

# Response–cue interval effects in extended-runs task switching: memory, or monitoring?

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**Abstract** This study investigated effects of manipulating the response–cue interval (RCI) in the extended-runs task-switching procedure. In this procedure, a task cue is presented at the start of a run of trials and then withdrawn, such that the task has to be stored in memory to guide performance until the next task cue is presented. The effects of the RCI manipulation were not as predicted by an existing model of memory processes in task switching (Altmann and Gray, *Psychol Rev* 115:602–639, 2008), suggesting that either the model is incorrect or the RCI manipulation did not have the intended effect. The manipulation did produce a theoretically meaningful pattern, in the form of a main effect on response time that was not accompanied by a similar effect on the error rate. This pattern, which replicated across two experiments, is interpreted here in terms of a process that monitors for the next task cue, with a longer RCI acting as a stronger signal that a cue is about to appear. The results have implications for the human factors of dynamic task environments in which critical events occur unpredictably.

## Introduction

A central question in the study of cognitive control is how the system is able to respond flexibly to changing environmental constraints. This question is often studied using task-switching procedures, in which there are different candidate tasks to perform on each imperative stimulus and

the environment periodically presents a cue to indicate which task to perform now (Kiesel et al., 2010; Vandierendonck, Liefoghe, & Verbruggen, 2010).

One experimental variable that has played a role in task-switching research for some time is the response–cue interval (RCI). The RCI is a temporal interval between a trial response and the onset of the subsequent task cue. During the RCI the task environment essentially freezes briefly, with no trial stimulus to process and no information available about the upcoming task. The RCI is followed by the cue–stimulus interval (CSI), which is the interval between onset of the task cue and onset of the subsequent trial stimulus.

Manipulations of the RCI and the CSI were first used to study the processes involved in establishing a task set. The RCI represents a period during which the old task has time to decay and the new task is not yet known. In contrast, the CSI represents a period during which the new task is known and the system can prepare to perform it. By manipulating the two variables separately, it is possible to separate the contributions of decay of the old task and active preparation of the new task to performance of the new task. Early findings supported the view that the greater the decay of the old task during the RCI, the smaller the cost of switching to a new task, suggesting that the old task interfered with the process of establishing the new task (e.g., Meiran, Chorev, & Sapir, 2000; Sohn & Anderson, 2001).

In a later study, Poljac and Bekkering (2009) showed that RCI effects reached beyond the processes involved in establishing a new task set. Previous studies had used the *explicit-cuing* procedure, a design in which a task cue is presented on every trial. Poljac and Bekkering used the *extended-runs* procedure, in which a task cue governs performance of multiple trials. Specifically, after a task cue

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was presented and withdrawn, two trials followed in succession, and the participant applied that task to each trial in turn. After the second trial, the next *run* of two trials began with another task cue. In this procedural context, the RCI was the interval between the response to the second trial of one run and onset of the task cue for the next run.

Poljac and Bekkering (2009) found that their RCI manipulation affected not only the first trial of the run, but also the second trial of the run. This finding indicated that the RCI affected not just the processes involved in establishing the task set. These processes have to complete in order for the first trial of the run to be performed. Thus, by the second trial of the run, the task set is already established, so the RCI manipulation must have affected some other process.

Poljac and Bekkering (2009) interpreted their findings in terms of memory processes. On the second trial of a run, the task cue is no longer perceptually available, so correct task performance requires a memory for the most recently cued task. Poljac and Bekkering proposed that this memory is more easily retrieved with a longer RCI because memory for the previous task is more decayed, and thus generates less interference with memory for the current task.

For theoretical support, Poljac and Bekkering (2009) cited a model of memory processes in task switching developed by Altmann and Gray (2008). That model was designed to account for performance in extended-runs procedures like the one used by Poljac and Bekkering, where each task cue is followed by multiple trials. Two core assumptions in the model are that memory for the previous task proactively interferes with memory for the current task, and that decay helps mitigate this interference. On its face, then, this model is consistent with Poljac and Bekkering's finding.

However, the Altmann and Gray (2008) model makes additional, specific predictions that could not be tested using Poljac and Bekkering's (2009) procedure. The predictions concern *within-run effects*, which are trends in performance across consecutive trials in the run following a task cue. For response time (RT) in particular, the trend generally begins with the second trial of a run because the first trial after a cue is presented and withdrawn shows elevated RT that reflects residual effects of processing the cue. Because Poljac and Bekkering's procedure only had two trials per run, trends beginning with the second trial could not be measured.

The basic within-run effects are that performance gradually worsens across trials in a run, in terms of RT (*within-run slowing*) and often also in terms of the error rate (*within-run error increase*; see Altmann, 2014, for a review). The Altmann and Gray (2008) model accounts for within-run effects in terms of gradual decay of memory for the current task—that is, the task currently governing performance. This decay is functional in that, when the next task is encoded in memory (when the next task cue is presented), memory for what at that point becomes the

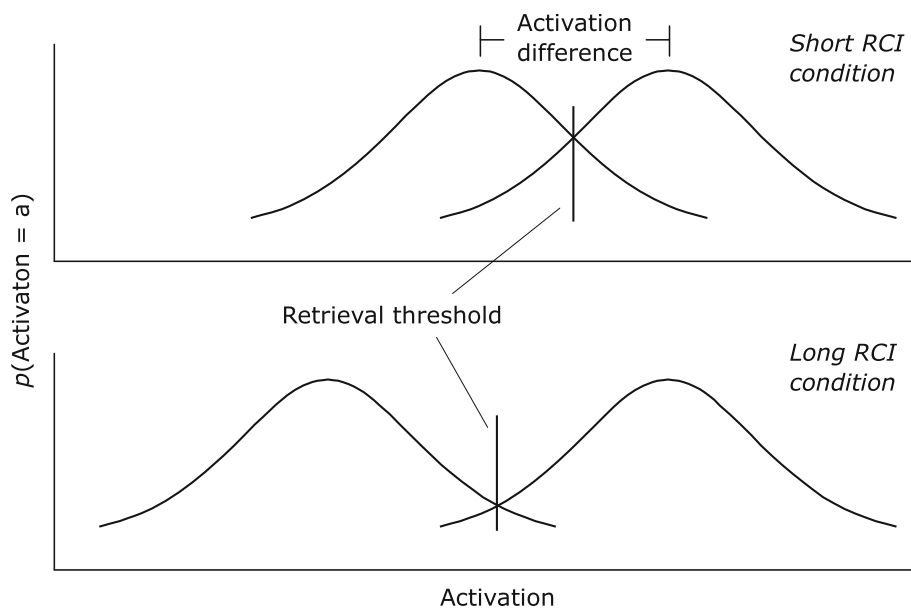
previous task has decayed, so generates less interference with memory for the new current task.

