the high/low task by a diamond-shaped background.) Following a preparation interval of 50, 650, or 1,250 msec (constant for a block), a digit was displayed in the center of the shape. As soon as the participant responded, either the shape or the color of the background always changed. Thus, the amount of stimulus change was equated on switch and nonswitch trials.

In the *random* switching condition, the task changed randomly from one trial to the next. In the *predictable* condition, the task changed every four trials. To help the participant keep track of position in a run in the latter condition, a small gray spot was displayed above the background shape and a line projecting from behind the shape rotated clockwise from northeast (P1) to southeast (P2) to southwest (P3) to northwest (P4). The impression was of a clock hand behind the cue “ticking” discretely

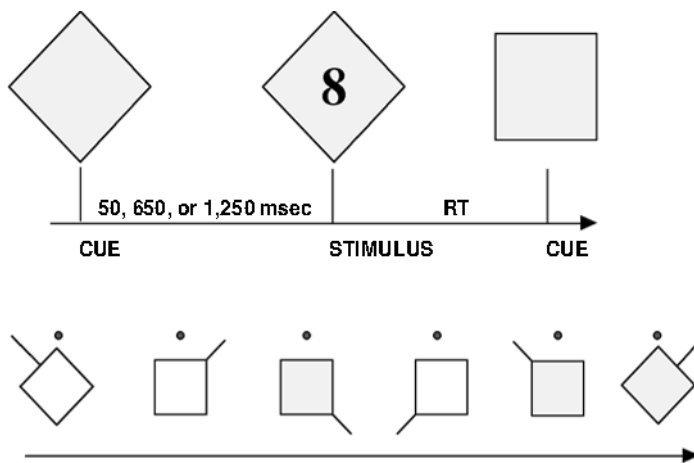


Figure 5. Top: Illustration of a trial and the following cue display in Experiment 2. Bottom: A sample sequence of background displays for the predictable switching condition, for a participant for whom shape signals task in Experiment 2. The cue color (pink, blue) changed on nonswitch trials.

around four directions with each cue onset, in parafoveal vision; when the hand passed the “12 o’clock” spot, the task changed. Although the rotating “clock hand” constituted a small difference in what the participant saw in the random and predictable conditions, it was seen on all trials of the latter and was phenomenally “in the background.”

We had the participants respond with the same pair of responses for both tasks, in order to assess interference between the tasks by comparing responses to incongruent stimuli and congruent stimuli. We varied preparation interval, as in Experiment 1, in order to examine interactions between preparation, position in run, and interference.

Method

Participants. Twelve paid participants (4 men and 8 women), between the ages of 17 and 38 years ($M = 23.3$ years), served for two sessions.

Design. After practice, each participant completed two sets of blocks per day. Each set consisted of 120 trials for each of the six block types (the combinations of RSI and random vs. predictable switching). These 120 trials were split into two blocks of 60, each preceded by 5–8 warm-up trials. A set consisted of one block for each block type, followed by another six blocks, reversing the order of block types. The RSI changed every two blocks, and the block type alternated between random and predictable switching. The order of block types was balanced by a Latin square over participants within sets and, as much as possible, within participants over sets.

The 120 trials for each predictable-switching block type in a set comprised 15 trials per combination of task and P (position in run), with 6–8 congruent stimuli and 6–8 incongruent stimuli per combination. Over two sets, each digit (1–4, 6–9) occurred three or four times per combination. The 120 trials for each random-switching block type in a set comprised 32, 16, 8, 4, 2, and 1 runs for run lengths $r = 1, 2, 3, 4, 5,$ and $6,$ respectively (very close to binomial expectation). Over two sets, the assignment of items to positions in runs was controlled for P1–P4 so that, for each P, each task \times digit combination occurred approximately equally often. In both random- and predictable-switching blocks, each digit was used equally often, and immediate repetitions of a digit were prohibited. Subject to these constraints, order of runs and assignment of items to trials was randomized anew for each participant and set. For the predictable-switching blocks, over four sets of blocks, each participant received 15 trials in each combination of RSI \times task \times run position \times congruence (similar to the number of trials at P2 in the random-switching blocks; there were, however, twice as many task switches in the latter).

