Component processes underlying voluntary task selection: Separable contributions of task-set inertia and
reconfiguration

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Abstract

Most theories describing the cognitive processes underlying task switching allow for contributions of active task-set reconfiguration and task set inertia. Manipulations of the Cue-to-Stimulus-Interval (CSI) are generally thought to influence task set reconfiguration, while Response-to-Cue (RCI) manipulations are thought to influence task set inertia. However, these theories do not adequately account for voluntary task switching, because a participant can theoretically prepare for an upcoming trial at any point. We used drift diffusion models to examine the contributions of reconfiguration and task set inertia to performance in single- and double-registrant voluntary task switching. In both paradigms, RSI length moderated nondecision time, suggesting both switch-specific and general preparation prior to cue presentation. In only the double registrant paradigm, RSI length additionally moderated task set inertia and CSI length affected general (but not switch-specific) preparation. The effects of cue timing (CSI length) depended upon required response to the cue. Future work should attempt to corroborate our findings regarding switch-specific and general preparation effects of interval lengths using EEG.

Introduction

Cognitive flexibility is considered a core aspect of executive function (Diamond, 2013) and dysfunction in flexibility is implicated in a number of disorders such as autism, depression, schizophrenia and OCD (Geurts et al., 2009; Meiran et al., 2011; Nolan et al., 2004). One of the most common methods of measuring cognitive flexibility in humans are variations of task switching paradigms (Kiesel et al., 2010; Koch et al., 2010), which involve switching between two simple task sets (e.g., classification of a digit as odd or even or a letter as a vowel or consonant). Task switching studies reliably produce the finding of a reaction time (RT) switch cost, i.e., worse RTs on task switch trials compared to task repeat (Monsell, 2003; Schneider & Logan, 2009; Wylie & Allport, 2000). While theories characterizing the cognitive processes underlying switch costs differ slightly, most agree that switch costs are composed primarily of two components: *task set inertia* and *task set preparation* (Koch et al., 2018; Meiran et al., 2000; Vandierendonck et al., 2010).

Task Set Inertia and Task Set Preparation

The first support for the processes of task set inertia and task set preparation composing switch costs came from manipulations of the response-stimulus interval (RSI) and cue-stimulus interval (CSI) in cued task switching paradigms, which involve a cue that indicates which task to perform on the upcoming trial. Researchers found that by lengthening the RSI, or the time response on trial $n-1$ and stimulus onset on trial n , reduced switch costs (Allport et al., 1994; Rogers & Monsell, 1995). It was thought that manipulating this interval reduced the proactive interference on task performance stemming from previous, now irrelevant, trials. This proactive interference is known as task set inertia.

Later, Meiran (1996) developed a classical design in which the intervals between task cue and task stimulus (cue-stimulus-interval, or CSI) and the response-cue-interval (RCI) were independently manipulated. In this design, the CSI and RCI together compose the RSI (response-

stimulus-interval). Therefore, by lengthening the RCI when the CSI was shortened and shortening the RCI when CSI was lengthened, Meiran manipulated the CSI (which should affect preparation) while holding RSI constant (theoretically not affecting inertia). This manipulation also yielded a decreased RT switch cost, supporting the idea that the contributions of preparation and inertia to switch cost are separable. Notably, more recent work has complicated this interpretation by demonstrating a relationship between better preparation prior to task performance and reduced inertia during task performance (Koch & Allport, 2006; Yeung & Monsell, 2003). Therefore, even when RSI is held constant, the effect of CSI manipulations on preparation might additionally affect inertia, making the two processes difficult to separate.

Further, our understanding of the mechanism by which RSI length affects task set inertia has evolved over time; while the reduction in switch cost during cued paradigms was originally attributed to dissipation of previous task sets over time (Allport et al., 1994), more recent work has indicated the effect might be additionally (or alternatively) attributable to learned associations between stimuli on the current trial and previous task sets (Wylie & Allport, 2000) and/or temporal distinctiveness between current and previous task sets that depend upon previous trial RSI length (Grange, 2016; Grange & Cross, 2015; Horoufchin et al., 2011a, 2011b). Nonetheless, manipulations of the RSI, RCI and CSI have proven valuable tools in examining task set inertia and task set preparation in task switching.

Task Set Inertia and Task Set Preparation in Voluntary Task Switching

The contributions of inertia and preparation to task switching are even more challenging to dissociate in voluntary task switching paradigms. In contrast to cued task switching paradigms, voluntary task switching paradigms involve a cue that indicates participants are to choose which of two tasks to perform. While previous work does indicate that manipulating the RSI reduces switch cost (Arrington & Logan, 2004), it is much more difficult to discern whether the reduction is due to facilitation of preparation, reduction of inertia, or both.

Further complicating the matter, participants in voluntary paradigms can theoretically prepare for an upcoming trial during both prior to cue presentation (during the RCI) and after cue presentation (the

CSI). For this reason, some previous work has referred to the entire RSI as a ‘preparation interval’ in voluntary task switching (Arrington, 2008). While some work comparing the effects of RSI manipulations in voluntary paradigms to CSI manipulations in cued paradigms has concluded that RSI manipulations in voluntary paradigms primarily affect preparation (Yeung, 2010), this idea is difficult to test directly without assuming further similarities across different paradigms. Further, other work has indicated that RSI manipulations additionally affect bottom-up processing in voluntary task switching (Arrington, 2008), raising the possibility that *both* top-down preparation and bottom-up task set inertia are affected by the manipulation.

In addition, the degree to which cue timing within the RSI affects performance in voluntary task switching might depend upon the specifics of the paradigm. While single-registrant voluntary task switching paradigms do not require participants to actively engage with the task choice cue, double-registrant paradigms require a response to the choice cue to indicate which task was chosen.

Previous work has demonstrated that both changing the CSI while holding the RSI constant *and* changing the RSI while holding the CSI constant reduced RT switch costs in a double-registrant paradigm, suggesting that cue timing does affect performance when choice response is required (Demanet & Liefoghe, 2014); however, because participants in a purely voluntary paradigm (with no intermittent cued trials) can prepare prior to the cue, it again must be assumed whether these manipulations affect task set inertia, task set preparation, or both when relying purely on reaction time measures.

Drift Diffusion Modeling Measures Latent Variables

Drift diffusion modeling (Ratcliff, 1978) provides a way to independently quantify the contribution of task set inertia and task set preparation to RT switch costs. Drift diffusion models assume that decision making occurs by accumulating evidence from a stimulus and that decisions are made when accumulated evidence reaches a decision threshold. As such, the models yield a ‘decision threshold’ parameter, which quantifies the amount of evidence necessary for a response

to be made. This is especially important for task switching, as this parameter captures speed-accuracy tradeoffs during switches (more evidence necessary for a decision represents a greater emphasis on accuracy and vice versa; Karayanidis et al., 2009; Schmitz and Voss, 2014, 2012), allowing for this tradeoff to be controlled for when examining switch cost.

More directly relevant to switch cost theories, drift diffusion models also assume that reaction times consist of a period during which evidence is *not* being collected, known as nondecision time. Nondecision time can quantify time spent loading relevant information for task performance on switch tasks, such as working memory load representations (Maldonado et al., 2019) – in a task-switching context, the parameter should then quantify the amount of time spent loading the relevant task set. Further, nondecision times are generally longer on switches compared to repeats, a difference which is thought to quantify the additional preparation necessary for switch trials (Karayanidis et al., 2009; Schmitz & Voss, 2012, 2014).

Similarly, the rate at which evidence is collected during decision making, known as drift rate, is worse on switch trials compared to repeat trials. The difference is thought to capture a decrease in the signal-to-noise ratio during decision making, quantifying the contribution of task set inertia to switch costs (Schmitz & Voss, 2014). Crucially, these interpretations of model parameters are supported by the fact that CSI manipulations affect nondecision time (Karayanidis et al., 2009; Schmitz & Voss, 2012, 2014) and RSI manipulations affect drift rate (Schmitz & Voss, 2012), in line with predictions from previous work in cued task switching.

Drift Diffusion Modeling to Assess Preparation in Voluntary Task Switching

No previous work, however, has sought to apply drift diffusion modeling to voluntary task switching. Because it is generally difficult to dissociate task set preparation from task set inertia in voluntary paradigms, the ability of a drift diffusion model to quantify each might be especially valuable whereas analysis of switch cost RT alone would confound the two.

Examination of the nondecision time parameter might help quantify the degree to which the effect of switching tasks, as well as RSI length and cue timing, might affect the contribution of task set

preparation to switch costs. For example, if cue timing affects preparation prior to stimulus presentation, manipulating the CSI while holding the RSI constant should affect the amount of preparation needed post-stimulus presentation (nondecision time). Similarly, if participants prepare prior to cue presentation in voluntary task switching paradigms, RSI manipulations would affect nondecision time whereas they do not in cued task switching.