In terms of RCI effects, the specific prediction of interest is that the slopes of within-run effects should be flatter with a longer RCI. The prediction can be understood in terms of signal detection constructs, as illustrated in Fig. 1. Within each panel, the density function for the signal (the right-hand density) represents the activation of the current task in memory, and the density function for noise (the left-hand density) represents the activation of the previous task in memory. The horizontal axis represents activation, increasing to the right. The dispersion of each density represents moment-to-moment fluctuation in activation values. The response criterion represents a retrieval threshold, a high-pass activation filter that screens out memory elements that are below threshold at the moment of a retrieval request, so that only those above threshold are contenders for retrieval. On a given trial, the system tries to retrieve a task memory to guide its performance, and the most active memory (of those above threshold) answers the request.

In this framework, the ability to perform the current task correctly depends on the activation difference between memory for the current task and memory for the previous task, represented in Fig. 1 as the distance between the means of the two densities. If this activation difference is large, the current task will (correctly) dominate performance. If the difference is small, the previous task will often intrude because it happens to be more active than the current task at the moment of a retrieval request. The functional role of decay is to maintain an adequate activation difference. A task is encoded in memory with high initial activation and then decays gradually until the next task is encoded. This decay can be visualized as the right-hand density shifting left along the horizontal axis. When the next task is encoded in memory, its activation is again initially high, and what is now the previous task has decayed, creating a situation in which the current task is on average more active than the previous task.

The slopes of within-run effects are determined by the activation difference and its effect on the location of the retrieval threshold. The greater the activation difference, the further left the retrieval threshold (in Fig. 1, compare the upper and lower panels), reflecting the same basic optimality constraints that apply in signal detection.<sup>1</sup> The

<sup>1</sup> In Fig. 1, the retrieval threshold is shown in the optimal location, midway between the two densities. However, the threshold is stable while the densities shift as they decay, so the threshold is not always exactly in this optimal location. The key point is that the greater the activation difference between the densities, the further left the threshold can be to improve the ratio of correct to incorrect retrievals. For more information on where the threshold is located in the Altmann and Gray (2008) simulation, see their Figure 12.



**Fig. 1** Hypothetical effects of manipulating the response-cue interval (RCI) on memory for the previous task, expressed in terms of the model of Altmann and Gray (2008; see their Figure 2). Within each panel, the right-hand density function represents memory for the current task and the left-hand density function represents memory for the previous task. The dispersion of density functions represents

further left the retrieval threshold, the thinner the tail of the signal density where the threshold intersects the density. The threshold remains stable as the signal density shifts leftward (decays), so as the density shifts, the area above threshold shrinks. The rate of shrinkage is smaller the thinner the tail passing across the retrieval threshold, and this rate of shrinkage determines the slopes of within-run effects. The Appendix describes the underlying mechanisms in more detail.

The RCI manipulation should affect the activation difference between the current and previous task memories. A task memory continues to decay indefinitely, so the previous task should be older, and therefore more decayed, after a long RCI than after a short RCI. In Fig. 1, the hypothetical effect on the activation difference is shown in the contrast between the upper and lower panels. In the lower panel, with a long RCI, the left-hand density is further left. The activation difference is therefore greater, so the retrieval threshold is further to the left, so the slopes of within-run effects should be flatter.

The general prediction of flatter slopes when the previous task is older was supported in two previous studies, though in each case the age of the previous task was determined not by the RCI but by the length of a run of trials. In one case, we manipulated run length by varying the number of trials per run (Altmann & Gray, 2008). In the other case, I manipulated run length by adding a response-stimulus interval between one trial and the next (Altmann,

transient fluctuation of activation levels. The retrieval threshold is a high-pass filter restricting the set of accessible memory elements to those whose activation is above threshold when a retrieval request is made. Activation increases to the right along the horizontal axis, and decay of a task memory is represented by a shift of its density function to the left

2014), lengthening the temporal duration of a run without affecting the number of trials per run. In both cases, the previous task was older when runs were longer, and therefore hypothetically more decayed, and the slopes in that condition were flatter.

Here I sought to test the prediction concerning slopes of within-run effects by manipulating the RCI. The two levels of RCI were 100 and 800 ms, manipulated between participants in Experiment 1 and within participants (with RCI selected randomly for each task cue) in Experiment 2. The run length was five trials (on average; see the “Procedure” section), which is ample to measure within-run effects. In terms of statistical contrasts, what the Altmann and Gray (2008) model predicts is an interaction of the RCI and the serial position of a trial within a run, with a smaller effect of serial position in the long RCI condition.

To preview the results, the RCI  $\times$  position interaction predicted by the Altmann and Gray (2008) model did not materialize in either experiment, suggesting that the model does not account for the present results or, by extension, those of Poljac and Bekkering (2009). In the General Discussion, I assess whether the problem is with the model or with the RCI manipulation. The RCI manipulation did have a main effect on RT on all trials of a run, though no accompanying effect on the error rate. This pattern only partially replicates the results of Poljac and Bekkering (2009), who also found an effect on the error rate, but it replicated internally here across both of the present

experiments. In the General Discussion, I explore the possibility that the main effect on RT reflects a process that monitors for the next impending task cue, with the RCI functioning as a stronger or weaker warning signal (depending on its duration) that a cue is about to be presented.

## Experiment 1

### Participants

Sixty students enrolled in undergraduate psychology classes at Michigan State University participated in exchange for credit toward a course requirement. Thirty were randomly assigned to each of the long and short RCI conditions. An additional ten participants (eight in the short RCI condition, two in the long RCI condition) were excluded from analysis because their session-wise accuracy indicated that they were not following task instructions, as further discussed in the “[Procedure](#)” section, below.

### Materials

The imperative stimulus was one of four rectangles formed by combining vertical and horizontal dimensions of 80 and 160 pixels. Figure 2 shows examples drawn roughly to scale. A rectangle was drawn in gray with a 5-pixel pen at the center of a black and otherwise-blank computer display. The rectangle for a given trial was randomly selected from the three rectangles that were not presented on the previous trial.

The participant performed one of two possible tasks on each stimulus rectangle. One task was to judge the height of the rectangle as “tall” or “short” and the other task was to judge the width of the rectangle as “thin” or “thick”. Participants responded with the “z” and “/” keys of a QWERTY keyboard. The mapping of task judgments to response keys was randomized for each participant and for each task.

The correct task for each run of trials was indicated by one of two task cues, the word “height” or the word “width” (see Fig. 2), printed in white in lowercase 40-point Monaco font in the center of the display. Each task cue was selected randomly from the two possible cues, subject to the constraint that the same cue could not be selected more than four consecutive times.

### Procedure

Participants were tested individually in sessions lasting about 45 min. A session began with an introduction to the stimuli and tasks, followed by a practice block. The practice block was the same as a block in the test phase of the session except that the experimenter was present to answer questions and labels were shown at the bottom of the display indicating

the response mapping for each task. At the end of the practice block, participants were told their score and were encouraged to work quickly and accurately for the rest of the session, and were told the number of blocks in the session.