Procedure. Digits were displayed in a black Times 48-pt font with a height of 1 cm centered on the cue (an outline square or diamond of side 2.8 cm, filled with either light pink or light blue) displayed in the lower half of the screen. In the predictable-switching blocks, the clock hand (a thin black line whose end was 4.2 cm from the shape’s center) projected from behind the shape in the direction 45°, 135°, 225°, or 315° for P = 1, 2, 3, or 4, respectively. The “12 o’clock” gray dot (diameter 0.7 cm) was displayed just above the cue region.

A trial began with the display of the next cue (accompanied, in the predictable condition, by apparent rotation of the clock hand). After a preparation interval of 50, 650, or 1,250 msec, a digit appeared in the center of the cue. A response triggered the immediate onset of the next cue, unless the wrong key was pressed, in which case the participant heard a beep and had a 2-sec delay to recover before onset of the next cue. Either the shape or the color of the cue changed on every trial; task was signaled by color for half the par-

ticipants and by shape for the other half. Each possible mapping of color value or shape value to task was used for 3 participants.

At the beginning of the first session, the participants were trained on both tasks, without switching, in two cycles of 32 trials on the odd/even task followed by 32 on the high/low task, with the digit displayed on the appropriate background for that task and with the irrelevant cue attribute changing every trial. The participants were then given instructions on the switching conditions and were given half a set of switching blocks (1 block of 60+ trials per block type) for practice. Each block was preceded by a display indicating whether task switching would be predictable or random and whether the participants had a long interval, a medium interval, or no interval to prepare. The participants were strongly encouraged to use any available time to prepare for the next stimulus.

Results and Discussion

In the first analysis, data were pooled over congruent and incongruent trials, including only trials following three correct responses. Mean correct RT and error rates (shown in Figure 6 as a function of random/predictable switching, RSI, and position in run [P1–P4]) were submitted to an ANOVA including these factors together with task and response. (The relatively few P5 and P6 trials in the random condition were not analyzed.) Response hand (left/right) had no effect ($F < 1$) and interacted with nothing else. The high/low task was, as usual, a little easier than the odd/even task [RT, 631 vs. 671 msec, $F(1,11) = 9.12$, $MS_e = 50,834$, $p < .05$; errors, 1.8% vs. 2.6%, $F(1,11) = 3.27$, $MS_e = 59.94$, n.s.], but this interacted with no other factors. (A further analysis included the between-subjects variable of whether the task-signaling dimension of the cue was its shape or its color, but this detected nothing of interest.)

Position in run. As in Experiment 1, RT in the predictable-switching condition dropped sharply from the first trial to the second trial of a run and changed little thereafter. In contrast, the random-switching blocks showed a more gradual approach to asymptotic performance after a task switch. The interaction between effects of predictability and run position was highly reliable for RT [$F(3,33) = 9.77$, $MS_e = 7,144$, $p < .001$] and reached significance for error rate [$F(3,33) = 3.48$, $MS_e = 14.13$, $p = .03$]. Separate RSI \times position in run ANOVAs were conducted for the predictable- and random-switching conditions, with and without the P1 data. With predictable switching, the substantial effect of run position on RT [$F(3,33) = 33.6$, $MS_e = 5,029$, $p < .001$] was eliminated when P1 was excluded ($F < 1$). The effect of run position on error rate over all four positions was not reliable [$F(3,33) = 1.95$, $MS_e = 3.039$]. With random switching, including P1, the effect of run position was highly reliable for RT [$F(3,33) = 34.65$, $MS_e = 5,029$, $p < .001$] and for errors [$F(3,33) = 10.01$, $MS_e = 4.399$, $p < .001$]. But there was also a reliable decrease from P2 to P4 in both RT [$F(2,22) = 8.27$, $MS_e = 2,976$, $p = .002$] and error rate [$F(2,22) = 3.79$, $MS_e = 4.350$, $p = .04$].