Further, examining the effect of RSI manipulations on drift rate during voluntary task switching might help determine the degree to which the manipulations affect task set inertia's contribution to switch costs. Equally valuable is the fact that the model quantifies both processes during task performance with independent parameters; therefore, if manipulations that improve task set preparation have a downstream effect on task set inertia (as has been suggested in cued task switching work), one would expect to see changes in both parameters.

Current paradigms

The current work seeks to examine the effects of concurrent CSI and RCI manipulations on switch cost and drift diffusion model parameters in two versions of voluntary task switching; one single registrant version (Experiment 1), which does not require a participant response to the task cue, and one double registrant version (Experiment 2), which does require a response to the task cue to indicate task choice.

Single registrant paradigms allow for more precise manipulation of the CSI and RSI; because there is no response to the task cue, CSIs in single registrant paradigms can be fixed at very short lengths. This is particularly important when examining the nondecision time parameter, as previous work in cued task switching has only consistently found longer nondecision times for task switches when CSIs were very short (Schmitz & Voss, 2012). However, because participants are not required to actively engage with the cue, it's possible that cue timing itself does not affect the way participants perform the task despite instructions to decide on the task for the upcoming trial upon cue presentation.

In contrast, double registrant paradigms require additional time within the CSI for the participant to respond to the cue; this additional time might obscure effects of switching on nondecision time. Further, because these response times naturally vary trial-to-trial, the CSI in a double registrant paradigm also varies trial-to-trial even when the interval between cue response and stimulus presentation (CRSI) is manipulated. Hence, these trial-level differences must be controlled for when examining the effects of CSI length. However, the additional engagement with the task cue might change the manner in which the timing of the cue affects preparation, supported by previous work which found an effect of CSI length on RT switch cost in a double registrant paradigm (Demanet & Liefoghe, 2014).

Hypotheses

We first aimed to examine the effects of switching on RT, drift rate and nondecision time within each interval combination - short RCI/short CSI (S/S), short RCI/long CSI (S/L), long RCI/short CSI (L/S), and long RCI/long CSI (L/L). Different combinations of RCI and CSI also enabled us to either change or hold constant the RSI (i.e., RCI + CSI). For example, the S/L and L/S combinations held RSI constant, while changing CSI. We were primarily interested in effects of RSI and CSI length, and it should be noted that some RSI conditions (S/S and L/L) contain only a single level of CSI condition; for this reason, we specified a-priori which interval pairs to compare directly rather than conduct a classical ANOVA.

For both paradigms, we predicted longer RTs in switch trials than repeat trials in all conditions. These analyses of switch effects were most important for the model parameters - because nondecision time only captures preparation that occurs after stimulus onset (during RTs), we hypothesized that longer intervals that allow for switch-specific preparation to occur entirely before stimulus onset might not yield a switch effect on nondecision time. Relatedly, we predicted a stronger effect of switching on nondecision time in the single registrant paradigm, as the CSI was shorter due to the lack of task choice response time within it.

In line with previous work, we expected a switch cost on drift rate in all conditions such that switching would lead to worse (decreased) drift rates on switches compared to repeats; while this has

been consistently reported in cued task switching (Karayanidis et al., 2009; Schmitz & Voss, 2012, 2014), the effect had never been previously examined in a voluntary paradigm.

We then aimed to examine how the effects of RSI manipulations (holding CSI constant) on preparation might affect preparation and inertia. We hypothesized that conditions with longer RSIs would yield decreased RT switch costs in both paradigms as well as a decreased effect of switching on nondecision time, quantifying preparation prior to cue presentation. We expected that this effect would be reduced in the double-registrant version, where more engagement with the cue would encourage more preparation post-cue presentation. Further, we also expected that, given previous work indicating the effects of RSI length on bottom-up processes in voluntary task switching (Arrington, 2008), RSI manipulations would additionally result in changes in the effect of switching on drift rate (quantifying task set inertia).

Importantly, there were two pairs of conditions for which RSI was manipulated and CSI was held constant. The first comparison, L/S vs. S/S, was hypothesized to yield the stronger effects of the two; the shorter CSIs meant less preparation, which should in turn mean greater inertia effects. We also examined the differences between the L/L and S/L conditions; here, we expected similar effects of longer RSIs on inertia and preparation, although we also expected that the increased preparation during the long CSI would reduce the magnitude of these effects (Koch & Allport, 2006). However, we chose to include the L/L condition in the experiment in order to make this comparison – if manipulating the RSI, even when the CSI is held long, affects nondecision time, it would lend further credence to the importance of the RCI for preparation independent of cue timing.

In sum, our experiments aim to examine the degree to which the processes of task set preparation and task set inertia account for switch costs in voluntary task switching. We also aimed to quantify the degree to which participants prepare for upcoming trials prior to cue presentation as well as the degree to which the timing of cue presentation affects preparation.

Finally, we examined whether there were any differences in these effects across single- and double-registrant paradigms.

Experiment 1 Methods

Participants

The sample consisted of undergraduate students ($n = 56$) who completed the study online for course credit. Participants in the who switched tasks on greater than 80% of trials or less than 20% of trials were removed from analyses ($n = 11$). We imposed a 60% accuracy criterion over the course of the experiment which all subjects met. Age and gender characteristics of the final sample are reported in Table 1. All study procedures were approved by the Texas A&M University Institutional Review Board.

Table 1. Demographics and Task Performance for Each Experiment.

	Experiment 1 ($n = 45$)	Experiment 2 ($n = 76$)
	<i>Demographic Information</i>	
Gender % (F/M)	66.67/33.33	65.79/34.21
Age	19.03 (1.09)	19.36 (1.57)
	<i>Task Performance</i>	
Accuracy (%)	94.50 (7.38)	94.78 (5.72)
Overall reaction time (ms)	882.28 (185.30)	863.64 (166.95)
Switch reaction time (ms)	943.32 (200.89)	950.06 (206.97)
Repeat reaction time (ms)	842.34 (181.33)	800.43 (144.13)
Switch rate (%)	42.69 (11.11)	45.66 (13.38)

Notes: Means and standard deviations are presented for age and each behavioral metric. Gender breakdown is presented as percentage females/percentage males. Behavioral data displayed are calculated after removal of reaction time outliers, post-error trials, and first trials in each block.

Paradigm

The experiment was coded in PsychoPy v. 2020.2.4 (Peirce et al., 2019), converted to javascript and hosted with Pavlovia (<https://pavlovia.org/>). Participants performed a modified version of a number Stroop task composed of a task choice and task stimulus phase. Each trial was composed of a task choice stimulus phase followed by a task stimulus phase. Task design is displayed in Figure 1.

In the task choice phase, a ‘?’ was presented in the middle of the screen. Participants were instructed to decide which of two possible tasks they chose to perform upon presentation of the stimulus. Participants were instructed to choose tasks randomly, without following a pattern, such that each task

was chosen equally often and that they chose to switch tasks and repeat tasks equally often. Participants were encouraged to pretend as though they were choosing tasks by flipping a coin in their head to reinforce the random nature of their choice. In the task stimulus phase, participants were presented with two numbers that differed in both numerical size and physical size, one number above the fixation cross and one below the fixation cross. Participants were to perform either a numerical comparison (choose the number that is numerically larger) or a physical comparison (choose the number that is physically larger). Participants indicated their response using the ‘f’, ‘v’, ‘j’ and ‘n’ keys on a keyboard, where ‘f’ or ‘j’ indicated the top number was chosen and ‘v’ or ‘n’ indicated the bottom number was chosen. The left hand keys (‘f’ and ‘v’) were mapped to one task and the right hand keys (‘j’ and ‘n’) were mapped to the other, with hand-to-task mappings counterbalanced across participants. ‘If participants responded incorrectly, a message that said ‘Error’ was displayed on the screen. If participants responded correctly, no feedback was presented.

Figure 1. Depiction of Experiment 1 paradigm. The response-cue interval (RCI) and cue-stimulus interval (CSI) compose the response-stimulus interval (RSI).

In each trial, RCI (time between task response and cue stimulus on the next trial) and CSI (time between task choice cue and task stimulus) were either short (S; 100 ms) or long (L; 1000 ms). Each combination of RCI/CSI conditions (S/S, S/L, L/S, L/L) was equally likely - average and minimum trial

numbers per participant for each condition are displayed in Table 2. Congruent trials (numerically larger number is also physically larger) and incongruent trials were also equally likely, although congruence effects were not analyzed. The full version of the task consisted of 6 blocks of 65 trials each.