During the test phase, the participant performed 24 blocks of trials, with each block consisting of 20 runs of trials, and each run consisting of an average of five trials. Thus, each participant performed an average of  $24 \times 20 \times 5 = 2400$  trials.

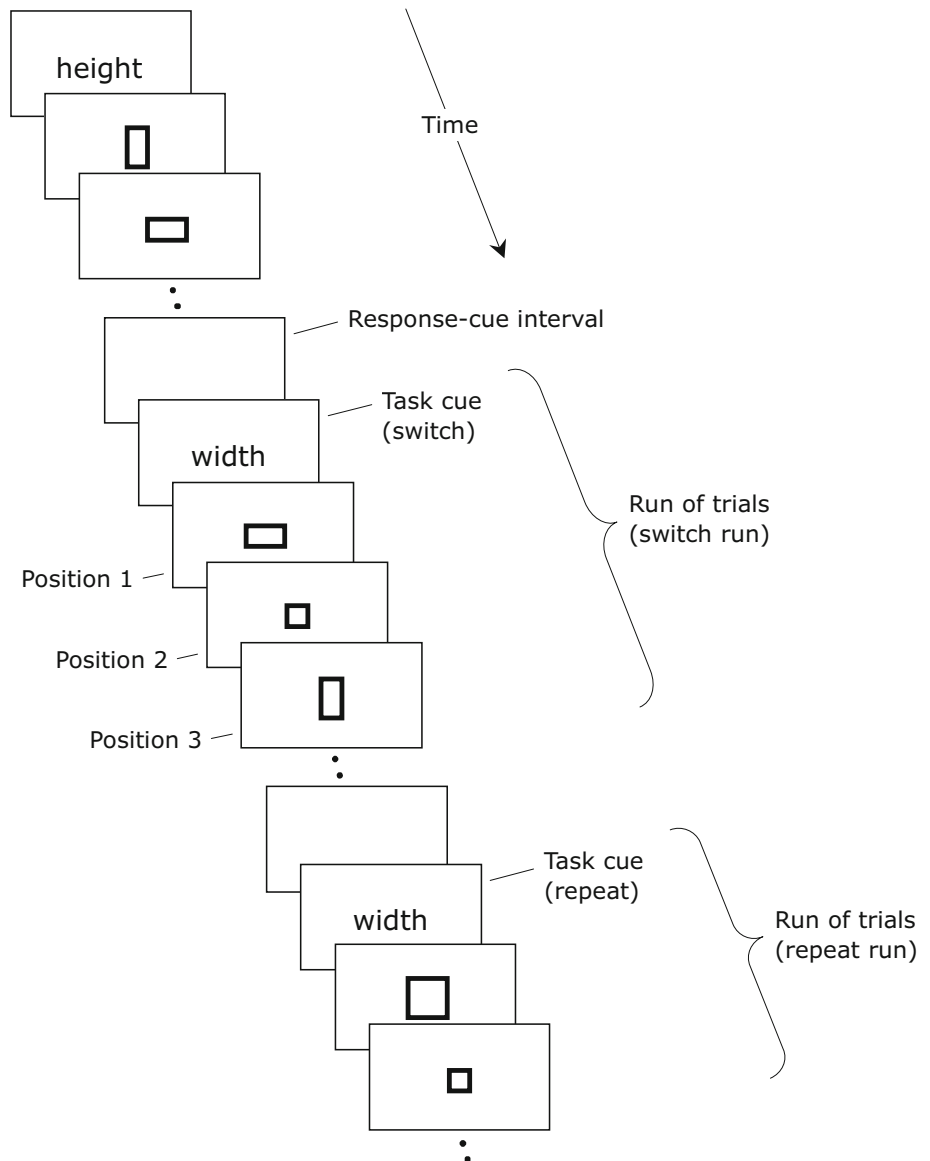
The number of trials per run was randomized so as to make the end of any given run, and thus the occurrence of the next task cue, unpredictable. Each run length was a sample taken from a geometric distribution with mean 2 and added to a constant 3, producing a mean of 5. The geometric distribution has a flat hazard function, meaning that the probability of a given trial being the last trial of the run was constant, starting after the third trial of the run. Thus, there was no objective information in the statistical structure of the task environment on which participants could base accurate predictions about when the next task cue would be presented, except that there would be at least three trials per run. Empirically, across the 60 sessions the longest run ranged from 21 to 28 trials.

Each run of trials was preceded by a task cue indicating the task to be performed on that run. This temporal structure is illustrated in Fig. 2, in terms of three consecutive runs of trials. Following the response to the last trial of a run (or, for the first run of a block, following the response that initiated the block), there was an RCI of 100 or 800 ms (depending on the group), during which the display was blank and the computer accepted no input. The task cue for the next run then onset and was visible for 100 ms. The task cue then offset, followed by a blank screen again for 100 ms, followed by onset of the imperative stimulus for the first trial of the run governed by that cue. On trials other than the last trial of a run, the response triggered immediate onset of the next trial, with no timed response–stimulus interval or feedback.

After a block, participants were given feedback and a chance to rest before starting the next block. The feedback included their percentage accuracy for that block, a message, and the number of the next block. If the accuracy was 100%, the message encouraged the participant to go faster. If the accuracy was below 90%, the display flashed and the message asked the participant to be more accurate. The participant pressed the space key to begin the next block. Participants who failed to achieve a threshold of 90% accuracy for the entire session were excluded from analysis on grounds that they were not following the direction given during the feedback to be more accurate.

The RT data submitted to analysis were means of participant medians on correct trials following correct trials. The error data were means of participant error percentages. The practice block was excluded from analysis, as was the

**Fig. 2** Timeline of events in the extended-runs task-switching procedure used in Experiments 1 and 2. The response–cue interval was 100 or 800 ms, manipulated between participants in Experiment 1 and within participants (randomized between runs) in Experiment 2



first run of each test block because the switching factor was ambiguous.

### Experimental design

The experimental design had three independent variables, one manipulated between participants and two manipulated within. The *response–cue interval* (RCI), with levels Short (100 ms) and Long (800 ms), was the interval preceding the task cue, and was manipulated between participants. *Switching*, with levels Switch and Repeat, represents whether the task for a run of trials differed from the previous run (Switch) or was the same (Repeat; see Fig. 2). Finally, *position*, with levels 1 through 7, was the serial position of a trial following a task cue.<sup>2</sup> Position 1 RT generally shows the effects of processing the task cue, even if the task cue is not concurrently visible with the imperative stimulus (Altmann,

2014), so to test effects of the RCI manipulation on within-run slowing I omit Position 1 from the trend analysis.