With predictable alternating runs of four trials, we thus confirmed our previous observations: Performance completely recovered after just one trial following a task

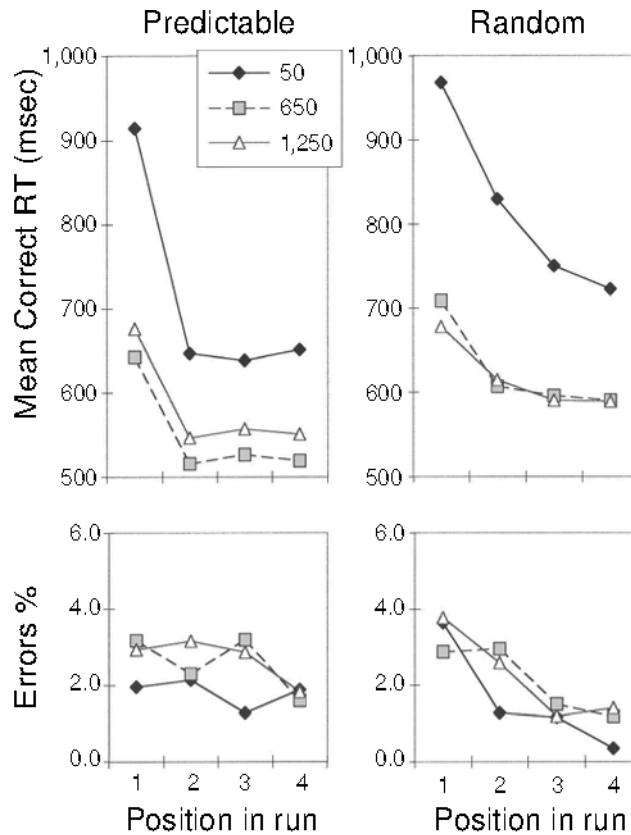


Figure 6. Mean correct RT and error rate, as a function of the predictability of task switches, position in run, and preparation interval (response-stimulus interval) in Experiment 2.

change. With random switching (other things being largely equal), we observed a significantly different pattern: a more gradual approach to asymptotic performance. This suggests expectation-based modulation of endogenous control input. Following the first trial of a run on a task, the relative readiness for that task was lower when there was an even chance of having to switch back to the other task. However, just one or two further performances of the task seemed to force the participant into a state of asymptotic readiness for the task, even though the probability of a switch back to the other task had not changed; indeed, subjective expectation of another switch probably increased (see below). We note, however, that the asymptotic RT achieved at later positions in a run in the predictable switching condition did remain above the asymptotic level seen with predictable switching. This might reflect a greater overall level of caution in the random-switching condition; error rate at P4 was lower with random switching than with predictable switching.

Preparation (RSI). In the overall analysis, significant main effects of RSI on RT [$F(2,22) = 39.41$, $MS_e = 95,164$, $p < .001$] and error rate [$F(2,22) = 8.18$, $MS_e = 7.842$, $p < .01$] indicate that performance at every posi-

tion in the run was notably slower at the 50-msec RSI than at the longer RSIs, though also slightly more accurate. This effect of RSI even on nonswitch trials was not observed in Experiment 1, with an RSI of 100 msec or by Rogers and Monsell (1995) with their shortest RSI of 150 msec. We speculate that a 50-msec RSI was so short that attending to or processing the cue change significantly delayed identification of the digit, regardless of the meaning of the cue. Of more interest is the reliable effect of preparation on the RT cost of a switch, as represented by the interaction between RSI and run position [$F(2,22) = 17.6$, $MS_e = 7,951$, $p < .001$ ($F < 1$ for error rate)]. In the two-way ANOVA on the predictable-switching data alone, the interaction between RSI and position in run [$F(6,66) = 19.09$, $MS_e = 1,132$, $p < .001$] reflects the fact that the RT switch cost ($P1 - P2$) was roughly halved (from 263 to 123 msec) as the time available for preparation (RSI) was increased to 650 msec, then showed no further reduction (124 msec) as RSI was increased to 1,250 msec. For random switching, the main source of the interaction between RSI and position in run [$F(6,66) = 9.07$, $MS_e = 1,897$, $p < .001$] was a more gradual approach to asymptotic performance after a task switch with a short preparation interval than with a longer one;

there is also some sign that the reduction in switch costs with preparation in this condition was not as complete at RSI = 650 msec: There was a further reduction as RSI increased to 1,250 msec, though this was not quite reliable [$t(11) = 1.76$]. These differences between the effects of preparation with random and predictable switching resulted in a reliable three-way interaction between RSI, predictability and position in run [$F(6,66) = 3.67, MS_e = 4,162, p < .01$].

