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Investigating a method for reducing residual switch costs in cued task switching

Darryl W. Schneider [1]

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Abstract Residual switch costs in cued task switching are performance decrements that occur despite a long cue–target interval (CTI) to prepare for a task switch. Verbruggen, Liefooghe, Vandierendonck, and Demanet (Journal of Experimental Psychology: Learning, Memory, and Cognition, 33; 342–356, 2007) showed that briefly presenting the cue during the CTI and leaving it absent after target onset yielded smaller residual switch costs than those obtained when the cue was available for the full CTI and remained present after target onset. The potential effects of cue availability during the CTI (full or partial) and cue status after target onset (present or absent) on residual switch costs were investigated in the present study. In Experiments 1 and 2, cue status was manipulated while holding cue availability constant. In Experiments 3 and 4, cue status and cue availability were manipulated factorially. Residual switch costs were obtained, but they were not modulated consistently by cue status or cue availability across experiments. In Experiment 5, a direct replication of one of Verbruggen and colleagues' experiments yielded divergent results. Implications for understanding task switching are discussed.

Keywords Task switching · Residual switch cost · Task cuing · Cue availability · Cue absence

Task switching is important in research on cognitive control because it highlights the capabilities and limitations of the cognitive system (Kiesel et al., 2010; Vandierendonck, Liefooghe, & Verbruggen, 2010). On the one hand, the cognitive system can perform different tasks in rapid succession. On the other hand, it is limited regarding how quickly and accurately task switching can be accomplished, as indicated by switch costs—worse performance for task switches than for task repetitions. This limitation is revealed especially by residual switch costs, which are performance decrements that sometimes occur despite a long time to prepare for a task switch (e.g., De Jong, 2000; Meiran, Chorev, & Sapir, 2000; Rogers & Monsell, 1995). The purpose of the present study was to investigate a method previously shown to reduce residual switch costs in cued task switching.

On each trial of a cued task-switching experiment, a cue indicates the relevant task to perform on a target. For example, the cue *odd–even* might indicate that a target digit should be categorized as odd or even, whereas the cue *small–large* might indicate that the target should be categorized as smaller or larger than 5. Random selection of the cues produces different transitions across trials, with some trials being task switches (e.g., odd–even followed by small–large), and others being task repetitions (e.g., odd–even followed by odd–even). The performance difference between task switches and task repetitions is the switch cost.

Two aspects of the typical cued task-switching procedure (see Meiran, 2014) are relevant for the present study. First, it is common to present the cue before the target, with the time from cue onset to target onset referred to as the cue–target interval (CTI). Studies in which the CTI has been manipulated have revealed that response times (RTs) become shorter and switch costs decrease with longer CTIs (e.g., Monsell & Mizon, 2006; Schneider & Logan, 2011), although residual switch costs have been observed after CTIs of 1,000 ms or longer (e.g., Longman, Lavric, Munteanu, & Monsell, 2014; Meiran, 1996; Meiran et al., 2000). Second, the cue (often a visual stimulus) is typically available for the full CTI and remains present after target onset. Potential effects related to this aspect of the procedure are addressed in the present study.

✉ Darryl W. Schneider
dws@purdue.edu

[1] Department of Psychological Sciences, Purdue University, 703 Third Street, West Lafayette, IN 47907, USA

Multiple explanations have been advanced for residual switch costs in cued task switching and other procedures. Allport, Styles, and Hsieh (1994) proposed a role for task set inertia, whereby persisting activation of the now-irrelevant task set interferes with execution of the relevant task set on task switch trials, yielding residual switch costs. Rogers and Monsell (1995) suggested that cognitive control in task switching involves task set reconfiguration processes, with an endogenous process occurring during the CTI (resulting in a smaller switch cost with a longer CTI), and an exogenous process occurring after target onset (resulting in a residual switch cost). De Jong (2000) also attributed residual switch costs to reconfiguration occurring after target onset, but as a consequence of occasionally failing to engage in preparatory reconfiguration during the CTI. Although these explanations provide insights regarding the origin of residual switch costs, they offer few recommendations for reducing the costs. For example, on the basis of De Jong's failure-to-engage hypothesis, one might predict that strongly incentivizing preparatory reconfiguration would reduce residual switch costs, but that prediction has received limited support (Lien, Ruthruff, Remington, & Johnston, 2005; Nieuwenhuis & Monsell, 2002).

However, an example of a method for reducing residual switch costs was provided by Verbruggen, Liefooghe, Vandierendonck, and Demanet (2007). In cued task-switching experiments involving numerical tasks (odd–even and small–large judgments of digits) and multiple CTIs, they assessed performance at their longest CTI in two cuing conditions. In one condition, the cue was present for the full CTI and remained present after target onset. In the other condition, the cue was presented briefly (e.g., 96 ms) and then removed (replaced by a masking stimulus), resulting in its absence for the remainder of the CTI and after target onset. The key finding was that residual switch costs were reliably smaller (and sometimes not significantly different from zero) when the cue was removed than when it remained present.[1] Verbruggen and colleagues interpreted their results as evidence that brief cue presentations can motivate subjects to fully prepare for a task switch during the CTI, implying that the residual switch cost does not reflect a fundamental limitation on task-switching performance.

Despite the importance of Verbruggen et al.'s (2007) study, nobody appears to have replicated their key finding, even though it was listed as a "robust finding" in a review of the task-switching literature (Vandierendonck et al., 2010, p. 616).[2] Moreover, nobody has demonstrated which aspect(s) of their method led to the reduced residual switch costs. To elaborate, the critical cuing condition differed from the typical cuing condition in two ways. First, the cue was presented briefly, which meant that it was partially available during the CTI. Second, the cue was absent after target onset, which meant that it was unavailable during target processing. It is unclear whether cue availability during the CTI (partial instead of full) or cue status after target onset (absent instead of present) affected the residual switch cost.

There are reasons to think that both attributes may be important. If residual switch costs arise from failures to engage in preparatory reconfiguration during the CTI (De Jong, 2000), then making the cue partially available during the CTI and leaving it absent after target onset might motivate subjects to prepare more often, resulting in smaller residual switch costs. Regarding cue availability in particular, briefly presenting the cue and leaving it unavailable for most of the CTI might be a more effective means of inducing endogenous processing than having the cue available for the full CTI. Foreknowledge that the cue will be partially available during the CTI on some trials may increase subjects' alertness, a factor that influences task-switching performance (Meiran & Chorev, 2005). Regarding cue status in particular, an exogenous process of reconfiguration occurring after target onset (Rogers & Monsell, 1995) might be impaired when the cue is absent instead of present during target processing, because it would only have access to an internal representation of the cue in memory. Relatedly, if the cue is used in conjunction with the target to retrieve information from long-term memory for response selection (Logan & Bundesen, 2003; Schneider & Logan, 2005), retrieval might be less effective when the target but not the cue is physically present. Thus, cue availability during the CTI, cue status after target onset, or the combination of both attributes might have been responsible for the findings of Verbruggen et al. (2007). However, their experiments do not allow one to distinguish between the potential effects of these attributes, and other studies have yielded inconclusive results.

In some previous studies, residual switch costs have been observed when the cue was partially available during the CTI and remained absent after target onset (Lenartowicz, Yeung, & Cohen, 2011; Longman et al., 2014; Mayr, 2001; Steinhauser, Maier, & Hübner, 2007; Yamaguchi & Proctor, 2011), but they lacked typical cuing conditions for comparison. In other studies, residual switch costs have been observed when cue status after target onset was manipulated, with the cue always being available for the full CTI (Gotler & Meiran, 2001; Proctor, Koch, Vu, & Yamaguchi, 2008). In both of these studies, the residual switch costs did not differ reliably as a function of cue status. These results are somewhat inconclusive, because the residual switch costs were small in all conditions (the largest effect was 33 ms), leaving little room to observe any differences between conditions, and some of the sample sizes may have been too small to detect true differences (e.g., eight subjects per condition in Exp. 1 of Gotler & Meiran, 2001).

[1] For the three experiments in which this effect was found in their RT data, the residual switch costs were 14, 16, and –3 ms when the cue was presented briefly.

[2] In a footnote, Elchlepp, Lavric, Mizon, and Monsell (2012, p. 1138) mentioned unpublished replication attempts: "In our laboratory, using brief cues (two per task) with other tasks and stimuli has not eliminated the switch cost."