### Results

Table 1 tabulates the results. The upper panel of Fig. 3 plots RT for Position 1. The upper panel of Fig. 4 plots RT for Positions 2–7, with a finer-grain scale on the ordinate. The upper panel of Fig. 5 plots percentage error for all positions.

<sup>2</sup> Because run length was sampled from a geometric distribution, the maximum run length was unbounded (and thus greater than 7), but the number of observations per data point also decreased for each successive position. In Experiment 1, there were 41.3 observations per RT data point for Position 7, which is ample. However, in Experiment 2, with an additional within-participants variable (RCI), this number decreased to 21.0, and was 14.2 for Position 8, which seemed low. Accordingly, I limited analysis to Positions 1–7 for both experiments.

**Table 1** Response time (ms) and error rate (%) for Experiment 1, with standard deviation (in parentheses)

RCI, Switching	Position						
	1	2	3	4	5	6	7
RT							
Short							
Switch	1025.4	599.8	587.9	589.1	602.5	614.5	621.2
Repeat	825.4	575.5	584.1	595.3	609.0	607.3	611.8
Long							
Switch	916.3	519.5	521.0	536.4	546.1	550.4	546.5
Repeat	731.7	511.0	515.7	529.7	546.9	552.6	552.5
Short							
Switch	(282.5)	(98.5)	(66.4)	(64.9)	(64.5)	(71.0)	(68.2)
Repeat	(211.2)	(67.7)	(64.8)	(61.0)	(68.3)	(67.6)	(76.3)
Long							
Switch	(241.9)	(64.0)	(56.3)	(48.0)	(55.2)	(49.4)	(55.7)
Repeat	(159.0)	(61.8)	(52.9)	(47.0)	(53.7)	(49.5)	(59.4)
PE							
Short							
Switch	3.64	3.87	3.49	3.54	3.37	3.82	4.87
Repeat	2.80	3.09	2.80	3.02	2.90	3.36	2.70
Long							
Switch	3.88	4.02	3.91	3.74	4.02	3.38	4.13
Repeat	1.97	2.67	2.72	3.10	3.33	2.84	3.09
Short							
Switch	(2.75)	(2.10)	(2.13)	(2.43)	(2.08)	(3.05)	(3.27)
Repeat	(2.91)	(2.66)	(2.61)	(2.79)	(2.99)	(2.75)	(3.45)
Long							
Switch	(3.90)	(2.84)	(2.89)	(2.72)	(3.23)	(2.62)	(4.17)
Repeat	(1.85)	(2.29)	(2.06)	(2.20)	(3.29)	(2.60)	(2.98)

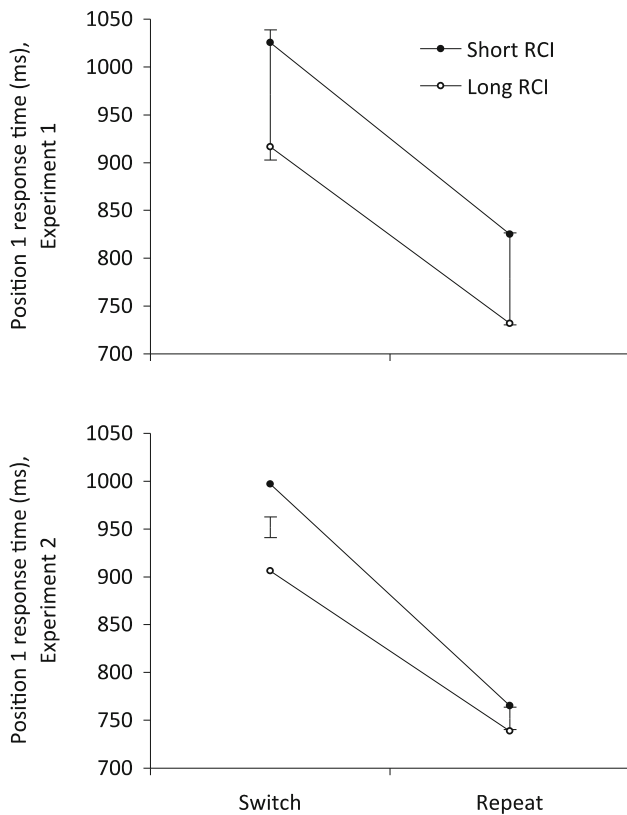
RCI response–cue interval, RT response time, PE percentage error

I first examined RT with a 2 (RCI)  $\times$  2 (switching)  $\times$  7 (position) omnibus analysis of variance (ANOVA). There were main effects of RCI,  $F(1, 58) = 13.64$ ,  $p < .001$ ,  $\eta_p^2 = .190$ ; switching,  $F(1, 58) = 78.80$ ,  $p < .001$ ,  $\eta_p^2 = .576$ ; and position,  $F(6, 348) = 151.64$ ,  $p < .001$ ,  $\eta_p^2 = .723$ . Neither the RCI  $\times$  switching nor the RCI  $\times$  position interactions were significant,  $F_s < 1$ . The switching  $\times$  position interaction was significant,  $F(6, 348) = 88.74$ ,  $p < .001$ ,  $\eta_p^2 = .605$ , reflecting a substantially larger effect of switching on Position 1 than on Positions 2–7. The three-way interaction was not significant,  $F < 1$ .

I then examined RT separately for Position 1 and Positions 2–7, given their substantially different performance profiles. For Position 1, the main effect of RCI (101.4 ms) was marginally significant,  $F(1, 58) = 3.26$ ,  $p = .076$ ,  $\eta_p^2 = .053$ , and the main effect of switching (192.3 ms) was significant,  $F(1, 58) = 116.26$ ,  $p < .001$ ,  $\eta_p^2 = .667$ . The RCI  $\times$  switching interaction was not

significant,  $F < 1$ , replicating one half of an earlier finding that this interaction is sensitive to how RCI is manipulated (Altmann, 2005; see the present Experiment 2 for the other half).