Hence, the overall picture is that task readiness following a task switch was influenced by three interacting factors: (1) the number of times the task had been performed after the switch, (2) the opportunity for preparation prior to the stimulus onset, and (3) the probability of an immediate switch away from the task. If we focus on the second trial of a run, it appears that the prospect of a possible further switch attenuated the improvement in readiness for a task produced both by having actually performed that task (autogenous biasing) and by having time to prepare for the task. It seems that, with unpredictable switching, the participants initially “held back” from an extreme bias toward a task that they had performed just once following a task change. However, an

accumulation of autogenous biasing through two or three performances was sufficient to overwhelm this “endogenous restraint.”

Interference. If weaker endogenous control is applied when task switching is random, we might expect to see more interference from the irrelevant task in the random-switching condition until the task has been performed two or three times. To partition the data into congruent and incongruent trials with adequate cell sizes, we looked at the first three run positions only, including only trials following two correct responses and averaging over response. Only interactions with congruence are discussed here. Figure 7 shows the relevant data

An ANOVA with the factors congruence, task, condition (random, predictable), RSI, and position in run yielded reliable main effects of congruence for both RT [$F(1,11) = 25.36, MS_e = 31,529, p < .001$] and error rate [$F(1,11) = 24.01, MS_e = 115.1, p < .001$]. Responses to incongruent stimuli were 61 msec slower than were those to congruent stimuli and were about six times as error-prone. In the RT analysis, interactions with congruence approached significance only for task [$F(1,11) = 4.17, MS_e = 4,802, p = .07$], with the easier task (high/low)

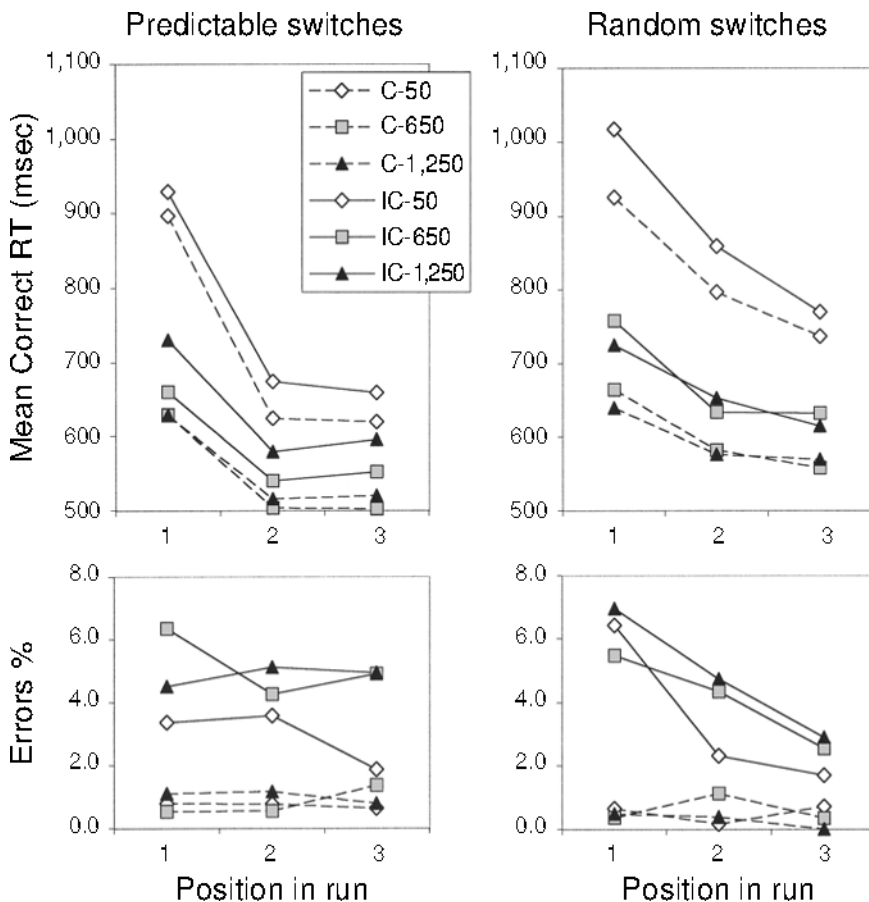


Figure 7. Mean correct RT and error rate, as a function of the predictability of task switches, position in run, and stimulus congruence in Experiment 2.

showing somewhat less interference, and for position in run [$F(2,22) = 3.08$, $MS_e = 2,576$, $p = .07$]. In the error analysis, there was a clear interaction between the predictability of a task switch, position in run, and congruence [$F(2,22) = 4.92$, $MS_e = 7.843$, $p = .017$].