Participants completed practice versions of the task prior to the full version, beginning with single tasks of practice blocks, then a shortened version of the full task. If a participant failed to reach 60% accuracy on a given portion of practice, they were required to repeat that portion of practice until the accuracy criterion was reached. Participants were given feedback after the final practice phase that displayed their task accuracy, switch rate, and percent of trials where they chose each task. If participants switched tasks on less than 20% of trials or greater than 80% of trials, they were asked to repeat that portion of practice. Similarly, if participants chose one of the tasks more than 80% of the time, they had to repeat that portion of practice. Accuracies and RTs are presented along with demographic information in Table 1.

Data preprocessing

The first trial of each block (neither a switch trial nor a repeat trial) was removed from analyses. Trials following errors were also removed from analyses to account for post-error slowing. Trials with task RTs less than 200 ms or greater than three standard deviations from the mean task RT were also removed. Finally, RTs were checked for normality visually, as a formal test of normality (such as a Shapiro-Wilk test) would be overpowered to detect small, inconsequential deviations from normality in the current sample of 34,000 trials (Ghasemi & Zahediasl, 2012). As RTs did not show a normal distribution, they were log transformed for all relevant analyses; the transformation yielded an adequately normal distribution.

Table 2. Average and minimum number of trials per participant by condition.

Paradigm	Switch/Repeat Condition	Interval Condition	Average number of trials	Min. number of trials
Single-Registrant Paradigm (Experiment 1)	Switch	S/S	29.00	11
		L/S	38.82	20
		S/L	38.98	18
		L/L	41.89	21
	Repeat	S/S	59.62	18

Double- Registrant Paradigm (Experiment 2)		L/S	48.98	13
		S/L	48.82	10
		L/L	45.13	17
	Switch	S/S	39.02	11
		L/S	41.29	20
		S/L	29.14	14
		L/L	41.55	11
	Repeat	S/S	49.05	17
		L/S	47.57	17
		S/L	49.08	11
		L/L	46.96	18

Notes: Mean and minimum number of trials by condition for each experiment after removal of reaction time outliers, post-error trials, and first trials in each block. Interval conditions are listed as response-cue interval/cue-stimulus interval for Experiment 1 and response-cue interval/choice response-stimulus interval for Experiment 2. Min. = Minimum.

RT analyses

To mirror the Bayesian hierarchical approach used in the drift diffusion model analyses, we examined log-transformed RTs using Bayesian multilevel regression via the ‘brms’ R package (Bürkner, 2017) with a random intercept for each subject. Convergence for all models was confirmed both by visually inspecting chains and by examination of $\hat{R}$ statistics (all $\hat{R}$ ’s ≤ 1.10). Regression coefficients were considered significant if their 95% credible interval (95% CI) did not contain zero, and coefficients representing the same effect across conditions were considered significantly different if their 95% CIs did not overlap.

Drift diffusion model analyses

All drift diffusion model analyses were conducted using the HDDM Python module (Wiecki et al., 2013) in Python 2.7. Responses were accuracy-coded such that a correct response was coded as 1 and an incorrect response was coded as 0. As such, the inclusion of a bias parameter in the model would assume that participants had foreknowledge of a correct response, so this parameter was fixed at 0.5 (no bias) for all subjects and conditions.

We were primarily concerned with examining how interval manipulations influenced the effect of switching on drift rate (thought to quantify task set inertia) and the effect of switching on nondecision time (thought to quantify task set reconfiguration). To allow for these comparisons, we allowed drift rate

and nondecision time to vary by levels of switch/repeat and interval combination (S/S, S/L, L/S, L/L). Because previous work indicated that switching can increase response boundary (Karayanidis et al., 2009; Schmitz & Voss, 2012), this parameter was also allowed to vary by levels of switch/repeat, although the effects of switching on this parameter were not of interest in this study. We did not allow the response boundary parameter to further vary by interval combination to avoid overfitting and because we did not have any clear hypotheses relating to possible effects of the interval conditions on this parameter.

The posterior probability that a parameter in one condition was greater than in another condition (P) was assessed by comparing the overlap of the posterior probability distributions of each parameter. Due to the one-tailed nature of these comparisons, a manipulation was considered significant when P was 97.5% or greater. However, previous work by the authors of the package (as well as the package documentation) has considered differences significant when $P > 95\%$ (Cavanagh et al., 2011, 2014); comparisons that would meet this previously established threshold, but not our more stringent threshold, are noted in the results section.

Examination of switch effects and pairwise interval comparisons

Our pattern of analyses followed the same logic for analyses of RT and analyses of model parameters. We first examined the effect of switching on RT, nondecision time and drift rate within all interval combinations in both task versions by comparing log RT, nondecision time and drift rate in switch vs. repeat trials. These analyses were meant to 1) confirm the existence of RT switch costs in all interval conditions and 2) examine the degree to which the previously established differences in model parameters between switches and repeats were present in double registrant and voluntary paradigms. Then, we examined how RT and each parameter were affected by changes in CSI and RSI by comparing the pairs of intervals outlined in the hypotheses section of the Introduction within switch and repeat trials separately. We were primarily interested in effects of RSI and CSI length, and it should be noted that some RSI conditions (S/S and L/L) contain only a single level of CSI condition; for this reason, we specified a-priori which interval pairs to compare directly rather than conduct a classical ANOVA.

Finally, we examined how the effects of switching on RT, drift rate and nondecision time were affected by changes in CSI and RSI using the same interval pair comparisons.

To quantify the effects of switching on RT, we compared the CIs of the switch regression coefficients (representing the difference in log RT between switch and repeat, or RT switch cost) in each interval condition to determine which conditions yielded significantly different effects of RT switch cost. If the CIs of the switch coefficient did not overlap between two conditions, we concluded the difference was significant.

To examine the effect of switching on each parameter, we calculated the difference in the parameter's posterior probability distribution between switch trials and repeat trials (similar to RT switch cost). To remain consistent with RT switch cost literature, we calculated each such that a positive number always meant worse performance on switch trials relative to repeat trials. For nondecision time, this meant the effect of switching on nondecision time was switch nondecision time minus repeat nondecision time, as larger nondecision times mean worse preparation; for drift rate, the effect of switching was repeat drift rate minus switch drift rate, as smaller drift rates mean worse processing. Then, we examined the differences in the effects of switching on RT, nondecision time, and drift rate across the interval comparisons of interest.

Exp 1. Results

Effects of Switching

The posterior probability distributions of the effect of switching on RT, drift rate, and nondecision time within each interval condition are depicted in Figure 2. Relevant statistics for each comparison are depicted in Tables 3 and 4. As expected, a significant RT switch cost was present in all interval combination conditions; log RT during switch trials was always larger than log RT during repeat trials.

Table 3. Reaction time measures within interval conditions for single-registrant task.

Measure	Interval (RCI/CSI)	Estimate	95% CI of estimate
Switch Trial log reaction time	S/S	6.90	(6.84, 6.96)
	L/S	6.81	(6.64, 6.77)

	S/L	6.71	(6.65, 6.77)
	L/L	6.69	(6.63, 6.75)
Repeat Trial log Reaction Time	S/S	6.69	(6.63, 6.75)
	L/S	6.60	(6.54, 6.66)
	S/L	6.62	(6.56, 6.68)
	L/L	6.64	(6.58, 6.70)
RT Switch Cost (Switch – Repeat)	S/S	0.215	(0.190, 0.240)
	L/S	0.112	(0.084, 0.130)
	S/L	0.089	(0.065, 0.112)
	L/L	0.049	(0.026, 0.072)

Notes: Positive switch costs indicate longer reaction times for switch trials. RCI = response cue-interval, CSI = cue-response interval, S = short, L = long, CI = credible interval.

There was a significant effect of switching on drift rate in the expected direction (drift rates were better on repeat trials than switch trials) in conditions with short CSIs; however, there was no significant difference between switch and repeat drift rates for the L/L condition and the difference in the S/L condition met the 95% significance threshold but not our a priori 97.5% threshold.

We hypothesized that, in line with previous work in cued task switching, nondecision times would be worse (larger) for switch trials than for repeat trials. This was only the case in the S/S condition; for both interval conditions with long RCIs, nondecision times were significantly better for switches than for repeats, suggesting that participants used the RCI to prepare more effectively for switches than for repeats.

Table 4. Switch effects on model parameters within interval conditions.