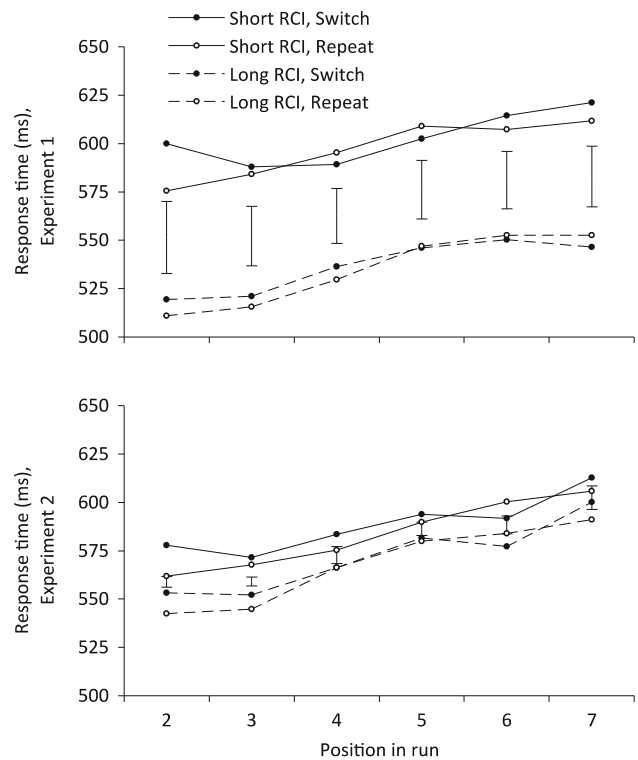
For Positions 2–7, the main effect of RCI (64.2 ms) was significant,  $F(1, 58) = 18.23$ ,  $p < .001$ ,  $\eta_p^2 = .239$ . The main effect of position was significant,  $F(5, 290) = 32.15$ ,  $p < .001$ ,  $\eta_p^2 = .357$ , as was the linear trend in position,  $F(1, 58) = 72.17$ ,  $p < .001$ ,  $\eta_p^2 = .554$ , replicating within-run slowing (Altmann & Gray, 2008). The RCI  $\times$  position interaction was not significant,  $F(5, 290) = 1.27$ ,  $p = .278$ ,  $\eta_p^2 = .021$ , indicating that RCI did not affect the slope of within-run slowing. Indeed, the slope was numerically greater in the long RCI condition (8.1 ms/trial) than in the short RCI condition (6.6 ms/trial), which is the opposite of the predicted difference in slopes. The main effect of switching was not significant,  $F(1, 58) = 2.38$ ,  $p = .129$ ,  $\eta_p^2 = .039$ . The RCI  $\times$  switching interaction was not significant,  $F < 1$ . The switching  $\times$  position



**Fig. 3** Response time for Position 1 for Experiments 1 and 2. Error bars are graphical significance tests (Altmann, 2011) for the effect of response-cue interval (RCI) at each level of switching (Switch, Repeat). The effect is significant ( $p < .05$ ) if the data points for Short RCI and Long RCI lie outside the bar

interaction was significant,  $F(5, 290) = 2.98, p = .012, \eta_p^2 = .049$ , as was the three-way interaction,  $F(5, 290) = 2.26, p = .049, \eta_p^2 = .037$ .

I examined percentage error with a 2 (RCI)  $\times$  2 (switching)  $\times$  7 (position) ANOVA. The main effect of switching (0.95%) was significant,  $F(1, 58) = 29.62, p < .001, \eta_p^2 = .338$ , but the switching  $\times$  position interaction was not,  $F(6, 348) = 1.76, p = .107, \eta_p^2 = .029$ , meaning that, unlike RT switch cost, error switch cost fell on all trials of the run. This dissociation between RT and error switch cost, which can be identified using the extended-runs procedure but not the more common explicit-cuing procedure (Altmann, 2014), suggests that RT and error switch costs reflect different mechanisms (Altmann & Gray, 2008, but see Poljac, de Haan, & van Galen, 2006). There was no main effect of RCI,  $F < 1$ . There was also no main effect of position,  $F(6, 348) = 1.17, p = .323, \eta_p^2 = .020$ , which means that within-run error increase did not replicate. The RCI  $\times$  switching and RCI  $\times$  position interactions were not significant,  $F_s < 1$ , nor was the three-way interaction,  $F(6, 348) = 1.12, p = .351, \eta_p^2 = .019$ .

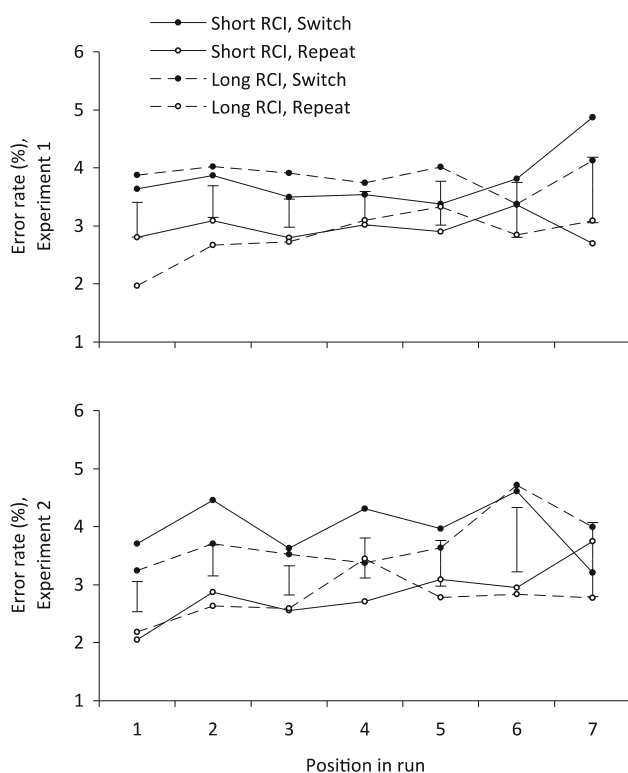


**Fig. 4** Response time for Positions 2–7 for Experiment 1 (upper panel) and Experiment 2 (lower panel). Error bars are graphical significance tests (Altmann, 2011) for the effect of response-cue interval (RCI) at each position. The effect is significant ( $p < .05$ ) if the mean of Short RCI, Switch and Short RCI, Repeat and the mean of Long RCI, Switch and Long RCI, Repeat lie outside the bar

### Discussion

The results were not as predicted. The Altmann and Gray (2008) model predicts that if the previous task is older and therefore more decayed, as it should have been with a longer RCI, the slopes of within-run effects should have been flatter. In terms of statistical contrasts, the prediction was for an interaction of RCI and position. This interaction was not present for either RT or the error rate. Indeed, within-run slowing was numerically greater with a long RCI than with a short RCI (8.1 ms/trial vs. 6.6 ms/trial), which is opposite of the prediction. Within-run error increase was absent here, but has also been less reliable than within-run slowing in previous studies (Altmann, 2014).

The main effect of RCI on RT reported by Poljac and Bekkering (2009) did replicate (Fig. 4, upper panel), with slower RTs in the short RCI condition than in the long RCI condition. Poljac and Bekkering also found that RCI affected the error rate, but there was no such effect here (Fig. 5, upper panel). Before further interpreting the results, I first report an internal replication.



**Fig. 5** Error rate for Experiment 1 (upper panel) and Experiment 2 (lower panel). Error bars are graphical significance tests (Altmann, 2011) for the effect of switching at each level of position. The effect is significant ( $p < .05$ ) if the mean of Short and Long response-cue intervals (RCIs) for Switch and the mean of Short and Long RCIs for Repeat lie outside the bar

## Experiment 2

Experiment 2 used the same design as for Experiment 1 except that RCI was manipulated within rather than between participants, with the RCI randomly selected for each task cue. Within-participants designs can introduce carryover effects, but these can be an important source of theoretical leverage (e.g., Altmann, 2004; Horoufchin, Philipp, & Koch, 2011).