Separate ANOVAs with the factors congruence, RSI, and position in run were conducted for the two conditions. As Table 2 shows, with random switching, interference was large on the switch trial and diminished with further performances of the task. This interaction was reliable for RT [$F(2,22) = 3.54$, $MS_e = 2,076$, $p = .05$] and for errors [$F(2,22) = 11.09$, $MS_e = 6.014$, $p < .001$]. In contrast, with predictable switching, there was no reliable interaction ($F_s < 1$), though the error rate diminished slightly with task repetition. This pattern is compatible with the hypothesis that a weaker endogenous bias is applied early in a run in the random condition, allowing greater crosstalk from the other task, but this is eventually made up for by the autogenous effect of repeatedly performing the task.

One of the more surprising observations in the task-switching literature has been that, although preparation prior to the stimulus reduces switch cost, it may not reduce cross-task interference (e.g., Meiran, 2000; Rogers & Monsell, 1995). This observation is amply confirmed here (see Table 2). Preparation that was effective in halving the switch cost did not decrease interference by any measure, with either random or predictable switching. Indeed, in the latter case, there was a reliable increase in the RT effect of congruence with RSI [$F(2,22) = 3.65$, $MS_e = 2,698$, $p = .04$].

The data in Table 2 suggest that crosstalk is sensitive to variations in endogenous control bias applied *after* performance of the task *only* if this bias is subasymptotic and that interference is not diminished at all by the otherwise effective application of endogenous control input *before* the stimulus onset. Having endogenously adjusted one's task bias to an asymptotic level, or been forced by task repetition to that level, one is still unavoidably vulnerable to interference from an active but irrelevant task set. An analogy might be preparing one's arm to resist a slap to the hand: The hand's position will change much less when the slap arrives, but there is an unavoidable yield nonetheless. Endogenous control is insufficient to inhibit exogenous retrieval of task set and/or response tendencies associated with the stimulus. Autogenous priming of task set reduces such interference only when readiness is not already asymptotic.

Incongruence of the previous stimulus. We repeated Goschke's (2000) exploration of the consequence of having just processed an incongruent stimulus, with an analysis of congruence \times congruence on previous trial \times condition \times RSI \times position in run (P1, P2), pooling over task and response and excluding trials following an error. On a switch trial, the RT was 20 msec longer and the error rate was 0.4% higher following an incongruent trial than following a congruent trial. On the first non-switch trial, the response was 2 msec faster and 1.0% more accurate following an incongruent trial. The interaction was reliable for RT [$F(1,11) = 4.98$, $MS_e = 3,117$, $p < .05$] and marginally reliable for error rate [$F(1,11) = 4.67$, $MS_e = 15.18$, $p = .054$]. This is consistent with the idea that an incongruent stimulus causes extra inhibition to be exerted on the competing task set, leaving it in a transiently less activated state on the next trial. (Note that stimuli were not repeated on successive trials.)

Run length. An analysis of the random condition data showed that, as the length of the previous run increased from 1 to 3, RT (for trials following three correct trials) decreased from 804 to 783 to 764 msec [$F(2,22) = 10.01$, $MS_e = 5,615$, $p < .001$] and errors from 4.1% to 3.5% to 2.1% [$F(2,22) = 3.84$, $MS_e = 48.13$, $p < .05$]. As in Experiment 1, this is opposite to the direction we would expect from dissipation over several trials of task-set priming or of stimulus to task-set associations. With random switching, however, run length is inextricably confounded with expectation of a switch because of the "gambler's fallacy" (Kahneman & Tversky, 1972). Subjective expectancy of a task switch is likely to increase with position in run and, hence, with previous run length, even when the probability of a switch remains roughly constant. This renders the effect of previous run length here ambiguous.