Parameter	Direction of Effect	Interval (RCI/CSI)	P of Switch Effect	Sig.
Nondecision Time	Sw > Rep	S/S	100%	*
	Rep > Sw	S/L	64.08%	
	Rep > Sw	L/S	98.86%	*
	Rep > Sw	L/L	99.31%	*
Drift Rate	Rep > Sw	S/S	99.98%	*
	Rep > Sw	S/L	90.53%	
	Rep > Sw	L/S	99.93%	*
	Rep > Sw	L/L	96.91%	#

Notes: Larger drift rates and smaller nondecision times indicate better performance. Most likely direction of effect is shown. RCI = response cue-interval, CSI = cue-response interval, S = short, L = long, CI = credible interval, Sig. = significance, * = significant at 97.5% threshold, # = significant at 95% threshold.

Figure 2. Violin plots of posterior probability distributions of single-registrant task performance and modeling parameters within each interval combination. An asterisk (*) denotes that the effect of switching was significant. RCI = response-cue interval, CSI = cue-stimulus interval.

Effects of CSI manipulation

Posterior probability distributions of RTs and model parameters across each pairwise interval comparison of interest are depicted in Figure 3. Statistics for relevant comparisons can be found in Table 2 (for RTs) and Tables 5 and 6 (for model parameters). Posterior probability distributions of RT, drift rate and nondecision time for switch and repeat trials separately are depicted in Figure 2 and can be found in Table 2 (for RTs) and Table 5 (for model parameters).

A comparison of conditions that represent different CSIs while RSI was held constant (S/L vs. L/S) revealed no effect on RT switch cost, nor any effects on RTs within switch or repeat trials individually. Further, there was no difference in either DDM parameter of interest in switch or repeat trials individually, nor did the effect of switching on either DDM parameter differ across S/L and L/S trials.

Table 5. Comparisons of single-registrant model parameters trial types across interval pairs of interest.

Parameter	Trial Type	Interval Comparison (RCI/CSI)	P of Difference	Sig.
Nondecision Time	Switch Trials	S/L < L/S	13.14%	
		S/L < S/S	100%	*
		L/L < L/S	95.84%	#

Drift Rate	Repeat Trials	S/L < L/S	80.86%	*
		S/L < S/S	100%	
		L/L < L/S	32.03%	
	Switch Trials	S/L > L/S	69.14%	
		S/L > S/S	77.66%	
		L/L > L/S	34.54%	
	Repeat Trials	S/L > L/S	7.37%	
		S/L > S/S	51.96%	
		L/L > L/S	57.96%	

Notes: Larger drift rates and smaller nondecision times indicate better performance. RCI = response cue-interval, CSI = cue-response interval, S = short, L = long, CI = credible interval, Sig. = significance, * = significant at 97.5% threshold, # = significant at 95% threshold.

Effect of RSI manipulation, CSI held short

A comparison of interval conditions that represented changes in RSI length holding CSI short (L/S vs. S/S) revealed significantly larger RT switch costs when RSIs were longer. An examination of RT within switch and repeat trials separately revealed the effect was attributable to better switch RTs for the L/S condition compared to the S/S condition; the difference in repeat RTs across the conditions was not significant.

Further, DDM analyses revealed that this reduction was attributable to modulation of switch effects on preparation; the effect of switching on nondecision time was reduced in the L/S condition compared to the S/S condition, and nondecision times in switch and repeat trials individually were better for L/S trials compared to S/S trials. There was no difference across the two interval conditions for any drift rate-related effects.

To summarize, lengthening the RSI while holding the CSI short reduced RT switch cost by improving switch trial RTs; however, modeling results revealed that this was attributable to a reduction in the difference in preparation across switch and repeat trials, but also that preparation for both trial types

was facilitated by the longer RSIs.

Figure 3. Violin plots of posterior probability distributions of single-registrant task performance and modeling parameters within switch and repeat trials across interval pairs of interest. The top row depicts switch trials, the bottom row depicts repeat trials. An asterisk (*) denotes that the effect of switching was significant. RCI = response-cue interval, CSI = cue-stimulus interval.

Effect of RSI manipulation, CSI held long

RT switch costs were unaffected when RSIs were changed but CSI was held long (L/L vs. S/L), as were RTs for switch and repeat trials individually. There was no significant difference in the effect of switching on drift rate or nondecision time between the two interval combinations, nor any differences in either parameter within repeat trials. Nondecision times were better for the L/L compared to S/L condition when the previously established 95% P criterion was used, although this difference did not reach significance at our more stringent 97.5% threshold.

Table 6. Comparisons of switch effects on single-registrant model parameters across interval pairs of interest.

Parameter	Direction of Switch Effect	Interval Comparison (RCI/CSI)	P of Difference	Sig.
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Nondecision Time	Varies	S/L < L/S	7.86%	*
		S/L < S/S	100%	
		L/L < S/L	94.09%	
Drift Rate	Repeat > Switch	S/L < L/S	91.18%	
		S/L < S/S	70.76%	
		L/L < S/L	33.40 %	

Notes: Nondecision times are larger (worse) for switches than repeats on S/S trials, but better than repeats for other interval combinations. RCI = response cue-interval, CSI = cue-response interval, S = short, L = long, CI = credible interval, Sig. = significance, * = significant at 97.5% threshold.

Exp 1. Discussion

In Experiment 1, we examined whether voluntary task switching affects DDM parameters, whether CSI and RSI length affects these parameters and RT measures, and whether the nature of these effects were comparable to previously reported effects in cued task switching.

We found effects of switching on the drift rate parameter only within conditions for which the CSI was short. This pattern is in contrast with work in cued task switching (Schmitz & Voss, 2012, 2014), which reports consistent effects of switching on drift rate across CSI. Further, while previous work in cued task switching consistently reports effects of RSI length on the difference in drift rate between switch and repeat trials (Schmitz & Voss, 2012, 2014), interval length manipulations had no effect on drift rate-related measures here.

Instead, lengthening RSIs while holding CSI short significantly reduced the effect of switching on the nondecision time parameter, as well as nondecision times for switch and repeat trials individually. This pattern suggests that, unlike in cued task switching, participants in voluntary task switching paradigms prepare for upcoming trials prior to cue presentation. Further, changing the CSI while holding the RSI constant did not affect any measures; together, these results suggest that manipulations of the RSI as a whole are important for modulation of task set preparation and task set reconfiguration in single-registrant VTS, independent of cue timing within the RSI, in line with some prior work (Yeung, 2010).

Previous work in cued task switching has reported worse nondecision times for switches than for repeats when CSIs are short, thought to index task set reconfiguration. We replicated this pattern for the shortest RSI condition (the S/S condition); however, in conditions for which the RCI was long,

participants displayed *better* nondecision times for switches than for repeats. This pattern suggests that participants actively prepare for upcoming trials during the RCI more effectively when they choose to switch tasks compared to when they choose to repeat tasks, possibly indicative of a more proactive mindset on switch trials than repeat trials (Orr & Banich, 2014; Orr & Weissman, 2011).

In sum, our results from Experiment 1 suggest that in a single registrant voluntary task switching paradigm: 1) participants prepare for the upcoming task throughout the entirety of the RSI rather than after cue presentation, 2) RSI manipulations primarily affect task set preparation rather than task set inertia, 3) the timing of cue presentation does not affect preparation, and 4) participants might choose to switch when they have prepared more effectively during the RCI.

In Experiment 2, we applied the same model to a double registrant paradigm. Here, we intended to test whether requiring a response indicating the task choice might change the way interval lengths interact with preparation when compared to a single registrant paradigm, as the required response might change the manner in which participants prepare for upcoming trials with respect to cue presentation.

Exp 2. Methods

Participants

The sample consisted of undergraduate students ($n = 114$) who completed the study in person for course credit. As in Experiment 1, participants who switched tasks on greater than 80% of trials or less than 20% of trials were removed from analyses ($n = 14$). Participants who did not reach an accuracy criterion of at least 60% were also excluded ($n = 2$). Further, some participants ($n = 22$) did not comply with task instructions and did not wait for the task choice cue to indicate their choice; because this made the cue-stimulus-interval for these participants qualitatively different from other participants, these early responder participants were removed from the sample. The process by which early responders were identified is outlined in the data preprocessing section of the Methods. Age and gender characteristics of the final sample are reported in Table 1. All study procedures were approved by the Texas A&M University Institutional Review Board.

Paradigm

Participants performed a modified version of a number Stroop task composed of a task choice and task stimulus phase as in Experiment 1. The experiment was coded in PsychoPy 3.0.7 (Peirce et al., 2019) running on 21.5" iMac computers. Each trial was composed of a task choice stimulus phase followed by a task stimulus phase. Task design is displayed in Figure 4.