The goal of the present study was to identify and disentangle the potential effects of cue availability and cue status on residual switch costs, which might lead to a refined explanation of the striking results reported by Verbruggen et al. (2007). I conducted five cued task-switching experiments involving odd–even and small–large judgments of target digits, the same tasks used by Verbruggen and colleagues. The tasks were signaled by cues that were either meaningful words (i.e., *odd–even* and *small–large*; Exps. 1–3) or arbitrary letters (e.g., *C* and *U*; Exps. 4 and 5). The cue preceded the target by a short or a long CTI on each trial, with residual switch costs being assessed at the longer CTI. In Experiments 1 and 2, cue status was manipulated while holding cue availability constant, partly to clarify the results of previous studies (Gotler & Meiran, 2001; Proctor et al., 2008). In Experiments 3 and 4, cue status and cue availability were manipulated factorially, thereby allowing me to assess their separate and combined effects on residual switch costs. In Experiment 5, I conducted a direct replication of one of Verbruggen and colleagues' experiments to assess the robustness of their results.

Experiments 1 and 2

Cue status after target onset (present or absent) was manipulated while holding cue availability constant (the cue was always available for the full CTI). Cue status was a within-subjects variable in Experiment 1 (as in Gotler & Meiran, 2001, Exp. 2), with the cue-present and cue-absent conditions randomly intermixed within blocks of trials. Consequently, subjects did not know until target onset whether the cue would be present or absent during target processing, which meant that any differences in residual switch costs between conditions could not reflect differences in preparatory processing during the CTI. Cue status was a between-subjects variable in Experiment 2 (as in Gotler & Meiran, 2001, Exp. 1; Proctor et al., 2008), with the cue-present condition being experienced by half of the subjects, and the cue-absent condition experienced by the other half. Consequently, subjects knew in advance whether the cue would be present or absent during target processing, which meant that any differences in residual switch costs between conditions could reflect differences in preparatory processing during the CTI. However, an overarching question of interest was whether cue status would modulate residual switch costs at all.

Method

Subjects A total of 144 students from Purdue University participated for course credit. Of these, 48 subjects took part in Experiment 1, and 96 subjects (48 per cue-status group) in Experiment 2. These sample sizes exceed those obtained in previous studies (Gotler & Meiran, 2001; Proctor et al., 2008; Verbruggen et al., 2007). For all experiments in the present study, all subjects reported having normal or corrected-to-normal vision.

Apparatus, tasks, stimuli, and responses The experiments were conducted on computers that displayed stimuli on monitors and registered responses from QWERTY keyboards. Stimuli were displayed in white 18-point Arial font on a black background at a viewing distance of approximately 50 cm. Two numerical categorization tasks were performed on the targets *1–9*, excluding *5*. The odd–even task, cued by the words *odd–even*, involved pressing a key to categorize a target as odd or even. The small–large task, cued by the words *small–large*, involved pressing a key to categorize a target as smaller or larger than 5. Responses were made with the "D" and "K" keys on the keyboard, with the same-task categories mapped to different keys (e.g., the odd and small categories mapped to the "D" key, and the even and large categories mapped to the "K" key). The four possible sets of category–response mappings were counterbalanced across subjects. Reminders of the category–response mappings were displayed throughout each trial at the bottom of the screen. The left–right order of the category words composing the cues matched the left–right order of the response keys for each subject.

Procedure Subjects were seated at computers in individual testing rooms after providing informed consent for a study protocol approved by the Purdue University Institutional Review Board. Instructions were presented onscreen and read aloud by the experimenter. Subjects completed six example trials (with accuracy feedback and, if necessary, experimenter guidance) during the instructions before beginning the experiment proper, which consisted of six blocks of 64 trials per block (without accuracy feedback or experimenter guidance).

Each trial started with two vertically arranged fixation crosses displayed in the center of the screen. After 500 ms, the top fixation cross was replaced by a cue. After a CTI of 300 or 1,200 ms, the bottom fixation cross was replaced by a target. In the cue-present condition, the cue remained present after target onset. In the cue-absent condition, the cue was replaced by a masking stimulus (###########) at target onset. The stimuli (cue/mask and target) remained onscreen until the subject responded, then the next trial commenced after a blank screen was displayed for 500 ms. Thus, the response–cue interval was 1,000 ms for all trials. The cue, CTI, and target were selected randomly on each trial, subject to the constraint that all possible combinations occurred equally often in each block. Due to the random selection of cues, task switches and task repetitions occurred randomly across trials in approximately equal proportions. Subjects were instructed to respond quickly and accurately on every trial. They were informed that the cues would be selected randomly, which meant that they would not be able to predict which task was next. However, they were also informed of the CTI manipulation and encouraged to prepare for the cued task during that interval.

In Experiment 1, cue status was manipulated within subjects. The cue-present and cue-absent conditions were randomly intermixed across trials, occurring equally often in each block. Subjects were informed that the cue would remain present after target onset on some trials, whereas it would be masked at target onset on other trials. They were instructed to attend to the cue on every trial as soon as it appeared; otherwise, they might not know which task to do.

In Experiment 2, cue status was manipulated between subjects. Half of the subjects experienced the cue-present condition, and the other half experienced the cue-absent condition. All trials involved only the cue-status condition to which a subject was assigned, and the instructions mentioned only the relevant condition.

Results

The first block and the first trial of each subsequent block were excluded from the analysis. Trials with RTs more than three standard deviations above the mean in each design cell for a given subject were excluded (1.9 % of trials for each experiment). Error trials were excluded from the RT analyses. The mean RT and error rate were calculated for each subject in the relevant cells of the 2 (Cue Status: present or absent) × 2 (Transition: task switch or task repetition) × 2 (CTI: 300 or 1,200 ms) experiment designs. Two sets of analyses of variance (ANOVAs) were conducted for each experiment, with Cue Status as a between-subjects factor for Experiment 2. The first set consisted of full analyses involving all levels of all factors, which allowed me to assess preparation effects related to the CTI manipulation. The second set consisted of restricted analyses involving the data only for the long CTI, which allowed me to assess effects on residual switch costs. Following Verbruggen et al. (2007), the full analyses are reported in the Appendix and the restricted analyses are reported in the main text. The ANOVA results for all analyses are summarized in Tables 1 and 2 for Experiments 1 and 2, respectively. To facilitate comparisons across conditions, residual switch costs are plotted in Fig. 1, and the mean RTs and error rates for all conditions are presented in Fig. 2.

Residual switch costs were obtained for RTs and error rates in Experiment 1 (93 ms for RTs and 1.4 % for error rates) and in Experiment 2 (62 ms and 1.7 %), resulting in significant main effects of transition (see Tables 1 and 2). However, the residual switch costs did not differ reliably between the cue-present and cue-absent conditions (see Fig. 1), as indicated by the nonsignificant interactions between cue status and transition in all cases. The only significant effect involving cue status was a main effect on RTs in Experiment 1, reflecting slower performance in the cue-absent condition (870 ms) than in the cue-present condition (815 ms). A nonsignificant difference (p = .07) in the same direction was obtained in Experiment 2, with numerically slower performance in the cue-absent condition (896 ms) than in the cue-present condition (820 ms).

Discussion

Overall performance was better and switch costs were generally smaller with the longer CTI (see Fig. 2 and the Appendix), indicating that subjects engaged in preparatory processing during the CTI. However, large and significant residual switch costs were obtained for RTs and error rates in both experiments (see Fig. 1 and Tables 1 and 2). Critically, the residual switch costs did not differ reliably between the cue-present and cue-absent conditions, regardless of whether subjects had foreknowledge of cue status. Thus, the results suggest that removing the cue at target onset (after having it available for the full CTI) is insufficient for reducing residual switch costs. These results are consistent with previous findings (Gotler & Meiran, 2001; Proctor et al., 2008), but are based on much larger residual switch costs (providing more room for observing any differences between conditions) and larger sample sizes (providing more power to detect differences). Given that the isolated manipulation of cue status did not modulate the residual switch costs in Experiments 1 and 2, I investigated whether cue availability (possibly in conjunction with cue status) would modulate residual switch costs in Experiments 3 and 4.