RT distributions. Figure 8 plots the cumulative density functions (averaged deciles) for each position in a run for each combination of preparation interval and block type. For RSI = 650 msec and RSI = 1,250 msec, which provide time for preparation, the variance is clearly larger on switch trials than nonswitch trials, and there is only a small difference between the lowest quantiles, which is compatible with the participant's using preparation, on a proportion of switch trials, to achieve a readiness as good (or nearly as good) as on nonswitch trials (cf. De Jong, 2000). Moreover, in the random condition, the higher mean RT at P2 than at P3 is clearly attributable only to the slow end of the distribution. For RSI = 50 msec, we see

Table 2
Interference Effects in Experiment 2: Difference in Correct Mean RT (in Milliseconds) and Percent Error (PE) Between Congruent and Incongruent Trials for the First Three Positions of a Run and for the Three Response-Stimulus Intervals (RSIs)

	Position in Run						RSI (msec)					
	P1		P2		P3		50		650		1,250	
	RT	PE	RT	PE	RT	PE	RT	PE	RT	PE	RT	PE
Random switching	91	5.8	63	3.2	51	2.0	62	3.0	73	3.5	70	4.6
Predictable switching	55	3.9	50	3.5	55	3.0	41	2.2	39	4.4	80	3.9

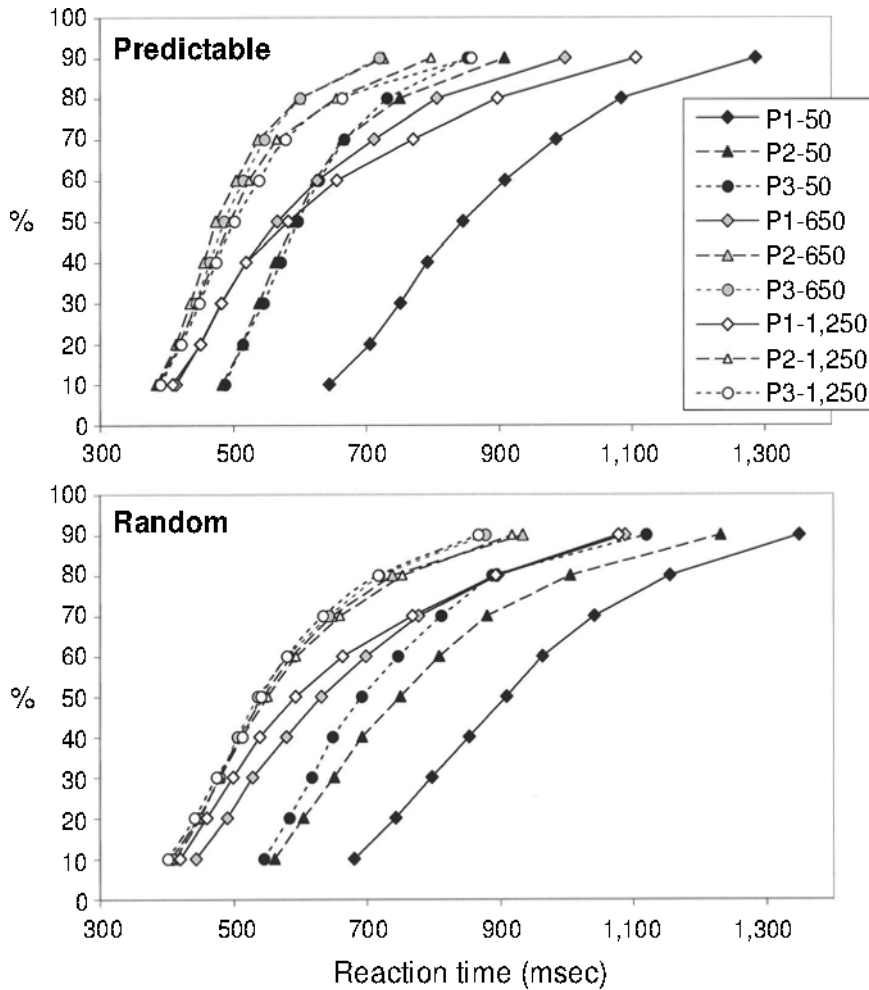


Figure 8. Average cumulative RT distributions, estimated as the average over participants of the deciles of the RTs for each combination of first, second, and third trials of a run, predictability of a switch, and the preparation interval in Experiment 2.