In the task choice phase, a '?' was presented in the middle of the screen. Upon seeing the stimulus, participants were to indicate whether they chose to perform a numerical comparison or a physical comparison by pressing the 'd' or 'f' keys (key mappings counterbalanced across participants). Participants were instructed to choose tasks randomly using the same instructions as in Experiment 1. In the task stimulus phase, participants were presented with two numbers that differed in both numerical size and physical size, one number above the fixation cross and one below the fixation cross. Participants indicated their response using the 'j' and 'n' keys on a keyboard, where 'j' indicated the top number was chosen and 'n' indicated the bottom number was chosen. Error feedback, task practice, and task length were identical to the task in Experiment 1.

In each trial, RCI (time between task response and cue stimulus on the next trial) and CRSI (time between task choice *response* and task stimulus) were either short (S; 100 ms) or long (L; 1000 ms). Each combination of RCI/CRSI conditions (S/S, S/L, L/S, L/L) was equally likely – average and minimum trial numbers per participant for each condition are displayed in Table 2. Notably, this meant that the true CSI (time between cue stimulus presentation and task stimulus presentation; CSI) was dependent upon participants' reaction time in response to the task choice cue. As in Experiment 1, congruent trials and incongruent trials were also equally likely.

Figure 4. Depiction of Experiment 2 paradigm. The choice-response-stimulus interval (CSRI) and choice reaction time compose the cue-stimulus interval (CSI). The response-cue interval (RCI) and cue-stimulus interval (CSI) compose the response-stimulus interval (RSI).

Data preprocessing and calculation of CSI

Initial data preprocessing followed the same process as in Experiment 1. The first trial of each block (neither a switch trial nor a repeat trial) was removed from analyses. Trials following errors were also removed from analyses to account for post-error slowing. Trials with task RTs less than 200 ms or greater than three standard deviations from the mean task RT were also removed. Further, trials with choice RTs greater than 4000 ms were removed. RTs were log transformed for all relevant analyses; the transformation yielded an adequately normal distribution.

Inspection of the data revealed that some participants did not comply with task instructions and, rather than responding to the task choice cue to indicate their task choice, frequently responded prior to the task cue presentation (during the RCI) to indicate their task choice. For these participants, the RT to the task cue (choice RT) was recorded as zero, and the CSRI began immediately after the task cue was presented on the screen. Most of the participants that responded early did so frequently (13 participants responded early on greater than 20% of trials, 17 on greater than 10%). As such, the early responses

would result in a qualitatively different interval manipulation throughout the course of the experiment when compared to non-early responders, as the CSI for the subjects that did comply with instructions would contain an additional period of time (the reaction time in response to the task cue, or choice RT). We then adopted a conservative threshold for subject exclusion due to early responses – participants that responded prior to the task choice cue on greater than 1% of trials were excluded from analyses ($n = 22$) – to ensure our manipulation was comparable across the entire sample.

Unlike in the single registrant paradigm, the CSI varied depending upon the choice RT during that trial. In order to account for this when analyzing the effect of RCI/CSI combinations on task RT, we calculated the CSI on each trial (the actual interval between task cue presentation and task stimulus presentation, including choice RT) and entered it as a continuous IV regressions involving CSI-related effects. Then, we plotted the distribution of the CSI at each trial; we identified two clear peaks (see Fig. 5) representing the most frequent ‘true CSI’ values within each level of the CRSI interval manipulation (CSI of 450 ms for the short CRSI manipulation, CSI of 1350 ms for the long CSRI manipulation). These values were used as ‘short’ and ‘long’ CSI values for all participants – this was accomplished by centering CSI at each of the two values in relevant regressions. This approach allowed us to account for trial-level differences in CSI length while also examining the longer and shorter CSIs resulting from the CRSI manipulation.

Figure 5. Density plots displaying distribution of cue-stimulus interval lengths (CSI) by choice response-stimulus interval condition (CRSI). Peaks of each distribution were used as 'short' and 'long' values for CSI calculations.

RT Analyses

As in Experiment 1, all RT analyses were conducted in R version 4.0.0 (R Core Team, 2020) using Bayesian multilevel regression via the *brms* R package (Bürkner, 2017) with a random intercept for each subject. Convergence for all models was confirmed both by visually inspecting chains and by examination of $\hat{R}$ statistics (all $\hat{R}$'s ≤ 1.10).

We first generated a regression where the DV was log-transformed task RT and IVs were CSI, RCI, switch/repeat and all possible interactions. This regression was meant to examine the effect of the RSI and CSI on RT switch cost and task RT within levels of switch/repeat. We then examined the estimated log RTs for each interval combination condition (using 450 ms and 1350 ms as values for long and short CSIs) within each level of switch/repeat, as well as the difference in switch RT and repeat RT at each interval combination.

Regression coefficients were considered significant if their 95% CI did not contain zero, and coefficients representing the same effect across conditions were considered significantly different if their 95% credible intervals did not overlap.

Drift diffusion model analyses

All drift diffusion model analyses were conducted using the *HDDM* Python module (Wiecki et al., 2013) in Python 2.7. As in Experiment 1, responses were accuracy-coded such that a correct response was coded as 1 and an incorrect response was coded as 0, the bias parameter was fixed at 0.5 (no bias) for all subjects and conditions, and response boundaries were allowed to vary by switching condition but not by other IVs.

Following the same logic as in the RT analyses, we ran a hierarchical regression involving CSI, RCI, and switch/repeat along with all possible interactions as IVs; we then examined parameter estimates at each combination of RCI, CSI (using 450 ms and 1350 ms as short and long conditions), switch/repeat,

and the difference between switch and repeat trials at each interval combination. Following the same logic as in Experiment 1, an effect was considered significant when P was 97.5% or greater, but effects that met a previously established threshold of $P > 95\%$ (Cavanagh et al., 2011, 2014) are noted in the results section.

Exp. 2 Results

Effects of Switching

The posterior probability distributions of the effect of switching on RT, drift rate, and nondecision time within each interval condition are depicted in Figure 6. Relevant statistics for each comparison are depicted in Tables 7 and 8.

Table 7. Reaction time measures within interval conditions for double-registrant task.

Measure	Interval (RCI/CSI)	Estimate	95% CI of estimate
Switch Trial log reaction time	S/S	6.77	(6.72, 6.81)
	L/S	6.77	(6.72, 6.81)
	S/L	6.75	(6.70, 6.79)
	L/L	6.73	(6.69, 6.78)
Repeat Trial log Reaction Time	S/S	6.53	(6.49, 6.58)
	L/S	6.61	(6.56, 6.65)
	S/L	6.58	(6.53, 6.62)
	L/L	6.62	(6.57, 6.66)
RT Switch Cost (Switch – Repeat)	S/S	0.231	(0.209, 0.253)
	L/S	0.156	(0.139, 0.174)
	S/L	0.168	(0.155, 0.181)
	L/L	0.119	(0.105, 0.134)

Notes: Positive switch costs indicate longer reaction times for switch trials. RCI = response cue-interval, CSI = cue-response interval, S = short, L = long, CI = credible interval.

As expected, a significant RT switch cost was present in all interval combination conditions; log RT during switch trials was always larger than log RT during repeat trials. As in the single registrant paradigm, nondecision times were worse on switches than repeats only within the S/S condition. Unlike in the single registrant paradigm, nondecision times were not better for switches than repeats in any condition, suggesting that engagement with the task cue reduced the more proactive preparation on switches than repeats seen in some single-registrant conditions. As in the single-registrant paradigm, drift rates were always better for repeat trials than switch trials.

Table 8. Switch effects on double-registrant model parameters within interval conditions.

Parameter	Direction of Effect	Interval (RCI/CSI)	P of Switch Effect	Sig.
Nondecision Time	Sw > Rep	S/S	100%	*
	Sw > Rep	S/L	60.87%	
	Sw > Rep	L/S	60.62%	
	Sw > Rep	L/L	87.77%	
Drift Rate	Rep > Sw	S/S	100%	*
	Rep > Sw	S/L	100%	
	Rep > Sw	L/S	100%	
	Rep > Sw	L/L	100%	

Notes: Larger drift rates and smaller nondecision times indicate better performance. Most likely direction of effect is shown. RCI = response cue-interval, CSI = cue-response interval, S = short, L = long, CI = credible interval, Sig. = significance, * = significant at 97.5% threshold.

Figure 6. Violin plots of posterior probability distributions of double-registrant task performance and modeling parameters within each interval combination. An asterisk (*) denotes that the effect of switching was significant. RCI = response-cue interval, CSI = cue-stimulus interval.

Effect of CSI manipulation

Posterior probability distributions of RTs and model parameters across each pairwise interval comparison of interest are depicted in Figure 7. The comparison of intervals representing different CSIs but fixed RSIs (S/L vs. L/S) revealed no effect of CSI length on RT switch cost nor RT on switch and repeat trials individually. Similarly, CSI length did not modulate the switch effect on nondecision time.