Experiments 3 and 4

Cue availability during the CTI (full or partial) and cue status after target onset (present or absent) were manipulated factorially, resulting in four cuing conditions that were randomly intermixed within blocks of trials: full-present, full-absent, partial-present, and partial-absent. In the full-present condition, the cue was available for the full CTI and remained present after target onset, as is typically done in cued task-switching studies. In the full-absent condition, the cue was available for the full CTI and then masked at target onset, resulting in its absence during target processing. The full-present and full-absent conditions corresponded to the cue-present and cue-absent conditions, respectively, investigated in Experiments 1 and 2. In the partial-present condition, the cue was available for the first 100 ms of the CTI, was masked for the rest of the CTI, and then reappeared at target onset. To my knowledge, the partial-present condition has not been examined in previously published research. In the partial-absent condition, the cue was available for the first 100 ms of the

Table 1 Summary of ANOVAs for Experiment 1

	Full Analyses						Restricted Analyses					
	Response Time			Error Rate			Response Time			Error Rate		
Effect	$F(1, 47)$	*MSE*	η_p^2	$F(1, 47)$	*MSE*	η_p^2	$F(1, 47)$	*MSE*	η_p^2	$F(1, 47)$	*MSE*	η_p^2
Cue status (S)	9.98*	15,805	.18	1.94	15	.04	14.73*	10,172	.24	2.46	11	.05
Transition (T)	109.63*	10,643	.70	40.56*	17	.46	39.13*	10,692	.45	8.14*	11	.15
Cue–target interval (I)	36.79*	18,752	.44	11.19*	11	.19						
S × T	0.20	6,768	<.01	1.18	8	.03	0.06	7,805	<.01	0.93	9	.02
S × I	3.18	7,085	.06	0.48	9	.01						
T × I	2.80	9,764	.06	12.11*	13	.21						
S × T × I	0.01	6,328	<.01	0.09	12	<.01						

* $p < .05$

CTI, was masked for the rest of the CTI, and remained absent after target onset. The partial-absent condition corresponds to the critical cuing condition in Verbruggen et al. (2007), in which residual switch costs were reduced relative to the full-present condition. Thus, these experiments include conceptual replications of the two conditions assessed by Verbruggen and colleagues. An advantage of the factorial design of my experiments is that the inclusion of the full-absent and partial-present conditions allowed me to distinguish between the separate and combined effects of cue availability and cue status on residual switch costs, which was not possible in previous research. However, an overarching question of interest was whether cue availability and cue status would modulate residual switch costs at all.

Experiments 3 and 4 were identical except for the cues. Experiment 3 involved the meaningful word cues (*odd–even* and *small–large*) used in Experiments 1 and 2. Experiment 4 involved arbitrary letter cues (*C* and *U*), for two reasons. First, arbitrary letter cues were used in most of the experiments by Verbruggen et al. (2007), and the lack of preexisting cue–task associations may have resulted in deeper cue processing during their experiments than what might have occurred with word cues that were already associated with the task categories. Second, arbitrary (or nontransparent) cues tend to yield larger switch costs than do meaningful cues (e.g., Arbuthnott & Woodward, 2002; Logan & Bundesen, 2004; Mayr & Kliegl, 2000; Miyake, Emerson, Padilla, & Ahn, 2004; Schneider & Logan, 2011), possibly making it easier to observe potential differences in residual switch costs between cuing conditions.

Method

Subjects A total of 96 students from Purdue University participated for course credit. There were 48 subjects per experiment, and none had participated in Experiment 1 or 2.

Apparatus, tasks, stimuli, and responses These aspects of the experiments were identical to those of Experiments 1 and 2, except different cues were used in Experiment 4. In that experiment, the tasks were cued by the letters *C* and *U*, which were chosen for their similar visual complexity and the lack of any obvious relationship with the task categories and response

Table 2 Summary of ANOVAs for Experiment 2

	Full Analyses						Restricted Analyses					
	Response Time			Error Rate			Response Time			Error Rate		
Effect	$F(1, 94)$	*MSE*	η_p^2	$F(1, 94)$	*MSE*	η_p^2	$F(1, 94)$	*MSE*	η_p^2	$F(1, 94)$	*MSE*	η_p^2
Cue status (S)	3.08	173,727	.03	0.05	34	<.01	3.43	80,213	.04	0.18	20	<.01
Transition (T)	124.33*	7,640	.57	86.40*	5	.48	25.51*	7,210	.21	39.45*	4	.30
Cue–target interval (I)	103.10*	7,305	.52	5.14*	5	.05						
S × T	0.58	7,640	.01	0.20	5	<.01	0.88	7,210	.01	0.89	4	.01
S × I	0.01	7,305	<.01	3.36	5	.04						
T × I	28.73*	4,717	.23	5.04*	3	.05						
S × T × I	0.46	4,717	.01	0.75	3	.01						

* $p < .05$

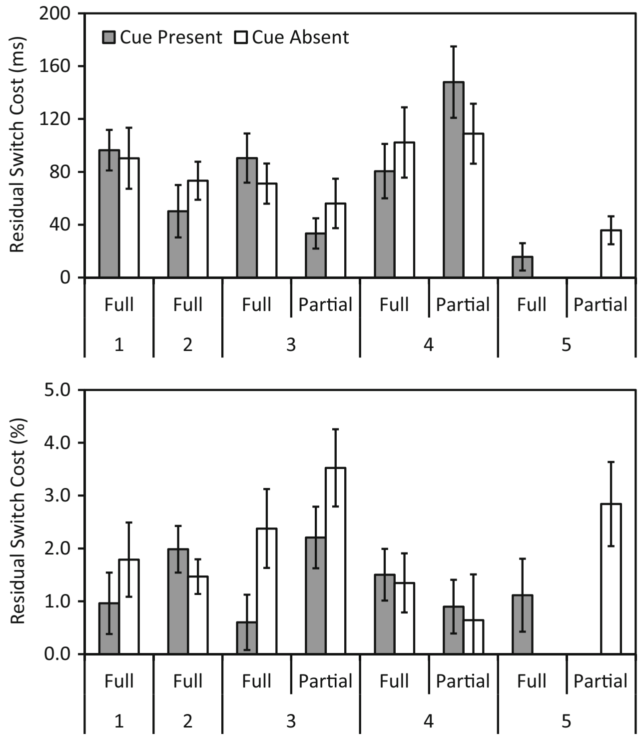

Fig. 1 Mean residual switch costs for response times and error rates as a function of cue availability (full or partial) and cue status (present or absent) in Experiments 1–5. Error bars represent standard errors of the means

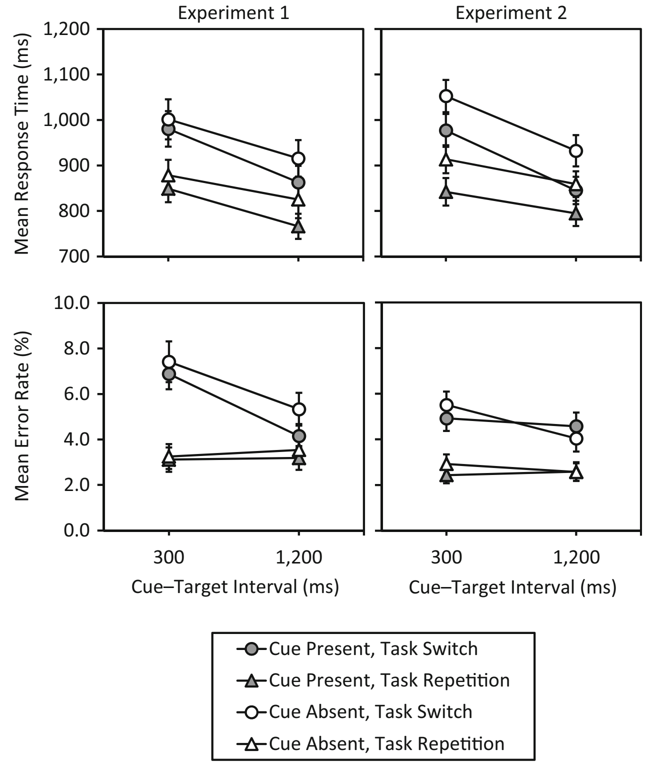

Fig. 2 Mean response times and error rates as a function of cue status (present or absent), transition (task switch or task repetition), and cue–target interval in Experiments 1 and 2. Error bars represent standard errors of the means

keys. The two possible sets of cue–task mappings were counterbalanced across subjects.