that, for the random condition, the improvement in mean RT from P1 to P2 is due to a shift in the whole distribution rather than a reduction in variance, and there is more of a reduction at the high end of the distribution from P2 to P3. It appears that, after an unpredictable switch and no time to prepare, the readiness to perform the task just performed is increased by mere usage; any of the factors of time to prepare, further performances, or a strong expectation of no further switch will then push the readiness nearer asymptotic levels.

Comparison with Tornay and Milan (2001). Tornay and Milan compared the preparation effect between random switching and predictable runs of two trials, using Rogers and Monsell’s (1995) letter/digit tasks. In Tornay and Milan’s Experiment 1, an increase in RSI from 200 to 1,200 msec reduced switch costs by more in the random condition (from ~150 to ~10 msec) than in the predictable condition (from ~100 to ~60 msec). They

argue for (to quote their title) “more complete task-set reconfiguration in random than in predictable task switch,” contrary to our claim. Our data do not replicate their observation. Their estimate of switch cost in the random condition pooled nonswitch trials regardless of position in run. To make a comparable estimate, we formed a frequency-weighted average of RTs for P2, P3, and P4. As RSI increased from 50 to 1,250 msec, the switch cost dropped from 269 to 124 msec for predictable switching and from 176 to 74 msec for random switching. In our data, the reduction in switch cost with preparation is thus absolutely less for random switching than for predictable switching (145 vs. 102 msec). As a proportion of the unprepared switch cost, the reduction in cost is comparable (58% vs. 54%). However, these comparisons are somewhat moot in the light of the slower approach to performance in the random condition, which suggests that the participants were in a less

fully reconfigured state *after* one trial of a task with random switching than with predictable switching.

GENERAL DISCUSSION

Experiment 1 and the predictable condition of Experiment 2 demonstrated, as did Rogers and Monsell (1995), that, when tasks alternate after runs of predictable length, one trial can be sufficient to “recover” from the switch. There was no improvement in performance with further repetitions of the task. In contrast, the random-switching condition of Experiment 2, otherwise matched to the predictable condition, showed that, when the task was unpredictable, two or three trials were needed to recover from a task switch. This result resolves an apparent conflict concerning the pattern of position-in-run effects identified by Salthouse et al. (1998) and has both methodological and theoretical implications.

A methodological implication is that the switch cost typically computed in experiments using unpredictable task cues (mean RT for P1 trials – mean RT for $P \geq 2$) somewhat underestimates the “true” cost of a task switch (i.e., the difference between level of performance on the switch trial and the asymptotic level to which performance eventually recovers). For cases in which a cuing paradigm is essential, we recommend analyzing the data by position in run over at least the first three or four trials of a run. This also means taking care to ensure that all conditions are equally represented at each run position. In other cases, the predictable-switching paradigm has certain advantages: It encourages fuller preparation, it is efficient in that runs of only two trials are sufficient to estimate the switch cost, there are equal numbers of trials per position in a run, and there is no need to worry about controlling run-length distributions. However, even with alternating runs, we recommend using runs of at least three trials to check that asymptotic recovery has indeed occurred, especially when testing participants for whom reconfiguration may be more difficult than it is for student participants.

The theoretical interpretation we propose is that the effect of one performance of a task on task readiness is subject to strategic modulation by expectation of the probability of a further task switch. After one trial of the changed task, if another switch is probable, participants to some degree voluntarily attenuate or restrain the increment in readiness that would otherwise result from one performance of the task; they adopt a less extreme task-set bias. We do not know whether this endogenous modulation of autogenous priming is exercised during or after generation of the response. Nor do we know whether it should be seen as directly modulating task-set activation/inhibition along a continuum (e.g., Gilbert & Shallice, 2002; Norman & Shallice, 1986; Yeung & Monsell, in press) or somehow changing the probability of success of a discrete preparation attempt (De Jong, 2000; Mayr & Kliegl, 2000). We can conclude, however, that this exercise of control is fragile: Two or three repetitions of