Longer CSIs yielded better nondecision times for both switch and repeat trials, indicating that longer CSIs were associated with better preparation in general. These results are in contrast with the effect of the same manipulation in the single registrant paradigm in which CSI length did not affect preparation, indicating that engagement with the task cue does moderate the effect of cue timing on preparation. There were no effects of CSI length on any drift rate related measures.

Table 9. Comparisons of double-registrant model parameters within across interval pairs of interest.

Parameter	Trial Type	Interval Comparison (RCI/CSI)	P of Difference	Sig.
Nondecision Time	Switch Trials	S/L < L/S	99.75%	*
		S/L < S/S	97.47%	#
		L/L < L/S	93.36%	
	Repeat Trials	S/L < L/S	99.45%	*
		S/L < S/S	35.00%	
		L/L < L/S	97.40%	#
Drift Rate	Switch Trials	S/L > L/S	46.73%	
		S/L > S/S	20.38%	
		L/L > L/S	56.72%	
	Repeat Trials	S/L > L/S	51.23%	
		S/L < S/S	99.99%	*
		L/L < L/S	99.99%	*

Notes: Larger drift rates and smaller nondecision times indicate better performance. RCI = response cue-interval, CSI = cue-response interval, S = short, L = long, CI = credible interval, Sig. = significance, * = significant at 97.5% threshold, # = significant at 95% threshold.

Effect of RSI manipulation, CSI held short

The S/L vs. S/S comparison revealed an effect of RSI length on RT switch cost such that longer RSIs reduced switch costs; however, there was no significant difference on switch and repeat trials individually. As in the single registrant paradigm, longer RSIs resulted in a reduced effect of switching on nondecision time, indicating participants used the longer RCIs to prepare more effectively. The effect of RSI length on nondecision time for switch and repeat trials individually was not significant at the 97.5% threshold, although improvement of preparation on switch trials for longer RSIs was significant at a 95% threshold. Longer RSIs, holding CSI short, resulted in a reduction in the effect of switching on drift rate, a reduction of drift rate for repeat trials, and no effect on drift rate for switch trials; this pattern suggests that

longer RSIs reduced task set inertia by harming repeat trial performance rather than facilitating switch trial performance.

Figure 7. Violin plots of posterior probability distributions of double-registrant task performance and modeling parameters within switch and repeat trials across interval pairs of interest. The top row depicts switch trials, the bottom row depicts repeat trials. * = significant at 97.5% threshold, # = significant at 95% threshold. RCI = response-cue interval, CSI = cue-stimulus interval.

Effect of RSI manipulation, CSI held long

The L/L vs. L/S comparison revealed an effect of RSI length on RT switch cost such that longer RSIs reduced switch costs; however, there was no significant difference on switch and repeat trials individually. Here, longer RSIs did not affect nondecision time-related measures, suggesting that the longer RSIs in both conditions used for this comparison (compared to the S/S and L/S conditions) allowed for enough pre-stimulus preparation that no interval effects were visible in post-stimulus preparation (nondecision time). As in the L/S vs. S/S comparison, the L/L vs. S/L comparison revealed

longer RSIs reduced the effect of switching on drift rate, reduced drift rate for repeat trials, and did not effect on drift rate for switch trials; this pattern again suggests that longer RSIs reduced task set inertia by harming repeat trial performance rather than facilitating switch trial performance, and that this effect does not depend on CSI length.

Table 10. Comparisons of switch effects on model parameters across interval pairs of interest.

Parameter	Direction of Switch Effect	Interval Comparison (RCI/CSI)	P of Difference	Sig.
Nondecision Time	Switch > Repeat	S/L < L/S	53.65%	*
		S/L < S/S	100%	
		L/L < S/L	25.99%	
Drift Rate	Repeat > Switch	S/L < L/S	41.30%	*
		S/L < S/S	100%	
		L/L < S/L	100%	

Notes: Nondecision times are larger (worse) for switches than repeats on S/S trials, but better than repeats for other interval combinations. RCI = response cue-interval, CSI = cue-response interval, S = short, L = long, CI = credible interval, Sig. = significance, * = significant at 97.5% threshold.

Experiment 2 Discussion

In Experiment 2, we examined the effects of switching, RSI length and CSI length on performance in a double-registrant paradigm. Broadly in line with Experiment 1 and previous work in cued task switching, drift rates were better for repeats than switches. As in Experiment 1, we found that preparation was worse for switches than for repeats only in the shortest RSI condition (S/S); in contrast to Experiment 1, however, preparation did not differ between switches and repeats in any other conditions. Together, these results suggest that participants prepare more effectively for switches than repeats in single registrant, but not double registrant, paradigms, unless the RSI is very short.

However, in contrast to previous work in cued task switching, participants in the double registrant paradigm still did not display worse nondecision times for switches than repeats for short CSIs if the RCI was long. This might suggest that lengthening the RCI serves to reduce the effect of switch-specific preparation; in line with this, lengthening the RCI when CSI was held short reduced the effect of switching on nondecision time. However, the effect of the manipulation on switch-trial nondecision time alone was not significant at the 97.5% threshold ($P = 97.47\%$), although the effect is in the expected direction. In any case, this interpretation is in line with conclusions regarding the role of the RSI in

Experiment 1; in other words, our results suggest that in both paradigms, participants at least partially prepare for upcoming trials during the RCI, reducing the effect of switching on nondecision time.

However, while RSI manipulations did not affect drift rate in the single registrant paradigm, the effect of switching on drift rate was consistently reduced when RSIs increased in the double registrant paradigm. This reduction in switch effects on drift rate was attributable to worse drift rates on repeat trials when RSIs were longer. This pattern is more in line with previous work in cued task switching, both with respect to the reduction in drift rate (Schmitz & Voss, 2012, 2014) and performance on repeat rather than switch trials (Grange, 2016; Grange & Cross, 2015; Horoufchin et al., 2011a, 2011b). These results suggest the effects of RSI manipulations on inertia might be more comparable to cued paradigms in double registrant voluntary paradigms than single registrant.

Unlike in Experiment 1, changing the timing of the cue while holding RSI constant affected preparation on both switch trials and repeat trials – longer CSIs meant better preparation. This suggests that requiring participants to respond to the cue encourages participants to partially prepare after the cue, whereas cue timing did not affect performance at all when participants were not required to respond to the cue. In sum, our results suggest that *both* cue timing and RCI length modulate the effect of task set preparation on performance in double-registrant paradigms; however, cue timing seems to affect preparation generally while RCI length seems more related to the effect of switching on preparation.

General Discussion

The current study sought to dissociate the degree to which RSI and CSI manipulations modulate the contributions of task set preparation and task set inertia to switch costs in voluntary task switching. We examined both single- and double-registrant paradigms, hypothesizing that the engagement with the task cue required by double-registrant paradigms might change the degree to which cue timing (CSI) modulates these processes. Further, we examined the degree to which participants prepare for upcoming trials prior to cue presentation by examining the effects of RSI length on task set preparation during task performance, as well as the effects of RSI length on drift rate and task set inertia reported in previous cued task switching work.

Evidence for preparation during the RCI in voluntary task switching

Cued task switching work has reported worse nondecision times for switches than for repeats (thought to index the contribution of preparation to switch costs) when CSIs are short, but that this difference is reduced or eliminated when CSIs are longer (Karayanidis et al., 2009; Schmitz & Voss, 2012, 2014). Here, nondecision times were only worse for switches when the RSI was short, independent of CSI length. Further, while RSI manipulations affect drift-rate related measures in cued task switching (Schmitz & Voss, 2012), they primarily affected preparation in both voluntary paradigms (both preparation on switch/repeat trials individually and the effect of switching on preparation).

This pattern is in line with previous work, which has suggested that RSI manipulations in voluntary task switching affect preparation in a manner similar to CSI manipulations in cued task switching (Yeung, 2010). In other words, because participants in voluntary paradigms can use the entire RSI to prepare for an upcoming task (rather than just the CSI in cued paradigms), manipulating the RSI necessarily affects preparation. We found this to be true whether or not participants are required to respond to the task cue itself, indicating participants use the RCI to prepare in both single- and double-registrant voluntary paradigms.

Evidence for proactive preparation during switch trials

In the single-registrant paradigm, nondecision times were unexpectedly *better* for switches than repeats (except in the S/S condition), and these effects were rather strong. This was not the case for the double-registrant version, where nondecision times across switch and repeat trials for these same conditions were virtually identical.