Procedure The procedure was identical to that used for Experiments 1 and 2, except for the following differences. Subjects completed eight example trials during the instructions (one for each combination of cue availability, cue status, and CTI) before beginning the experiment proper, which consisted of 12 blocks of 64 trials per block.

Each trial started with two vertically arranged fixation crosses displayed in the center of the screen. After 500 ms, the top fixation cross was replaced by a cue. In the full-availability conditions, the cue was visible for the full CTI. In the partial-availability conditions, the cue was replaced by a masking stimulus (########### in Exp. 3, or # in Exp. 4) after 100 ms, and the mask was visible for the rest of the CTI. After the CTI of 300 or 1,200 ms, the bottom fixation cross was replaced by a target. In the cue-present conditions, the cue either remained present (full-present condition) or reappeared in place of the mask at target onset (partial-present condition). In the cue-absent conditions, either the cue was replaced by a mask at target onset (full-absent condition) or the existing mask remained in the place of the cue (partial-absent condition). The stimuli (cue/mask and target) remained onscreen until the subject had responded, then the next trial commenced after a blank screen was displayed for 500 ms. The cue, CTI, cue availability, cue status, and target were selected randomly on each trial, subject to the constraint that all possible combinations occurred equally often every two blocks.

In addition to the instructions from Experiments 1 and 2 about quick and accurate responding, random selection of the cues, preparation during the CTI, and attending to the cue on every trial as soon as it appeared, the subjects were informed that sometimes the cue would remain present for the entire trial, but at other times it would be replaced by a mask either temporarily or permanently during the trial.

Results

The first block and the first trial of each subsequent block were excluded from the analysis. The data trimming was identical to that of Experiments 1 and 2 (2.1 % and 2.3 % of trials were RT outliers in Exps. 3 and 4, respectively). Error trials were excluded from the RT analyses. The mean RT and error rate were calculated for each subject in each cell of the 2 (Cue Availability: full or partial) × 2 (Cue Status: present or absent) × 2 (Transition: task switch or task repetition) × 2 (CTI: 300 or 1,200 ms) experiment designs. Full analyses involving all levels of all factors are reported in the Appendix. Restricted analyses involving the data only for the long CTI are reported in the main text. The ANOVA results for all analyses are summarized in Tables 3 and 4 for Experiments 3 and 4, respectively. Residual switch costs are plotted in Fig. 1, and mean RTs and error rates for all conditions are presented in Figs. 3 and 4 for Experiments 3 and 4, respectively.

Residual switch costs were obtained for RTs and error rates in Experiment 3 (63 ms for RTs and 2.2 % for error rates) and in Experiment 4 (110 ms and 1.1 %), resulting in significant main effects of transition (see Tables 3 and 4). The residual switch costs differed reliably between some conditions, but the pattern of differences varied between experiments and between RTs and error rates within each experiment, as will be described next.

In Experiment 3, the residual switch costs for RTs were larger in the full-availability conditions (81 ms) than in the partial-availability conditions (45 ms), whereas the residual switch costs for error rates were smaller in the full-availability conditions (1.5 %) than in the partial-availability conditions (2.9 %), resulting in significant interactions between cue availability and transition. These contrasting patterns are evident in Fig. 1. Moreover, whereas the residual switch costs for RTs were not affected by cue status (64 and 62 ms in the cue-absent and cue-present conditions, respectively), residual switch costs for error rates were larger in the cue-absent conditions (3.0 %) than in the cue-present conditions (1.4 %), resulting in a significant interaction between cue status and transition for error rates.

Overall performance at the longest CTI was affected by cue availability and cue status in Experiment 3. Performance was slower but more accurate in the full-availability conditions (862 ms for RTs and 4.1 % for error rates) than in the partial-availability conditions (838 ms and 4.9 %), resulting in significant main effects of cue availability. Performance was numerically faster and more accurate in the cue-present conditions (841 ms and 3.6 %) than in the cue-absent conditions (860 ms and 5.4 %), resulting in significant (for error rates) or nearly significant ($p = .051$ for RTs) main effects of cue status. Finally, significant interactions emerged between cue availability and cue status for both RTs and error rates. The cue availability effect (partial minus full) was effectively zero in the cue-present conditions (0 ms and –0.2 %), whereas there were effects in different directions for RTs and error rates in the cue-absent conditions (–49 ms and 1.8 %).

In Experiment 4, the residual switch costs for RTs were smaller in the full-availability conditions (91 ms) than in the partial-availability conditions (128 ms), resulting in a significant interaction between cue availability and transition for RTs. This pattern is evident in Fig. 1. No other significant interactions involved transition (see Table 4).

Overall performance at the longest CTI was affected by cue availability and cue status in Experiment 4. Performance was faster and more accurate in the full-availability conditions (915 ms for RTs and 4.5 % for error rates) than in the partial-availability conditions (946 ms and 5.2 %), resulting in significant main effects of cue availability. The only remaining significant effect was an interaction between cue availability and cue status for RTs, which reflected a cue

Table 3 Summary of ANOVAs for Experiment 3

	Full Analyses						Restricted Analyses					
	Response Time			Error Rate			Response Time			Error Rate		
Effect	$F(1, 47)$	*MSE*	η_p^2	$F(1, 47)$	*MSE*	η_p^2	$F(1, 47)$	*MSE*	η_p^2	$F(1, 47)$	*MSE*	η_p^2
Cue availability (A)	0.01	18,878	<.01	5.39*	11	.10	5.84*	9,662	.11	5.94*	12	.11
Cue status (S)	4.46*	15,768	.09	21.18*	20	.31	4.00	8,826	.08	17.63*	17	.27
Transition (T)	59.64*	25,092	.56	51.77*	23	.52	56.66*	6,686	.55	29.93*	15	.39
Cue–target interval (I)	43.53*	41,667	.48	3.10	8	.06						
A × S	8.89*	6,376	.16	18.32*	8	.28	4.20*	13,896	.08	11.70*	8	.20
A × T	7.99*	7,335	.15	4.30*	14	.08	4.72*	6,575	.09	4.76*	10	.09
A × I	10.37*	10,250	.18	1.97	8	.04						
S × T	0.32	8,511	.01	7.01*	11	.13	0.01	7,312	<.01	5.86*	10	.11
S × I	0.00	6,427	<.01	1.50	8	.03						
T × I	17.36*	7,172	.27	1.69	12	.04						
A × S × T	0.80	7,060	.02	0.01	6	<.01	2.20	4,827	.05	0.19	7	<.01
A × S × I	0.50	21,335	.01	0.22	10	.01						
A × T × I	0.01	9,212	<.01	0.22	12	.01						
S × T × I	0.55	7,524	.01	0.35	9	.01						
A × S × T × I	0.93	5,354	.02	0.24	7	.01						

* $p < .05$

Table 4 Summary of ANOVAs for Experiment 4

	Full Analyses						Restricted Analyses					
	Response Time			Error Rate			Response Time			Error Rate		
Effect	$F(1, 47)$	*MSE*	η_p^2	$F(1, 47)$	*MSE*	η_p^2	$F(1, 47)$	*MSE*	η_p^2	$F(1, 47)$	*MSE*	η_p^2
Cue availability (A)	10.40*	17,622	.18	4.11*	11	.08	4.25*	21,525	.08	4.18*	12	.08
Cue status (S)	0.83	22,900	.02	2.98	64	.06	0.33	23,779	.01	2.51	34	.05
Transition (T)	86.94*	48,689	.65	58.02*	9	.55	52.18*	22,223	.53	13.28*	9	.22
Cue–target interval (I)	5.52*	41,400	.11	2.83	16	.06						
A × S	2.34	18,045	.05	5.53*	10	.11	5.34*	15,971	.10	1.07	8	.02
A × T	3.15	7,456	.06	0.67	12	.01	5.48*	6,019	.10	0.95	11	.02
A × I	0.00	12,177	<.01	0.94	11	.02						
S × T	6.31*	9,736	.12	0.47	9	.01	0.11	16,109	<.01	0.10	9	<.01
S × I	0.01	11,956	<.01	0.08	7	<.01						
T × I	26.08*	10,957	.36	5.23*	12	.10						
A × S × T	2.46	10,378	.05	6.45*	6	.12	1.75	12,711	.04	0.01	8	<.01
A × S × I	4.21*	10,218	.08	0.88	11	.02						
A × T × I	2.01	5,363	.04	5.22*	10	.10						
S × T × I	2.26	15,628	.05	0.05	8	<.01						
A × S × T × I	0.25	10,231	.01	3.22	14	.06						

* $p < .05$

availability effect (partial minus full) in the cue-present conditions (61 ms) but not in the cue-absent conditions (1 ms).