Fifty new participants were recruited from the same pool. Twelve additional participants were excluded because their session-wise accuracy was below threshold, as in Experiment 1. The method was identical to that for Experiment 1 except that the RCI before every task cue was selected randomly from the two possible choices. In the analysis, the level of RCI for the run of trials following a task cue is the RCI immediately preceding that cue.

## Results

Table 2 tabulates the results. The lower panel of Fig. 3 plots RT for Position 1, the lower panel of Fig. 4 plots RT for Positions 2–7, and the lower panel of Fig. 5 plots percentage error for all positions.

I first examined RT with a 2 (RCI)  $\times$  2 (switching)  $\times$  7 (position) ANOVA. There were main effects of RCI,  $F(1, 49) = 109.58$ ,  $p < .001$ ,  $\eta_p^2 = .691$ ; switching,  $F(1, 49) = 140.91$ ,  $p < .001$ ,  $\eta_p^2 = .742$ ; and position,  $F(6, 294) = 233.44$ ,  $p < .001$ ,  $\eta_p^2 = .827$ . There was a significant RCI  $\times$  switching interaction,  $F(1, 49) = 8.11$ ,  $p = .006$ ,  $\eta_p^2 = .142$ ; a significant RCI  $\times$  position interaction,  $F(6, 294) = 12.47$ ,  $p < .001$ ,  $\eta_p^2 = .203$ ; a significant switching  $\times$  position interaction,  $F(6, 294) = 90.09$ ,  $p < .001$ ,  $\eta_p^2 = .648$ ; and a significant three-way interaction,  $F(6, 294) = 5.17$ ,  $p < .001$ ,  $\eta_p^2 = .095$ .

I then examined RT separately for Position 1 and Positions 2–7. For Position 1, the main effect of RCI (58.9 ms) was significant,  $F(1, 49) = 54.42$ ,  $p < .001$ ,  $\eta_p^2 = .526$ . The main effect of switching (199.6 ms) was also significant,  $F(1, 49) = 140.76$ ,  $p < .001$ ,  $\eta_p^2 = .742$ . The RCI  $\times$  switching interaction was significant,  $F(1, 49) = 16.11$ ,  $p < .001$ ,  $\eta_p^2 = .247$ , replicating the other half of the earlier finding that this interaction is sensitive to how RCI is manipulated (Altmann, 2005).

For Positions 2–7, the main effect of RCI (16.1 ms) was significant,  $F(1, 49) = 74.15$ ,  $p < .001$ ,  $\eta_p^2 = .602$ . The main effect of position was significant,  $F(5, 245) = 35.08$ ,  $p < .001$ ,  $\eta_p^2 = .417$ , as was the linear trend in position,  $F(1, 49) = 78.49$ ,  $p < .001$ ,  $\eta_p^2 = .616$ , again replicating within-run slowing. The RCI  $\times$  position interaction was not significant,  $F(5, 245) = 1.24$ ,  $p = .289$ ,  $\eta_p^2 = .025$ , indicating that RCI did not affect the slope of slowing, which was again numerically greater in the long RCI condition (10.0 ms/trial) than in the short RCI condition (8.3 ms/trial). The main effect of switching (4.4 ms) was marginally significant,  $F(1, 49) = 2.93$ ,  $p = .093$ ,  $\eta_p^2 = .056$ , and the switching  $\times$  position interaction was significant,  $F(5, 245) = 2.59$ ,  $p = .026$ ,  $\eta_p^2 = .050$ , reflecting a small residual switch cost on Position 2; these effects were not significant when Position 2 was excluded,  $ps > .128$ . The RCI  $\times$  switching and the three-way interactions were not significant,  $F_s < 1$ .

I examined percentage error with a 2 (RCI)  $\times$  2 (switching)  $\times$  7 (position) ANOVA. The main effect of switching (1.06%) was significant,  $F(1, 49) = 24.90$ ,  $p < .001$ ,  $\eta_p^2 = .337$ , but the switching  $\times$  position interaction was not,  $F(6, 294) = 1.52$ ,  $p = .171$ ,  $\eta_p^2 = .030$ , replicating the finding that error switch cost falls on all trials of a run. The main effect of RCI was not significant,  $F(1, 49) = 1.18$ ,  $p = .282$ ,  $\eta_p^2 = .024$ . The main effect of position was significant,  $F(6, 294) = 2.68$ ,  $p = .015$ ,  $\eta_p^2 = .052$ , as was the linear trend in position,  $F(1, 49) = 6.24$ ,  $p = .016$ ,  $\eta_p^2 = .113$ , which is evidence for within-run error increase. The RCI  $\times$  switching and RCI  $\times$  position interactions were not significant,  $F_s < 1$ .



**Table 2** Response time (ms) and error rate (%) for Experiment 2, with standard deviation (in parentheses)

RCI, Switching	Position						
	1	2	3	4	5	6	7
RT							
Short							
Switch	997.1	577.9	571.6	583.6	593.9	591.6	612.7
Repeat	765.5	561.8	567.7	575.2	589.7	600.4	605.9
Long							
Switch	906.2	553.2	552.1	566.3	581.6	577.2	600.1
Repeat	738.6	542.5	544.9	566.2	580.0	584.0	591.1
Short							
Switch	(196.4)	(83.8)	(62.5)	(67.3)	(72.7)	(70.2)	(87.4)
Repeat	(129.7)	(72.0)	(65.2)	(70.6)	(71.0)	(78.8)	(103.4)
Long							
Switch	(194.6)	(72.4)	(66.0)	(63.9)	(75.5)	(73.6)	(97.6)
Repeat	(134.0)	(66.5)	(59.9)	(56.7)	(77.8)	(74.9)	(76.0)
PE							
Short							
Switch	3.70	4.46	3.63	4.31	3.97	4.61	3.21
Repeat	2.05	2.88	2.56	2.71	3.09	2.95	3.75
Long							
Switch	3.24	3.71	3.52	3.38	3.64	4.72	4.00
Repeat	2.18	2.63	2.59	3.44	2.78	2.84	2.77
Short							
Switch	(2.55)	(2.94)	(2.52)	(3.36)	(3.11)	(4.50)	(3.83)
Repeat	(1.90)	(2.21)	(2.01)	(2.22)	(3.06)	(2.87)	(4.34)
Long							
Switch	(2.61)	(2.50)	(2.65)	(3.00)	(3.22)	(4.88)	(6.04)
Repeat	(2.05)	(2.28)	(2.01)	(2.82)	(2.94)	(3.74)	(3.93)

RCI response–cue interval, RT response time, PE percentage error

The three-way interaction was marginally significant,  $F(6, 294) = 1.83$ ,  $p = .093$ ,  $\eta_p^2 = .036$ .