This suggests that, in the single-registrant version only, participants prepare more effectively during the RSI on switches than for repeats, despite the assumed necessity of loading a new task set. This is in line with neuroimaging work that suggests switches in voluntary paradigms might indicate a more proactive strategy (Orr & Banich, 2014; Orr & Weissman, 2011). Requiring participants to respond to the task cue seemed to eliminate the preparation advantage on switches, resulting in a pattern more in line with what has been reported in cued task switching (Karayanidis et al., 2009; Schmitz & Voss, 2012).

However, the portion of our double-registrant participants that was excluded due to responses prior to the task choice cue should be noted here. While we chose to exclude these participants in order to ensure our analyses of CSI length were consistent within the sample, it is possible that these participants are systematically more likely to more proactively prepare on switches than repeats (resulting in a propensity for early choice responses). While this is an interesting question, we did not have the sample size to more closely examine this subgroup, or other individual differences.

In sum, our results indicate that the contribution of task set preparation to switch costs is qualitatively different in single-registrant paradigms compared to double-registrant or cued paradigms, likely due to a more proactive strategy during switch trials. The current work is not well-suited to examine whether switches are more likely to occur *because* of the increase in proactive preparation, or if participants actively engage in more proactive preparation because more preparation is required for switching; however, the results suggest that future work should examine this distinction further, particularly in single-registrant paradigms.

RSI effects in double-registrant VTS are similar to RSI effects in cued task switching

Prior work in cued task switching has reported that RSI manipulations modulate the effect of switching on drift rate, thought to index the contribution of task set inertia to switch costs (Schmitz & Voss, 2012). Here, we found no such effects of RSI length within the single-registrant paradigm (nor any effects on drift rate), suggesting that RSI manipulations primarily affect the contribution of preparation to switch costs in these paradigms.

However, we found consistent and robust effects of RSI length on drift rate in the double-registrant paradigm; longer RSIs, whether CSI was held short or long, resulted in a reduction of the effect of switching on drift rate, similar to the effects reported in cued task switching. Moreover, we found the effect was attributable to a reduction in repeat drift rate, rather than a facilitation in switch drift rates, with longer RSIs. These results are in line with a number of studies that have reported the same pattern in cued task switching (Grange, 2016; Grange & Cross, 2015; Horoufchin et al., 2011a, 2011b). Notably, these studies support the idea that proactive interference during task performance originates from temporal

distinctiveness between current and previous memory traces relating to task sets rather than a process of passive dissipation of task sets, and that RSI effects are additionally dependent upon similarity between current and previous RSI length.

Our results suggest that, for double-registrant paradigms only, RSI effects might be similarly attributable to temporal distinctiveness of memory traces in voluntary task switching. It is possible that the increased attention paid to the task cue in the double-registrant paradigm (due to the required response to the cue) strengthens the memory trace relating the cue to task sets; however, the current work is not well-suited to examine this. Future work might wish to explore the degree to which different choice cues and current/previous RCI length similarity moderate the effect of RSI on drift rates.

The current work, then, suggests that the effects of RSI manipulations on proactive interference in cued task switching are more comparable to RSI manipulations in double-registrant voluntary task switching than single-registrant voluntary task switching. However, RSI manipulations additionally affected preparation in both voluntary task switching paradigms.

CSI effects depend upon task design

The degree to which cue timing affected performance depended upon whether participants were required to respond to the cue to indicate their task choice. When participants were not required to respond to the cue, the timing of the cue did not affect performance in any way. However, when a task choice response was required, increasing the time between cue presentation and stimulus presentation reduced the preparation time necessary post-stimulus presentation.

Here, we suggest that the necessity of waiting for the cue to indicate task choice results in less preparation prior to the cue than in a single-registrant paradigm, although pre-cue preparation also seems to occur in both paradigms. Notably, though, the effect of cue timing still does not seem to modulate the effect of preparation on switch cost; rather, longer CSIs in the double-registrant paradigm facilitated better overall, not switch-specific, preparation.

Therefore, the current work suggests that manipulating RSI and CSI length independently within double-registrant voluntary task switching paradigms might partially dissociate the effects of switch-

specific and general preparatory processes to switch costs, which prior work has suggested are separable in cued task switching (Karayanidis et al., 2011). However, we caution that RSI manipulations additionally affected the contributions of inertia to switch costs and preparation on switches and repeats individually; therefore, our work does not suggest that RSI manipulations *only* affect switch-specific preparation in double-registrant voluntary task switching.

Limitations and Future Directions

While the current study demonstrates the strength of drift diffusion modeling in quantifying preparation time during task performance, the specific timing of preparatory processes prior to stimulus presentation must be assumed based on the effects of interval manipulations on post-stimulus preparation time. Future work should examine the effects reported here using other modalities, such as EEG, to help corroborate DDM post-stimulus findings with pre-stimulus preparatory components. In particular, replicating previous findings of separable switch-specific and general processes in cued task switching (Karayanidis et al., 2011) and examining how each might relate to the effects of RSI and CSI manipulations on nondecision time in double-registrant tasks would help corroborate the explanations proposed in the current study.

Alternatively, other variants of drift diffusion models might prove useful for more directly quantifying preparation prior to stimulus presentation; for example, attractor-state-based drift diffusion models which have been employed in cued task switching quantify stability/flexibility measures prior to task performance along with a drift diffusion process during task performance (Ueltzhöffer et al., 2015). Examining the relationship between CSI, RSI, attractor states, and post-stimulus preparation might clarify relationships between pre-stimulus behavior and the effect of interval lengths on components of switch costs. Similarly, models which more directly measure timing of task choice within the RSI (rather than solely the effects of interval lengths on switch cost components) would contribute greatly to our understanding of task processing in voluntary paradigms and might help distinguish between choice strategies within and between participants.

It is important to note that the conclusions here likely only apply to purely voluntary tasks; that is, voluntary task switching paradigms that do not include intermixed cued trials. Including cued trials increases the salience of the task cue itself which likely changes the effects of RSI and CSI lengths on these processes; future work might wish to examine these manipulations on DDM parameters and compare to the results presented here to test this idea.

Conclusions

The current work demonstrates the utility of drift diffusion modeling in voluntary task switching in quantifying contributions of task set preparation and task set inertia to switch costs. While we demonstrated a consistent contribution of task set inertia to switch costs, we found that task set preparation only negatively impacted switch costs when RSIs were very short; in a single-registrant voluntary paradigm, longer RCIs allowed participants to prepare more effectively on switch trials than repeat trials, supporting the idea of more proactive strategies during switch trials. While RCI length in voluntary task switching modulates the contribution of task set preparation to switch costs, it additionally modulates the effect of task set inertia to switch costs in double registrant paradigms. Finally, CSI length independent of RSI length affects general preparatory processes (but not switch-specific processes) only when participants were required to respond to the task choice cue.

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References

- Allport, A., Styles, E. A., & Hsieh, S. (1994). Shifting Intentional Set: Exploring the Dynamic Control of Tasks. In *Attention and Performance XV: Conscious and Unconscious Information Processing* (pp. 421–452). <https://www.researchgate.net/publication/312615987>
- Arrington, C. M. (2008). The effect of stimulus availability on task choice in voluntary task switching. *Memory and Cognition*, 36(5), 991–997. <https://doi.org/10.3758/MC.36.5.991>
- Arrington, C. M., & Logan, G. D. (2004). The cost of a voluntary task switch. *Psychological Science*, 15(9), 610–615. <https://doi.org/10.1111/j.0956-7976.2004.00728.x>
- Bürkner, P. C. (2017). brms: An R package for Bayesian multilevel models using Stan. *Journal of Statistical Software*, 80(1), 1–28. <https://doi.org/10.18637/jss.v080.i01>
- Cavanagh, J. F., Wiecki, T. V., Cohen, M. X., Figueroa, C. M., Samanta, J., Sherman, S. J., & Frank, M. J. (2011). Subthalamic nucleus stimulation reverses mediofrontal influence over decision threshold. *Nature Neuroscience*, 14(11), 1462–1467. <https://doi.org/10.1038/nn.2925>
- Cavanagh, J. F., Wiecki, T. V., Kochar, A., & Frank, M. J. (2014). Eye tracking and pupillometry are indicators of dissociable latent decision processes. *Journal of Experimental Psychology: General*, 143(4), 1476–1488. <https://doi.org/10.1037/a0035813>
- Demanet, J., & Liefoghe, B. (2014). Component processes in voluntary task switching. *Quarterly Journal of Experimental Psychology* (2006), MAY, 1–18. <https://doi.org/10.1080/17470218.2013.836232>
- Diamond, A. (2013). Executive Functions. *Annual Review of Psychology*, 64(1), 135–168. <https://doi.org/10.1146/annurev-psych-113011-143750>
- Geurts, H. M., Corbett, B., & Solomon, M. (2009). The paradox of cognitive flexibility in autism. *Trends in Cognitive Sciences*, 13(2), 74–82. <https://doi.org/10.1016/j.tics.2008.11.006>
- Ghasemi, A., & Zahediasl, S. (2012). Normality tests for statistical analysis: a guide for non-statisticians. *International Journal of Endocrinology and Metabolism*, 10(2), 486–489. <https://doi.org/10.5812/ijem.3505>