Discussion

Overall performance tended to be better and switch costs were generally smaller with the longer CTI (see Figs. 3 and 4, and the Appendix), indicating that subjects engaged in preparatory processing during the CTI. However, large and significant residual switch costs were obtained for RTs and error rates in both experiments (see Fig. 1 and Tables 3 and 4). Although the residual switch costs differed reliably between some conditions of cue availability and cue status (which also affected overall performance), no consistent pattern emerged across measures or experiments. The residual switch costs for RTs in Experiment 3 were larger in the full-availability conditions than in the partial-availability conditions, but the residual switch costs for error rates showed the opposite pattern (see Fig. 1), plus an additive effect of cue status (i.e., residual switch costs were larger in the cue-absent conditions than in the cue-present conditions). The residual switch costs for RTs in Experiment 4 were larger in the partial-availability conditions than in the full-availability conditions—the opposite of the pattern observed in Experiment 3—and the residual switch costs for error rates were not affected by cue availability or cue status (see Fig. 1). There were no indications that the divergent patterns for RTs and error rates reflected overall speed–accuracy trade-offs (see Figs. 3 and 4). Critically, the residual switch costs for RTs in the partial-absent conditions were highly significant, medium-sized effects [56 ms in Exp. 3, $t(47) = 3.01$, $SE = 19$, $p = .004$, $d = 0.43$; and 109 ms in

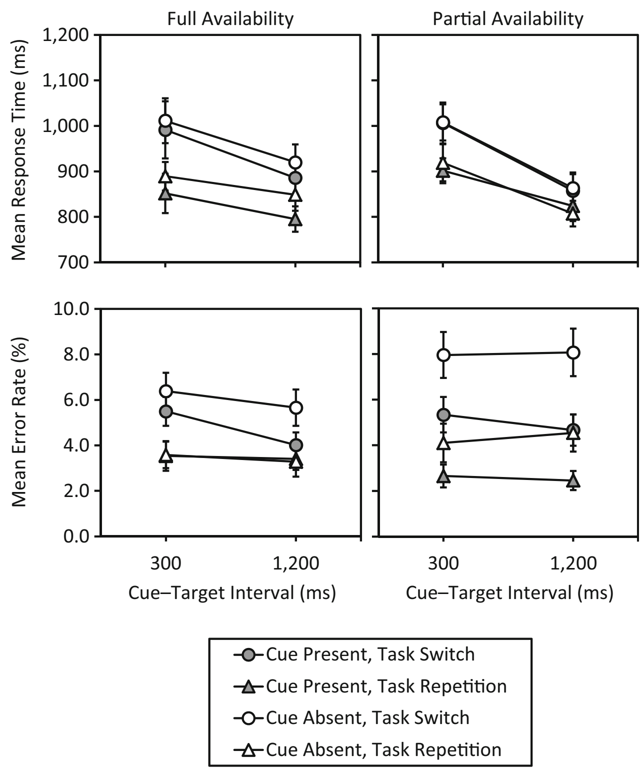

Fig. 3 Mean response times and error rates as a function of cue availability (full or partial), cue status (present or absent), transition (task switch or task repetition), and cue–target interval in Experiment 3. Error bars represent standard errors of the means

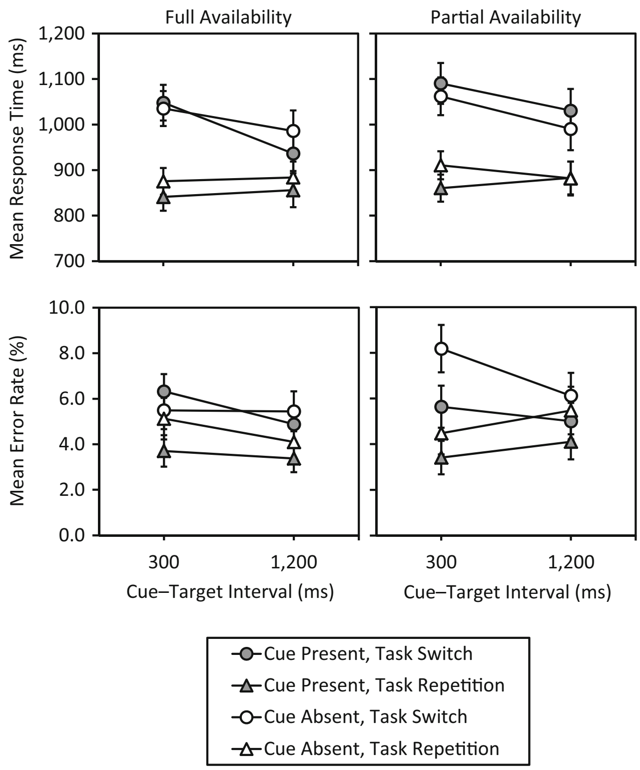

Fig. 4 Mean response times and error rates as a function of cue availability (full or partial), cue status (present or absent), transition (task switch or task repetition), and cue–target interval in Experiment 4. Error bars represent standard errors of the means

Exp. 4, $t(47) = 4.80$, $SE = 23$, $p < .001$, $d = 0.69$]. Recall that the partial-absent condition is the same condition in which Verbruggen et al. (2007) obtained greatly reduced (and sometimes nonsignificant) residual switch costs for RTs. The results of Experiments 3 and 4 indicate that making the cue partially available during the CTI and leaving it absent after target onset does not consistently reduce or eliminate residual switch costs.

Experiment 5

As was discussed earlier, the goal of the present study was to identify and disentangle the potential effects of cue availability and cue status on residual switch costs, which might lead to a refined explanation of the results reported by Verbruggen et al. (2007). However, Experiments 1–4 showed that residual switch costs were not modulated consistently by cue status or cue availability. Given these findings, as well as general concerns about reproducibility in psychological science (Open Science Collaboration, 2015) and low direct-replication rates (Makel, Plucker, & Hegarty, 2012), it seemed prudent to assess the robustness of Verbruggen and colleagues' results by replicating one of their experiments.

Experiment 5 replicated the method used in Experiment 2 of Verbruggen et al. (2007). In the letter-cue version of their experiment, arbitrary letters cued odd–even and small–large judgments of target digits. There were two cuing conditions (full-present and partial-absent, using my terminology) and two CTIs (192 and 1,472 ms), with the cue presented for the first 96 ms of the CTI and then masked in the partial-absent condition. A response deadline of 1,920 ms was imposed on each trial, and the instructions emphasized fast and accurate responding, supplemented by end-of-block feedback about errors and mean RT. Verbruggen and colleagues reported a significant residual switch cost of 56 ms in the full-present condition and a nonsignificant residual switch cost of 16 ms in the partial-absent condition, resulting in a significant interaction between cuing condition and transition. They did not obtain any significant residual switch costs for error rates.

I chose to replicate Experiment 2 from Verbruggen et al. (2007) for three reasons. First, full-present and partial-absent conditions occurred equally often in a within-subjects design in their Experiment 2, whereas they occurred in unequal proportions in their Experiment 1 and in a between-subjects design in their Experiment 4. The equal-proportion, within-subjects design of their Experiment 2 is consistent with the designs of my Experiments 3 and 4. Second, they used one cue presentation time in the partial-absent condition and two CTIs in their Experiment 2, but two cue presentation times in their Experiment 1 and four CTIs in their Experiments 3 and 4. The simpler design of their Experiment 2 might facilitate finding a difference between cuing conditions. Third, the data pattern may have been more stable in their Experiment 2, because it was based on a larger sample size (37 subjects) than those obtained in their Experiments 1 and 3 (15 and 17 subjects, respectively).

Following the methodological details reported by Verbruggen et al. (2007), my Experiment 5 was designed to replicate their Experiment 2 as closely as possible, with one notable exception: They also included a between-subjects manipulation of cue type (arbitrary letters or arbitrary colored plus signs), but found no effects of cue type on the residual switch costs; therefore, I used only their arbitrary letter cues, to establish continuity with my Experiment 4. Due to computer hardware and software differences, there were small discrepancies in the cue presentation times in the partial-absent condition (100 ms vs. the original 96 ms), short CTIs (200 vs. 192 ms), and long CTIs (1,500 vs. 1,472 ms). Due to population and language differences, my subjects were recruited from an American university and instructed in English, whereas their subjects were recruited from a Belgian university and instructed in Dutch. Aside from these differences, my Experiment 5 was a direct replication of their Experiment 2. The question of interest was whether the residual switch cost for RTs would be smaller in the partial-absent condition than in the full-present condition, as was originally found.