the task seemed sufficient to overwhelm any endogenous restraint and reach an asymptotic level of readiness, even though the objective probability of a task switch remained unchanged, and the subjective expectation of a switch presumably increased. The strength of Stroop-like interference between the two tasks was modulated in a way similar to the switch cost. Interference was greater when the participants had to allow for a further task switch than when they did not, until they had repeated the task two or three times (Table 2). These interactions between expectation, performance, and stimulus valence—or between endogenous, autogenous, and exogenous influences on task-set readiness—will need to be captured in the formal or computational models of task-set reconfiguration now being developed by a number of researchers (e.g., Gilbert & Shallice, 2002; Kieras, Meyer, Ballas, & Lauber, 2000; Logan & Gordon, 2001; Meiran, 2000; Yeung & Monsell, in press).

Could the differential effects of position in run on random and predictable switching have another explanation? Perhaps participants do not try to improve after the switch trial with predictable switching. Perhaps when the cue must be more carefully attended to (i.e., in the random condition), there is more priming of cue processing or strengthening of cue–task associations through a run (cf. Mayr & Kliegl, 2000). These suggestions have in common the idea that performance benefits more from task repetition in the random condition than in the predictable condition. Were this the case, performance should end up better on the third task repetition in the random condition than in the predictable condition. Instead, both the overall level of performance and the crosstalk from the irrelevant attribute started out worse early in a run in the random condition and only converged toward performance in the predictable condition after two or three trials.

The effect of preparation (as manipulated through RSI) on interference was also interesting. As often observed, providing an RSI of just over half a second for preparation reduced the switch cost (by about half), and additional time resulted in no further reduction: the standard “preparation” and “residual cost” effects. But this apparently effective task-set preparation produced no reduction in interference. Effective endogenous preparation before the stimulus onset apparently provides no defense against task-set interference. We cannot claim that modulation of endogenous control has no effect on interference, since interference was greater at the beginning of a run in the random condition when the participants were, we propose, exercising “endogenous restraint.” The resolution may be that endogenous control of interference is purely reactive: It can only be applied when the irrelevant stimulus attribute has generated a conflict signal. When conflict is detected, extra control input is evoked to suppress it (cf. Gehring, Goss, Coles, Meyer, & Donchin, 1993; MacDonald, Cohen, Stenger, & Carter, 2000), as suggested by the greater switch cost we and Goschke (2000) detected following an incongruent trial. Executive processes can modulate this reactive ap-

plication of control input. They apparently cannot (or do not) apply such a strong control bias in advance that crosstalk is prevented.

The use of predictable alternating runs in Experiment 1 allowed us to manipulate run length unconfounded with subjective expectancy of a task switch (unlike a random-switching experiment). It did not become harder to switch to the other task when the lag since the last performance of that task increased from two to eight trials. This would appear incompatible with the attribution of part of the switch cost to a "task-set inertia" that decays over just a few trials (e.g., Ruthruff et al., 2001). Because only eight stimuli were available, all or most of which will have occurred in the previous eight trials, this finding also seems incompatible with the attribution of part of the switch cost to retrieval of the task set most recently associated with the stimulus. Of course, this finding does not rule out task-set inertia lasting just one trial (see Yeung & Monsell, in press) or stimulus-to-task-set bindings that persist for just one trial, though the latter cannot have contributed to switch costs in Experiment 2, since there were no immediate stimulus repetitions. This result is perfectly compatible with there being long-term priming of task sets, carried by stimulus-specific associations, as demonstrated by Waszak et al. (in press). However, in many task-switching experiments, including ours, a small set of stimuli occur repeatedly in both tasks; therefore, long-term associations between the stimuli and each task must be effectively at ceiling and would seem unlikely to play a role in causing the switch cost.

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NOTE

1. The distinction between *endogenous* (voluntary, top-down) and *exogenous* (stimulus-driven, bottom-up) control is common currency in the attention literature (see, e.g., Monsell & Driver, 2000). But we seem to need a third term to summarize influences of habit strength and recency of activation on the intrinsic readiness of a task set (or availability of a schema) as distinct from endogenous and exogenous influences—hence, the coinage *autogenous*.

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