- Grange, J. A. (2016). Temporal Distinctiveness in Task Switching: Assessing the Mixture-Distribution Assumption. *Frontiers in Psychology*, 7, 251. <https://doi.org/10.3389/fpsyg.2016.00251>
- Grange, J. A., & Cross, E. (2015). Can time-based decay explain temporal distinctiveness effects in task switching? *Quarterly Journal of Experimental Psychology*, 68(1), 19–45. <https://doi.org/10.1080/17470218.2014.934696>
- Horoufchin, H., Philipp, A. M., & Koch, I. (2011a). Temporal distinctiveness and repetition benefits in task switching: Disentangling stimulus-related and response-related contributions. *Quarterly Journal of Experimental Psychology*, 64(3), 434–446. <https://doi.org/10.1080/17470218.2010.496857>
- Horoufchin, H., Philipp, A. M., & Koch, I. (2011b). The Dissipating Task-Repetition Benefit in Cued Task Switching: Task-Set Decay or Temporal Distinctiveness? *Journal of Experimental Psychology: Human Perception and Performance*, 37(2), 455–472. <https://doi.org/10.1037/a0020557>
- Karayanidis, F., Mansfield, E. L., Galloway, K. L., Smith, J. L., Provost, A., & Heathcote, A. (2009). Anticipatory reconfiguration elicited by fully and partially informative cues that validly predict a switch in task. *Cognitive, Affective and Behavioral Neuroscience*, 9(2), 202–215. <https://doi.org/10.3758/CABN.9.2.202>
- Karayanidis, F., Provost, A., Brown, S., Paton, B., & Heathcote, A. (2011). Switch-specific and general preparation map onto different ERP components in a task-switching paradigm. *Psychophysiology*, 48(4), 559–568. <https://doi.org/10.1111/j.1469-8986.2010.01115.x>
- Kiesel, A., Steinhauser, M., Wendt, M., Falkenstein, M., Jost, K., Philipp, A. M., & Koch, I. (2010). Control and interference in task switching-a review. *Psychological Bulletin*, 136(5), 849–874. <https://doi.org/10.1037/a0019842>
- Koch, I., & Allport, A. (2006). Cue-based preparation and stimulus-based priming of tasks in task switching. *Memory and Cognition*, 34(2), 433–444. <https://doi.org/10.3758/BF03193420>
- Koch, I., Gade, M., Schuch, S., & Philipp, A. M. (2010). The role of inhibition in task switching: A

- review. *Psychonomic Bulletin and Review*, 17(1), 1–14. <https://doi.org/10.3758/PBR.17.1.1>
- Koch, I., Poljac, E., Müller, H., & Kiesel, A. (2018). Cognitive structure, flexibility, and plasticity in human multitasking-an integrative review of dual-task and task-switching research. *Psychological Bulletin*, 144(6), 557–583. <https://doi.org/10.1037/bul0000144>
- Maldonado, T., Goen, J. R. M., Imburgio, M. J., Eakin, S. M., & Bernard, J. A. (2019). Single session high definition transcranial direct current stimulation to the cerebellum does not impact higher cognitive function. *PLoS ONE*, 14(10). <https://doi.org/10.1371/journal.pone.0222995>
- Meiran, N. (1996). Reconfiguration of processing mode prior to task performance. In *Journal of Experimental Psychology: Learning Memory and Cognition* (Vol. 22, Issue 6). <https://doi.org/10.1037/0278-7393.22.6.1423>
- Meiran, N., Chorev, Z., & Sapir, A. (2000). Component Processes in Task Switching. *Cognitive Psychology*, 41(3), 211–253. <https://doi.org/10.1006/cogp.2000.0736>
- Meiran, N., Diamond, G. M., Toder, D., & Nemets, B. (2011). Cognitive rigidity in unipolar depression and obsessive compulsive disorder: Examination of task switching, Stroop, working memory updating and post-conflict adaptation. *Psychiatry Research*, 185(1–2), 149–156. <https://doi.org/10.1016/j.psychres.2010.04.044>
- Monsell, S. (2003). Task switching. *Trends in Cognitive Sciences*, 7(3), 134–140. [https://doi.org/10.1016/S1364-6613\(03\)00028-7](https://doi.org/10.1016/S1364-6613(03)00028-7)
- Nolan, K. A., Bilder, R. M., Lachman, H. M., & Volavka, J. (2004). Catechol O-Methyltransferase Val158Met Polymorphism in Schizophrenia: Differential Effects of Val and Met Alleles on Cognitive Stability and Flexibility. *American Journal of Psychiatry*, 161(2), 359–361. <https://doi.org/10.1176/appi.ajp.161.2.359>
- Orr, J. M., & Banich, M. T. (2014). The neural mechanisms underlying internally and externally guided task selection. *NeuroImage*, 84, 191–205. <https://doi.org/10.1016/j.neuroimage.2013.08.047>
- Orr, J. M., & Weissman, D. H. (2011). Succumbing to bottom-up biases on task choice predicts increased switch costs in the voluntary task switching paradigm. *Frontiers in Psychology*, 2(FEB), 1–9.

<https://doi.org/10.3389/fpsyg.2011.00031>

- Peirce, J., Gray, J. R., Simpson, S., MacAskill, M., Höchenberger, R., Sogo, H., Kastman, E., & Lindeløv, J. K. (2019). PsychoPy2: Experiments in behavior made easy. *Behavior Research Methods*, 51(1), 195–203. <https://doi.org/10.3758/s13428-018-01193-y>
- R Core Team. (2020). *R: A Language and Environment for Statistical Computing*. (3.6.3). R Foundation for Statistical Computing.
- Ratcliff, R. (1978). A theory of memory retrieval. *Psychological Review*, 85(2), 59–108. <https://doi.org/10.1037/0033-295X.85.2.59>
- Rogers, R. D., & Monsell, S. (1995). Costs of a Predictable Switch Between Simple Cognitive Tasks. *Journal of Experimental Psychology: General*, 124(2), 207–231. <https://doi.org/10.1037/0096-3445.124.2.207>
- Schmitz, F., & Voss, A. (2012). Decomposing task-switching costs with the diffusion model. *Journal of Experimental Psychology: Human Perception and Performance*, 38(1), 222–250. <https://doi.org/10.1037/a0026003>
- Schmitz, F., & Voss, A. (2014). Components of task switching: A closer look at task switching and cue switching. *Acta Psychologica*, 151, 184–196. <https://doi.org/10.1016/j.actpsy.2014.06.009>
- Schneider, D. W., & Logan, G. D. (2009). Task Switching. *Encyclopedia of Neuroscience*, 9, 869–874. <https://doi.org/10.1016/B978-008045046-9.00426-5>
- Ueltzhöffer, K., Armbruster-Genç, D. J. N., & Fiebach, C. J. (2015). Stochastic Dynamics Underlying Cognitive Stability and Flexibility. *PLoS Computational Biology*, 11(6), 1004331. <https://doi.org/10.1371/journal.pcbi.1004331>
- Vandierendonck, A., Liefooghe, B., & Verbruggen, F. (2010). *Task Switching: Interplay of Reconfiguration and Interference Control*. Psychological Bulletin. <https://doi.org/10.1037/a0019791>
- Wiecki, T. V., Sofer, I., & Frank, M. J. (2013). HDDM: Hierarchical bayesian estimation of the drift-diffusion model in Python. *Frontiers in Neuroinformatics*, 7(JULY 2013), 14. <https://doi.org/10.3389/fninf.2013.00014>

- Wylie, G., & Allport, A. (2000). Task switching and the measurement of “switch costs.” In *Psychological Research* (Vol. 63, Issues 3–4). <https://doi.org/10.1007/s004269900003>
- Yeung, N. (2010). Bottom-Up Influences on Voluntary Task Switching: The Elusive Homunculus Escapes. *Journal of Experimental Psychology: Learning Memory and Cognition*, 36(2), 348–362. <https://doi.org/10.1037/a0017894>
- Yeung, N., & Monsell, S. (2003). Switching Between Tasks of Unequal Familiarity: The Role of Stimulus-Attribute and Response-Set Selection. *Journal of Experimental Psychology: Human Perception and Performance*, 29(2), 455–469. <https://doi.org/10.1037/0096-1523.29.2.455>