Method

Subjects A total of 49 students from Purdue University participated for course credit. None of them had participated in Experiments 1–4. The targeted sample size of 48 was exceeded because an extra subject was available on the last day of data collection.

Apparatus, tasks, stimuli, and responses The apparatus and tasks were identical to those of Experiments 1–4. The stimuli and responses were identical to those used in the letter condition of Experiment 2 in Verbruggen et al. (2007). Stimuli were displayed in white Courier font that matched the onscreen sizes reported for the original experiment. The odd–even task was cued by the letters *WW*, and the small–large task was cued by the letters *ZZ*. Responses were made by pressing the "V" and "N" keys with the left and right index fingers, respectively. For all subjects, the odd and small categories were mapped to the "V" key, and the even and large categories were mapped to the "N" key.

Procedure Except for the small timing differences noted earlier, the procedure was identical to that used in the letter condition of Experiment 2 in Verbruggen et al. (2007). Instructions were presented onscreen and read aloud by the experimenter. I did not have the original instructions, but my instructions included all details noted explicitly by Verbruggen and colleagues. In particular, subjects received instructions about (a) the differences between the cuing conditions; (b) paying full attention to the cue letters and processing them as soon as they appeared, so that subjects would know which task to do when the target digit appeared; (c) responding quickly and accurately; (d) the response deadline of 1,920 ms and the consequences of not responding in time; and (e) the end-of-block feedback about errors and mean RT. Following the instructions, subjects completed one practice block of 64 trials and then five experimental blocks of 64 trials per block.

Each trial started with a blank screen for 1,500 ms, followed by a fixation display for 500 ms. The fixation display consisted of the letters *XX* presented to the left and right of the center of the screen. Cue letters then replaced the fixation signs. In the full-present condition, the cue was visible for the full CTI and remained present after target onset. In the partial-absent condition, the cue was replaced by the fixation signs (which served as masking stimuli) after 100 ms, remaining absent for the rest of the CTI and after target onset. After the CTI of 200 or 1,500 ms, the target appeared in the center of the screen between the cue letters (full-present condition) or the fixation signs (partial-absent condition). The stimuli (cue/fixation and target) remained onscreen until the subject had responded or until a response deadline of 1,920 ms had elapsed. The next trial commenced immediately thereafter, except in the practice block, in which immediate feedback was provided in the center of the screen (displayed below the stimuli) for 500 ms, based on how the subject responded. The word "wrong" was the feedback following an error; the words "respond faster" were the feedback following no response before the deadline; and no feedback followed a correct response before the deadline. At the end of every block, a feedback display appeared for 15 s and indicated the number of errors and the mean RT for the just-completed block. If the error rate exceeded 10 %, an additional message instructed subjects to try to make fewer errors. If the mean RT was longer than 1,250 ms, an additional message instructed subjects to try to respond faster.

The cue, CTI, cuing condition, and target were selected randomly on each trial, subject to the constraint that all possible combinations occurred equally often in each block. Consequently, the cuing conditions occurred equally often in random order, and approximately half of the trials (51 % averaged across subjects) were task switches.

Results

The first trial of each experimental block was excluded from the analysis. Following Verbruggen et al. (2007), error trials and trials immediately following errors were excluded from the RT analyses. Given that the response deadline prevented very long RTs, no data trimming for RT outliers was required. Nonresponses due to missing the deadline were classified as errors, but the error data pattern was similar when nonresponses were excluded from the analysis. The mean RT and error rate were calculated for each subject in each cell of the 2 (Cuing Condition: full-present or partial-absent) × 2 (Transition: task switch or task repetition) × 2 (CTI: 200 or 1,500 ms) experiment design. Full analyses involving all levels of all factors are reported in the Appendix. Restricted analyses involving the data only for the long CTI are reported in the main text. The ANOVA results for all analyses are summarized in Table 5, residual switch costs are plotted in Fig. 1, and the mean RTs and error rates for all conditions are presented in Fig. 5.

Residual switch costs were obtained for RTs (26 ms) and error rates (2.0 %), resulting in significant main effects of transition (see Table 5). However, the residual switch costs did not differ reliably between the full-present and partial-absent conditions, as indicated by nonsignificant interactions between cuing condition and transition.[3] Moreover, the numerical differences were in the opposite direction of what Verbruggen et al. (2007) found: As is shown in Fig. 1, the residual switch costs were numerically larger in the partial-absent condition (36 ms for RTs and 2.8 % for error rates)

[3] If nonresponses were excluded instead of classified as errors, then the interaction between cuing condition and transition became significant for error rates (see Table 5). However, the interaction reflected a larger residual switch cost in the partial-absent condition (2.8 %) than in the full-present condition (0.8 %).

Table 5 Summary of ANOVAs for Experiment 5

	Full Analyses						Restricted Analyses					
	Response Time			Error Rate			Response Time			Error Rate		
Effect	$F(1, 48)$	MSE	η_p^2	$F(1, 48)$	MSE	η_p^2	$F(1, 48)$	MSE	η_p^2	$F(1, 48)$	MSE	η_p^2
Cuing condition (C)	37.20*	3,609	.44	9.23*	54	.16	0.15	2,629	<.01	6.50*	39	.12
Transition (T)	87.75*	3,748	.65	37.25*	22	.44	11.94*	2,726	.20	11.77*	16	.20
Cue–target interval (I)	595.63*	8,420	.93	67.65*	22	.59						
C × T	0.38	2,501	.01	1.08	17	.02	1.85	2,659	.04	3.37†	11	.07
C × I	54.18*	2,873	.53	0.00	15	<.01						
T × I	29.52*	3,434	.38	3.73	20	.07						
C × T × I	5.38*	3,148	.10	0.80	22	.02						

* $p < .05$. † Effect becomes significant ($p < .05$) if nonresponses are excluded instead of classified as errors

than in the full-present condition (16 ms and 1.1 %). The only significant effect involving cuing condition was a main effect on error rates, reflecting a higher error rate in the partial-absent condition (6.4 %) than in the full-present condition (4.1 %; see Fig. 5).

Discussion

Overall performance was better and switch costs were generally smaller with the longer CTI (see Fig. 5 and the Appendix), indicating that subjects engaged in preparatory processing during the CTI. However, significant residual switch costs were obtained for both RTs and error rates (see Fig. 1 and Table 5), and they did not differ reliably between the full-present and partial-absent conditions (but see note 3). Critically, the residual switch cost of 36 ms for RTs in the partial-absent condition was a highly significant, medium-sized effect: $t(48) = 3.38$, $SE = 11$, $p = .001$, $d = 0.48$. This finding contrasts with the nonsignificant residual switch cost for RTs observed in the same condition in Experiment 2 of Verbruggen et al. (2007). Moreover, the residual switch costs were numerically larger in the partial-absent condition than in the full-present condition for RTs and error rates in Experiment 5, opposite the RT pattern observed by Verbruggen and colleagues. The RT pattern in Experiment 5 resembles that of Experiment 4, whereas the error pattern in Experiment 5 resembles that of Experiment 3 (see Fig. 1). Thus, the results of Experiment 5 add to the mixed results of Experiments 3 and 4, and suggest that the findings of Verbruggen and colleagues may not be as robust as was previously thought (cf. Vandierendonck et al., 2010).

General discussion

In the present study, I investigated a method previously shown to reduce residual switch costs in cued task switching. Verbruggen et al. (2007) showed that briefly presenting the cue during the CTI and leaving it absent after target onset yielded smaller residual switch costs than those obtained when the cue was available for the full CTI and remained present after target onset. Taking their results at face value, I was interested in disentangling the potential effects of cue availability during the CTI (full or partial) and cue status after target onset (present or absent) on residual switch costs.