## Discussion

Experiment 2 replicated the core results of Experiment 1. RCI  $\times$  position interactions again failed to materialize, and the slope of within-run slowing was again numerically greater after a long RCI than after a short RCI (10.0 vs. 8.3 ms/trial), contrary to the predicted interaction. RCI again had a main effect on RT and no effect on the error rate. Here within-run error increase was evident, even though it was not in Experiment 1.

## General discussion

The Altmann and Gray (2008) model of memory processes in task switching makes a prediction that was not supported here. The model incorporates a representation of time-

based decay of memory for a task that starts when the memory is encoded from a task cue. The most direct predictions of this decay are within-run slowing and within-run error increase, which hypothetically reflect decay of the current task as it is being performed. In one sense, then, the model's predictions were upheld, in that within-run slowing replicated in both experiments and within-run error increase replicated in Experiment 2.

However, at a more detailed level, the model also predicts that any factor that causes the previous task to be more decayed should reduce the slopes of within-run slowing and error increase. In previous studies supporting this prediction, the factor was the length of a run of trials. In the experimental results reported by Altmann and Gray (2008), the mean runlength was 6 trials in one condition and 12 trials in the other. For positions shared across the two runlength conditions, the slopes of within-run slowing and error increase were flatter in the condition with long runs. In the experimental results reported by Altmann (2014), the mean number of trials per run was the same

across conditions, but in one condition there was a 500 ms response–stimulus interval between successive trials. Like the manipulation in Altmann and Gray, this manipulation roughly doubled the age of the previous task, given that RTs were also about 500 ms. The slopes of within-run slowing and within-run error increase were again flatter in the condition with the temporally longer runs.

In the present study, the factor that should have affected decay was the RCI, which made the previous task older when the RCI was longer. However, the predicted RCI  $\times$  position interactions were null, in all four instances (RT and error rate for both experiments). Indeed, in both experiments the slope of within-run slowing in particular was numerically (though not significantly) steeper with a longer RCI. The null interactions could mean that the Altmann and Gray (2008) model is incorrect, in which case some other explanation would be necessary to account for within-run effects here and in previous studies and for the changing slopes of within-run effects where these have occurred (Altmann, 2014; Altmann & Gray, 2008).

The null interactions could also mean that the time scale of the RCI manipulation was too small to generate behaviorally detectable results mediated by decay. The previous task was 700 ms older in the long RCI condition than in the short RCI condition. In previous studies in which the changing-slopes prediction was supported, the previous task was about 3 s (Altmann & Gray, 2008) and about 5 s (Altmann, 2014) older in the condition with longer runs. These larger differences in the age of the previous task may be necessary to generate detectable behavioral effects. Some converging evidence comes from studies using the explicit-cuing procedure, in which there is only one trial per task cue; several studies suggest that when RCI manipulations are effective, the affected process is not actually decay (Altmann, 2005; Grange & Cross, 2015; Horoufchin et al., 2011). These two lines of evidence, then, suggest that typical RCI manipulations do not induce a sufficient temporal difference in the age of the previous task to have behavioral effects mediated by decay of the previous task.

It remains to explain the main effect of RCI on RT, specifically on Positions 2–7, which replicated in both experiments. Any account of this effect in terms of memory processes begs the question of why RCI did not also affect the error rate. If the RCI manipulation affected interference in memory for task sets—whether interference is characterized as in the Altmann and Gray (2008) model, or as in some other memory model—the difference in interference should have affected the ability to remember the current task correctly. The error rate was sensitive enough to show other experimental effects, including a switching effect, and, in Experiment 2, within-run error increase.

A more parsimonious account of the main effect of RCI on RT may actually involve an additional process, one that would logically have an effect on RT but not on the error rate. Although potentially many candidate processes are possible, here I explore one in particular. Under the conditions of the procedure used here, the system may have had to monitor for the appearance of task cues, which appeared unpredictably. Indeed, the method for determining the length of a run of trials between task cues was designed to minimize the amount of information available to the participant to predict when the next cue would appear. Moreover, the cue was visible for only 100 ms. Given these factors, there is the possibility that the system could fail to detect a cue and therefore fail to encode the memory representation of the cued task that was necessary to perform a run of trials correctly. A functional response of the system to this possibility of failure to detect a task cue would be to monitor for task cues continuously.<sup>3</sup> This monitoring process would have been aided by a signal that a task cue was about to onset. A short RCI would have been a less effective signal than a long RCI, producing a greater probability of failing to detect a task cue, and thus placing a greater burden on the monitoring process. According to this logic, the monitoring process would have had to work harder, or have a higher priority, with a short RCI, and thus consume more system cycles (which are the critical resource in the model of Altmann & Gray, 2008).

Although this account proposes an extra process, it has some attractive characteristics. First, there is evidence that monitoring for unpredictable events increases RT in other contexts also. Specifically, monitoring for a prospective memory target when this target is still pending slows performance of the ongoing task (Smith, Hunt, McVay, & McConnell, 2007). Second, a monitoring process that is ancillary rather than directly involved in responding to the imperative stimulus would not be expected to affect accuracy of that response. Indeed, accuracy of responses in the ongoing task was not affected in the prospective memory results cited above. Third, a monitoring process would fit with the view that part of mixing cost can be attributed to vigilance for task cues (Mari-Beffa, 2014).

One challenge to this monitoring account is that the main effect of RCI on RT was still present in Experiment 2, where RCI was randomized between runs. With RCI randomized, the system would not have been able to adjust the priority of the monitoring process to match the next anticipated RCI. However, it could still have adjusted the priority in response to experienced RCIs. In general, the

<sup>3</sup> A task cue could not occur on positions 1, 2, or 3 of a run, but a reasonable theoretical assumption seems to be that any monitoring process would have been deployed consistently on all trials rather than being cycled on and off in a way that requires an additional process that monitors position in run.

past is a good predictor of the future, even if it is only a heuristic and fails under some conditions. If the system was adapting to experienced RCIs rather than to anticipated RCIs, and if there were some weighting toward recency, this account would fit with the finding of a smaller but still present RCI effect in Experiment 2.

To test whether the results here were consistent with this explanation, I conducted two additional analyses. The first tested inferentially whether the RCI effect on RT on Positions 2–7 was in fact smaller in Experiment 2 than in Experiment 1. Descriptively, the effects were 16.1 and 64.2 ms, respectively. To test this difference inferentially I used a procedure that involves recoding within-participants data in a between-participants format, then analyzing the combined data with the contrast of interest and the design of the manipulation as between-participants factors (Erlbacher, 1977). The analysis recovers some of the power lost by recoding within-participants data as between-participants data by averaging the error sum of squares and error degrees of freedom across the two data sets. Using this approach, the RCI  $\times$  design interaction was significant,  $F(1, 60.97) = 12.48$ ,  $p = .001$ ,  $\eta_p^2 = .178$ . Thus, manipulating RCI within participants did reduce the size of the RCI effect.