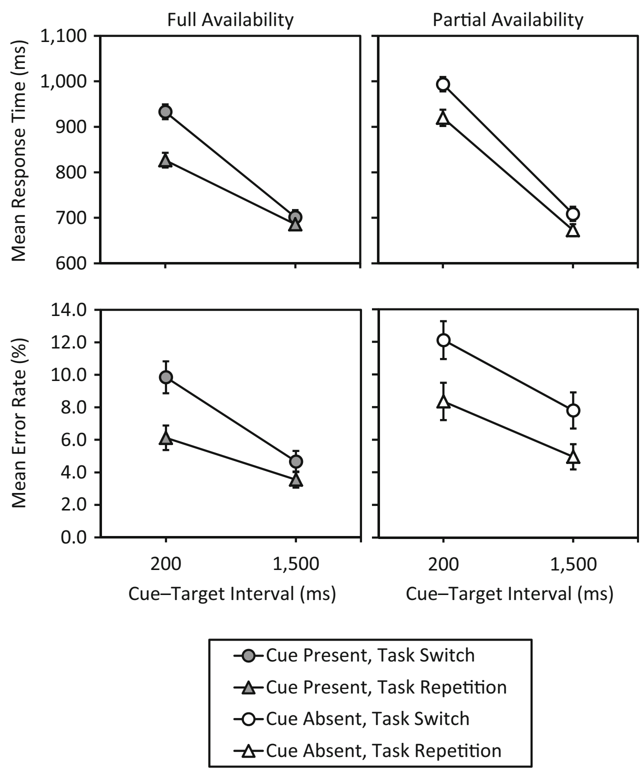

Fig. 5 Mean response times and error rates as a function of cue availability (full or partial), cue status (present or absent), transition (task switch or task repetition), and cue–target interval in Experiment 5. Error bars represent standard errors of the means. Note that the y-axis scales differ from those in Figs. 2, 3, and 4, due to differences in overall performance levels

In Experiments 1 and 2, I manipulated cue status either within or between subjects, while holding cue availability constant (the cue was always available for the full CTI). Residual switch costs were obtained, but they did not differ reliably between the cue-present and cue-absent conditions. In Experiments 3 and 4, I factorially manipulated both cue status and cue availability to distinguish between their effects and to replicate the two cuing conditions assessed by Verbruggen et al. (2007). Residual switch costs were again obtained, but they were not modulated consistently by cue status or cue availability. In Experiment 5, I replicated the method used in one of Verbruggen and colleagues' experiments, which afforded a comparison between full-present and partial-absent conditions. Residual switch costs were obtained, but they were numerically larger in the partial-absent condition than in the full-present condition, contrary to the original finding. Collectively, the results of Experiments 1–5 indicate that manipulations of cue status after target onset and cue availability during the CTI do not consistently reduce or eliminate residual switch costs (see Fig. 1).

Even though residual switch costs were not modulated consistently by cue status or cue availability, it is worth noting the findings that were consistent across the experiments. The first consistent finding was that overall residual switch costs were obtained for both RTs and error rates in all experiments (see Fig. 1 and Tables 1, 2, 3, 4, and 5). This is important because the residual switch costs on RTs had been small in the previous studies in which cue status had been investigated (Gotler & Meiran, 2001; Proctor et al., 2008), leaving little room to observe any differences between conditions, and they were nonsignificant across cuing conditions in Experiment 3 of Verbruggen et al. (2007). Moreover, residual switch costs have not been found routinely for error rates in previous studies addressing cue status or cue availability. For example, such effects were nonsignificant in the experiments of Verbruggen and colleagues in which residual switch costs for RTs differed significantly between cuing conditions. It seems reasonable to conclude that my experimental methods were suitable for consistently producing residual switch costs for RTs and error rates. What was less consistent was the modulation of those costs by manipulations of cue status and cue availability.

The second consistent finding was that the CTI manipulation often produced large effects on RTs and error rates across experiments (see Figs. 2, 3, 4, and 5, Tables 1, 2, 3, 4, and 5, and the Appendix). In general, RTs were shorter and error rates were smaller at the longer CTI, and in many cases there were also decreases in switch costs. This is important because it indicates that the sizable residual switch costs obtained in the present study were not due to subjects never engaging in preparatory processing during the CTI. Moreover, the effects of cue availability observed in Experiments 3 and 4 indicate that subjects were sensitive to the removal of the cue during the CTI, which would be possible only if they were processing the cue in advance of the target. Thus, although the residual switch costs may reflect occasional failures to engage in preparation (De Jong, 2000), they were obtained in contexts in which some preparation did occur.

The present results fit with some previous findings, but not with others. The results of Experiments 1 and 2, in which residual switch costs were not modulated by the isolated manipulation of cue status, replicate the findings of Gotler and Meiran (2001) and Proctor et al. (2008), but with larger residual switch costs and larger sample sizes. Those results also fit with some research addressing the potential effect of cue status on lag-2 repetition costs in task switching. When switching among three tasks (denoted A, B, and C), performance tends to be worse for lag-2 repetitions (e.g., ABA) than for lag-2 switches (e.g., CBA). This lag-2 repetition cost is thought to reflect task set inhibition (Mayr & Keele, 2000; for a review, see Koch, Gade, Schuch, & Philipp, 2010). Druey and Hübner (2007) manipulated cue status and found that lag-2 repetition costs were smaller when the cue was absent than when it was present after target onset. However, in follow-up experiments that included a direct replication, Grange and Houghton (2009) found no such effect of cue status on lag-2 repetition costs, mirroring the findings for residual switch costs in Experiments 1 and 2.

The results of Experiments 3–5 do not replicate the findings of Verbruggen et al. (2007). Experiments 3 and 4 included the two cuing conditions (full-present and partial-absent) assessed by Verbruggen and colleagues, but they occurred in the context of two other cuing conditions (full-absent and partial-present). My Experiment 5 was a direct replication of their Experiment 2 and included only the full-present and partial-absent conditions, mitigating any concerns about context effects and other methodological differences between the studies. Figure 1 shows that the residual switch costs on RTs and error rates were not consistently smaller in the partial-absent condition than in the full-present condition. A combined analysis of the data from Experiments 3–5 revealed a nonsignificant difference in residual switch costs (full-present minus partial-absent) for RTs of –5 ms, $t(144) = 0.32$, $SE = 15$, $p = .75$, $d = 0.03$, 95 % confidence interval (CI) [–34, 25]. There was a significant difference in error rates of –1.3 %, $t(144) = 2.22$, $SE = 0.57$, $p = .03$, $d = 0.18$, 95 % CI [–2.4, –0.1]. Note that this effect reflects a larger residual switch cost in the partial-absent condition than in the full-present condition (opposite the RT effect observed by Verbruggen et al., 2007), largely driven by the data from Experiments 3 and 5.

The pattern of residual switch costs across experiments (see Fig. 1) suggests that cue availability during the CTI (full or partial) may be more important than cue status after target onset (present or absent). The effect of manipulating cue availability could vary with cue type, which might help explain the differences in residual switch costs for RTs when Experiment 3 is compared with Experiments 4 and 5. More specifically, the limited time provided for initial cue processing (with the cue visible) in the partial-availability conditions may have affected encoding of the long word cues used in Experiment 3 (*odd–even* and *small–large*), but not the short letter cues used in Experiments 4 (*C* and *U*) and 5 (*WW* and *ZZ*). The cues differed not only perceptually (in terms of length), but also conceptually (words vs. letters), and recent research has indicated that cue encoding has distinct perceptual and conceptual components (Schneider, 2016). The way in which these differences may have resulted in the empirical pattern of residual switch costs remains unclear, but subsequent manipulations of cue type might shed light on this matter. In addition, it might be useful to manipulate the time that the cue is partially available for initial processing during a long CTI. Verbruggen et al. (2007) compared two very short cue presentation times (64 and 128 ms) in their Experiment 1 and found no differences in performance, but greater temporal separation (e.g., 100 vs. 500 ms) could have more pronounced effects, especially if cue encoding is prolonged for more complex cues.

If briefly presenting the cue during the CTI and leaving it absent after target onset is to be investigated further as a potential method for reducing residual switch costs, then critical aspects of the method will need to be identified and manipulated in future research (e.g., cue type and cue presentation time). The novel design of Experiments 3 and 4, which allowed me to disentangle the potential effects of cue availability and cue status, may prove useful in such an endeavor. Going beyond methodological issues, the present results draw attention to the importance of attempting to independently replicate findings in multiple experiments with adequate sample sizes, not just in the task-switching domain, but in psychological research more generally (Klein et al., 2014; Open Science Collaboration, 2015).