The second analysis tested the effect of the RCI repeating from one cue to the next, in Experiment 2. If the history of RCIs was driving adjustments to the monitoring process, then the RCI effect should have been greater between a repeated long RCI and a repeated short RCI than between a non-repeated long RCI (i.e., a long RCI that followed a short RCI) and a non-repeated short RCI (a short RCI that followed a long RCI). On Positions 2–7, the RT difference between repeated long RCIs and repeated short RCIs ( $589.1 - 569.5 = 19.6$  ms) was in fact marginally larger than the difference between non-repeated long RCIs and non-repeated short RCIs ( $585.7 - 573.4 = 12.3$  ms),  $F(1, 49) = 3.32$ ,  $p = .075$ ,  $\eta_p^2 = .063$ . Thus, there is some evidence that the effect of experienced RCI accumulates over successive instances, consistent with the view that the system adapts to experienced RCI.

This monitoring account is merely consistent with the current data, and could be tested more directly by various means, such as by manipulating the perceptual detectability of the cue, or through the use of non-focal cues (as in prospective memory studies), or through demonstrating an interaction with the difficulty of trial performance. It would also be important to test an alternative account that appeals to monitoring, which is that the RCI manipulation induced different monitoring strategies rather than different levels of monitoring difficulty. With a long RCI participants might have monitored for the absence of the imperative stimulus on trials, whereas with a short RCI participants

might have monitored for the presence of the task cue, and this difference could somehow have accounted for the difference in RT on Positions 2–7 (even in Experiment 2, if strategy choice were again sensitive to experienced RCI) without producing a difference in the error rate.

The main effect of RCI on RT may have applied relevance. The extended-runs task-switching procedure is not the worst proxy for a dynamic task environment in which an operator must attend to critical but unpredictable events to perform correctly. The present results suggest that in such an environment, the perceptual distinctiveness of critical events—represented here by task cues preceded by RCIs—has implications for performance between critical events. Exactly how perceptual distinctiveness might affect performance reaches again to the theoretical question, but knowing in general terms that the manner of presentation of critical events can affect performance between one critical event and the next is food for thought where there are choices to be made about how to present critical events.

## Summary and conclusions

RCI effects in task switching are often interpreted in terms of memory mechanisms (e.g., Kiesel et al., 2010; Meiran et al., 2000; Poljac & Bekkering, 2009). The present results are inconsistent with a memory-based account, at two levels. At the more specific level, the Altmann and Gray (2008) model predicts an effect of RCI on the slope of within-run effects that did not materialize here. The problem could be with the model, but could also reflect a relatively small effect of the RCI manipulation on decay of the previous task. At a more general level, the present results are inconsistent with a generic account in which reduced interference from the previous task after a longer RCI serves to reduce the error rate, which was not affected by RCI.

The effect of RCI on RT but not the error rate is evidence for a process that takes time but does not affect the accuracy of trial-related operations. One possible function for such a process might be to monitor for task cues, which in this procedure occurred unpredictably and were visible only briefly. This account implies that strong signaling of unpredictable critical events could speed responding between those events in dynamic task environments generally. In future work, it would be important to develop converging evidence for a monitoring process, or, if this is not what affected RT here, to understand what did.

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### Compliance with ethical standards

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**Conflict of interest** The author declares that he has no conflict of interest.

**Ethical approval** All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

**Informed consent** Informed consent was obtained from all individual participants included in the study.

### Appendix

In the body of the paper I described the basic dynamics of the Altmann and Gray (2008) task-switching model to develop the prediction linking the RCI manipulation to a change in slopes of within-run effects. Here I describe the underlying mechanisms in more detail, based on the computational implementation described by Altmann and Gray.

In terms of Fig. 1, the critical quantities for this analysis are the areas of the two density functions within each panel that lie to the right of the retrieval threshold. Each of these areas represents the probability that on a given retrieval attempt, the activation of the corresponding memory (for the current task or the previous task) will be above threshold. These probabilities in turn affect RT and the error rate. On a given trial (hypothetically including Position 1 of a run; Altmann, 2013), the system attempts to retrieve a task memory to guide its interpretation of the imperative stimulus. The retrieval attempt succeeds if a task memory is above threshold. If more than one memory is above threshold, the one with the highest activation at that moment is returned. The retrieval attempt fails if no task memory is above threshold. In case of a failure, the system tries another retrieval. One attempt may fail and the next succeed, because activation values fluctuate from moment to moment (as reflected in the dispersion of the density functions). Each retrieval attempt costs a 50 ms system cycle. Thus, the more retrieval attempts, the longer the retrieval time and the longer the RT for that trial.

Under these operating principles, within-run slowing arises as follows. RT is inversely related to the total area of the density functions that is above threshold, summed across the two density functions (in the general case, older task memories are included in this sum as well; see Altmann & Gray, 2008). The smaller this area, the lower the probability that one task memory or the other will be above threshold to answer a retrieval request, so the greater the

average retrieval time and thus the greater the RT. As the right-hand density shifts left (decays) from one trial to the next within a run, the total area above threshold shrinks, so RT increases, causing within-run slowing. With a greater activation difference between the current and previous tasks (lower panel of Fig. 1, compared with the upper panel), hypothetically due to a longer RCI and thus more time for the previous task to decay, the retrieval threshold intersects both densities at a thinner portion of their tails. Thus, as the right-hand density shifts left, the change in the area above threshold per unit decay is smaller, predicting flatter within-run slowing.

Within-run error increase arises for similar reasons. The error rate is related not to the total above-threshold area of the two densities, but to the proportion of the total area contributed by the right-hand density. This proportion determines the conditional probability of retrieving the current task, given that a task is retrieved. Like the total area, this proportion shrinks as the right-hand density shifts left, causing within-run error increase. With a greater activation difference between the current and previous tasks, the retrieval threshold is located further to the left, so the shrinkage is less per unit decay, predicting a flatter increase.

One important difference between the error rate and RT, according to this model, is that a retrieval error—that is, a retrieval of the previous task instead of the current task—only translates into a performance error if the previous task is incorrect. The previous task is incorrect on switch runs but not repeat runs (see Fig. 2). Thus, in addition to within-run effects, another prediction of the model is full-run error switch cost (Altmann & Gray, 2008), meaning a main effect of switching on the error rate that does not interact with position. This effect was present in both experiments, lending additional support to the model, and thus indirectly to the interpretation that the RCI manipulation was too weak to affect the activation difference between the current and previous tasks (Fig. 1) to a degree that was behaviorally detectable.

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