The present study has two important implications for understanding task switching. The first is that the residual switch cost does seem to reflect a strong limitation on the ability to prepare for a task switch. Previous efforts to reduce residual switch costs have yielded modest success (Lien et al., 2005; Meiran & Chorev, 2005; Nieuwenhuis & Monsell, 2002; cf. Verbruggen et al., 2007), perhaps because it is difficult for the cognitive system to frequently and fully engage in the requisite preparatory processing during the CTI that would eliminate residual switch costs (De Jong, 2000; Poboka, Karayanidis, & Heathcote, 2014). If a mechanistic basis for this limitation can be implemented in a model of task switching, then it may be possible to devise methods to improve task-switching performance. Although residual switch costs have received some attention in past modeling work (e.g., Altmann & Gray, 2008; Meiran, 2000; Schneider & Logan, 2005), there is a paucity of model-inspired methods for reducing the costs.

The second implication is that the cognitive system is capable of fast and accurate task switching (residual switch costs notwithstanding), even with limited access to cue information in the environment. Consider the partial-absent conditions in Experiments 3–5, in which the cue was externally available for only 100 ms near the start of a trial. Evidently, on most trials, subjects were able to sufficiently encode the cue during its brief presentation to produce an internal representation in memory that guided subsequent cognitive processes, such as an exogenous process of task set reconfiguration (Rogers & Monsell, 1995). The way in which processing based on memory of the cue might produce residual switch costs is open to debate. One possibility is that the residual switch costs observed for RTs and error rates in the present study might arise from a stochastic decision-making process that uses the cue representation in memory to select a task representation, such as a goal (Rubinstein, Meyer, & Evans, 2001), mediator (Logan & Schneider, 2006), or task code (Altmann & Gray, 2008). If the frequency and recency with which a task representation has been selected in the past influences the speed and accuracy of selection on subsequent trials, then task switches might be slower and more error-prone than task repetitions. Memory-based selection that occurs after the CTI has elapsed could produce a residual switch cost, regardless of whether the cue was fully or partially available during the CTI or whether it is present or absent after target onset, consistent with the results of the present study. Implementing this idea in a computational model might provide additional insight regarding the origin of the residual switch cost, which remains an important phenomenon to be explained satisfactorily by theories of task switching.

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Appendix

Experiments 1 and 2

Task switches were slower and more error-prone than task repetitions, reflecting switch costs in Experiment 1 (110 ms for RTs and 2.7 % for error rates) and in Experiment 2 (99 ms and 2.1 %), and resulting in significant main effects of transition. RTs were shorter and error rates were smaller at the longer CTI (see Fig. 2), resulting in significant main effects of CTI. Switch costs decreased with CTI in Experiment 1 (127 to 93 ms for RTs and 4.0 % to 1.4 % for error rates) and in Experiment 2 (137 to 62 ms and 2.5 % to 1.7 %), and the relevant interaction was significant in all cases except for RTs in Experiment 1 (p = .10).[4] The only significant effect

[4] A1 A combined analysis of the RT data from both experiments revealed that changes in switch costs with CTI did not differ significantly between Experiments 1 and 2.

involving cue status was a main effect on RTs in Experiment 1, reflecting slower performance in the cue-absent condition (905 ms) than in the cue-present condition (865 ms). Numerical differences in the same direction were obtained for RTs in Experiment 2 and for error rates in both experiments (see Fig. 2).

Experiments 3 and 4

Task switches were slower and more error-prone than task repetitions, reflecting switch costs in Experiment 3 (88 ms for RTs and 2.5 % for error rates) and in Experiment 4 (149 ms and 1.7 %), and resulting in significant main effects of transition. RTs were shorter at the longer CTI (see Figs. 3 and 4), resulting in significant main effects of CTI on RTs. Switch costs decreased with CTI in Experiment 3 (114 to 63 ms for RTs and 2.8 % to 2.2 % for error rates) and in Experiment 4 (187 to 110 ms and 2.2 % to 1.1 %), and the relevant interaction was significant in all cases except for error rates in Experiment 3 ($p = .20$).

In Experiment 3, performance was slower and more error-prone in the cue-absent conditions (908 ms and 5.4 %) than in the cue-present conditions (889 ms and 3.9 %), consistent with the numerical differences obtained in Experiments 1 and 2, and resulting in significant main effects of cue status. Performance was more error-prone in the partial-availability conditions (5.0 %) than in the full-availability conditions (4.4 %), resulting in a main effect of cue availability on error rates. Although there was no main effect of cue availability on RTs, this variable did interact significantly with CTI, with the partial-availability conditions being 23 ms slower than the full-availability conditions at the short CTI, but 24 ms faster at the long CTI.

Significant interactions between cue availability and cue status reflected different patterns for RTs and error rates: There was a cue-status effect on RTs in the full-availability conditions (917 vs. 881 ms for full-absent vs. full-present trials), but not in the partial-availability conditions (899 vs. 897 ms for partial-absent vs. partial-present trials), whereas there was a larger cue-status effect on error rates in the partial-availability conditions (6.2 % vs. 3.8 % for partial-absent vs. partial-present trials) than in the full-availability conditions (4.7 % vs. 4.1 % for full-absent vs. full-present trials). Significant interactions between cue availability and transition also reflected different patterns for RTs and error rates: There was a larger switch cost on RTs but a smaller switch cost on error rates in the full-availability conditions (106 ms and 1.9 %) than in the partial-availability conditions (71 ms and 3.1 %). The only remaining significant effect was an interaction between cue status and transition for error rates, reflecting a smaller switch cost in the cue-present conditions (1.9 %) than in the cue-absent conditions (3.1 %).

In Experiment 4, performance was slower and more error-prone in the partial-availability conditions (964 ms and 5.3 %) than in the full-availability conditions (933 ms and 4.8 %), resulting in significant main effects of cue availability. A significant interaction between cue availability and cue status occurred for error rates, reflecting a larger cue-status effect in the partial-availability conditions (6.1 % vs. 4.5 % for partial-absent vs. partial-present trials) than in the full-availability conditions (5.0 % vs. 4.6 % for full-absent vs. full-present trials), consistent with Experiment 3. Although the interaction between cue availability and cue status was nonsignificant for RTs ($p = .13$), a significant three-way interaction involving CTI reflected no difference in the cue availability effects (partial minus full) between cue-present and cue-absent conditions at the short CTI (both 31 ms), but a larger effect for the cue-present conditions (61 ms) than for the cue-absent conditions (1 ms) at the long CTI.

The only remaining significant effect on RTs was an interaction between cue status and transition, reflecting a larger switch cost in the cue-present conditions (166 ms) than in the cue-absent conditions (131 ms). The two remaining significant effects on error rates were three-way interactions. First, a significant interaction between cue availability, transition, and CTI reflected a smaller switch cost in the full-availability conditions (1.5 %) than in the partial-availability conditions (3.0 %) at the short CTI, but a larger switch cost in the full-availability conditions (1.4 %) than in the partial-availability conditions (0.8 %) at the long CTI. Second, a significant interaction between cue availability, cue status, and transition reflected a larger switch cost in the full-present condition (2.1 %) than in the full-absent condition (0.9 %), but a smaller switch cost in the partial-present condition (1.6 %) than in the partial-absent condition (2.2 %).

Experiment 5

Task switches were slower and more error-prone than task repetitions, reflecting switch costs (58 ms for RTs and 2.9 % for error rates) and resulting in significant main effects of transition. RTs were shorter and error rates were smaller at the longer CTI (see Fig. 5), resulting in significant main effects of CTI. Switch costs decreased with CTI (90 to 26 ms for RTs and 3.7 % to 2.0 % for error rates), and the relevant interaction was significant for RTs and nearly significant for error rates ($p = .059$).

Performance was slower and more error-prone in the partial-absent condition (824 ms and 8.3 %) than in the full-present condition (787 ms and 6.0 %), resulting in significant main effects of cuing condition. The only remaining significant effects were two interactions for RTs. First, a significant interaction between cuing condition and CTI reflected a large effect of cuing condition (partial-absent minus full-present) at the short CTI (77 ms), but not at the long CTI (–3 ms).

Second, a significant interaction between cuing condition, transition, and CTI reflected a larger decrease in switch costs with CTI in the full-present condition (106 to 16 ms) than in the partial-absent condition (74 to 36 ms).

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