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-Stimulus Interval (RSI) manipulations are generally thought to influence task set inertia (i.e., proactive interference from the previous task-set). However, these theories do not adequately account for the processes underlying voluntary task selection, because a participant can theoretically prepare for an upcoming trial at any point. To this end we used drift diffusion models to examine the contributions of reconfiguration and task set inertia in 216 undergraduate students who performed either cued or voluntary task switching paradigms. In both task versions, longer CSIs allowed for better preparation on all trial types. For the voluntary condition, but not the explicit condition, longer RSIs also reduced the effect of switching on preparation when CSIs were short. Further, when given enough time to prepare, participants in the voluntary version prepared more efficiently for switches than repeats. Together, these results indicate the use of a more proactive strategy when participants chose to switch in the voluntary version. In both paradigms, RSI manipulations produced the expected effect on switch costs; however, they consistently slowed repeat performance and generally did not affect performance on switch trials. The results suggest that drift diffusion models can quantify differences in strategy across voluntary and explicit task switching as well as measure contributions of inertia and preparation to voluntary task switching performance, including identifying preparation that occurs outside of the CSI in voluntary switching. The results also suggest that reductions in switch cost caused by reduced inertia might be more related to impeding repeat performance rather than facilitating switch performance. Future work should extend the current findings with manipulations of proactive vs. reactive strategies and other manipulations of inertia.

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, Corbett, & Solomon, 2009; Meiran, Diamond, Toder, & Nemets, 2011; Nolan, Bilder, Lachman, & Volavka, 2004). One of the most common methods of measuring cognitive flexibility in humans are variations of task switching paradigms (Kiesel et al., 2010; Koch, Gade, Schuch, & Philipp, 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, 2010; 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* (c.f., Meiran et al., 2000; Vandierendonck et al., 2010).

Task Set Inertia

Task set inertia is characterized by impaired performance on switch trials, presumably due to proactive interference from a previous, now irrelevant, task set. Support for this idea comes from studies which found that increasing time between the response on trial *n-1* and stimulus onset on trial *n* (known as the response-stimulus interval, or RSI) reduces RT switch costs on trial *n* (Allport, Styles, & Hsieh, 1994; Rogers & Monsell, 1995). It is thought that increasing the RSI allows time for the previous task set to dissipate. However, this definition did not account for the fact that RSI manipulations also affected repeat trials; later theories additionally attributed inertia to learned associations between stimuli on trial *n* and irrelevant task sets from previous trials (not solely on trial *n*-1), which could explain effects on both switch and repeat trials (Wylie & Allport, 2000).

Task Set Preparation

Notably, many early studies that manipulated RSI did not account for task predictability; for paradigms in which task order is predictable (such as the landmark 1994 study by Allport), the time between trials might also be used to prepare for an upcoming task. Therefore, effects of RSI manipulations on RT in these situations could be attributed not only to a reduction in proactive interference, but to a facilitation of task set preparation. To manipulate preparation, Meiran (1996) developed a design in which 1) the task order was unpredictable and 2) 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. 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, lending the first major support to the idea that the contributions of preparation and inertia to switch cost are separable.

However, more recent work has complicated this interpretation by demonstrating a relationship between better preparation prior to task performance and reduced inertia during task performance. For example, Yeung & Monsell (Yeung & Monsell, 2003b) demonstrated that longer CSIs reduced the effects of increased inertia induced by task practice. This effect was later replicated by Koch and Allport (2006) using a different manipulation of inertia. 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.

Dissociating Task Set Inertia and Task Set Preparation

The contributions of inertia and preparation to task switching are even more challenging to dissociate as paradigms become more complex. While the studies discussed thus far focus on explicit task switching, where participants are given a cue that indicates which task to perform, research has since expanded to include voluntary task switching paradigms. In voluntary task switching experiments, participants are instead given a cue that indicates they are to choose which of two tasks to perform. While previous work does indicate that manipulating time between trials 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. Unlike in explicit task switching paradigms, participants in voluntary paradigms can theoretically prepare for an upcoming trial during both the RCI and the CSI;

therefore, the classic manipulation of these intervals first employed by Meiran (1996) cannot purport to dissociate the two processes, even when possible effects of preparation on inertia are ignored.

More recent work has applied a drift diffusion model (Ratcliff, 1978) to explicit task switching paradigms in an attempt to dissociate the contributions of task set inertia and task set preparation to 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 for non-switch tasks, such as working memory load representations (Maldonado, Goen, Imburgio, Eakin, & Bernard, 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.

No previous work, however, has sought to apply drift diffusion modeling to voluntary task switching. As mentioned earlier, it is generally difficult to dissociate task set preparation from task set inertia in voluntary paradigms, as participants can theoretically prepare for an upcoming trial at any point. The ability of a drift diffusion model to quantify each, then, might be especially valuable in voluntary task switching paradigms - the model might help quantify the degree to which RSI manipulations affect task set preparation and task set inertia individually, for example, whereas analysis of switch cost RT alone would confound the two.

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 voluntary task switching. We employed a double registrant paradigm similar to that used in previous work (Orr & Banich, 2014; Orr, Carp, & Weissman, 2012; Orr & Weissman, 2011), during which participants respond twice on each trial - once to indicate their task choice upon presentation of a choice cue, and another to indicate their task response after stimulus onset. While this type of voluntary paradigm allows for the independent manipulation of CSI and RCI in voluntary task choices, it does add an additional layer of complexity in that participants are now required to respond to more than one stimulus. In particular, the additional response might affect preparation time as participants have time to prepare for the next task prior to responding with their choice, which would complicate comparisons between the current paradigm and previous explicit task switching work that applied a drift diffusion model. To account for this, we employed a comparable double registrant explicit paradigm in a separate sample, where participants were required to press a button to confirm the task they were to perform prior to stimulus presentation. This allowed us to better isolate any effects of the voluntary component of the paradigm by comparing our conclusions across the two paradigms.

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 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 reconfiguration or preparation to occur entirely before stimulus onset might not yield a switch effect on nondecision time. Further, in the case of voluntary task switching, participants can theoretically prepare for a task at any time; therefore, it was not immediately clear that a switch effect on nondecision time would be detectable in the voluntary version at all. Finally, previous work has only consistently found longer nondecision times for task switches when preparation intervals were very short (Schmitz & Voss, 2012), so the additional time spent responding to the task cue might eliminate this difference even in the explicit version.

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 explicit 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 differ between the voluntary and explicit paradigms. As outlined above, we expected that manipulating RSI without changing CSI would affect only inertia in the explicit paradigm, but might also allow for better preparation in the voluntary paradigm as participants in the voluntary condition can theoretically prepare for upcoming trials at any time. We therefore hypothesized that conditions with longer RSIs would yield decreased RT switch costs in both paradigms as well as a decreased effect of switching on drift rate (which indexes inertia). Furthermore, we only expected an effect of switching on nondecision time (which indexes preparation) within the voluntary condition.

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. However, we also examined the differences between the L/L and S/L conditions; here, we expected similar effects of longer RSIs on inertia, although we also expected that the increased preparation during the long CSI would reduce the magnitude of these effects (Koch & Allport, 2006).

We also aimed to examine whether the effects of manipulating CSI while holding RSI constant (Meiran, 1996) on RT switch cost would be accounted for by model parameters indexing preparation, inertia, or both. To examine this, we compared the two conditions in which RSI was consistent and CSI was changed (S/L vs. L/S). We hypothesized that RT switch cost would be reduced in the S/L condition compared to the L/S condition due to the increased preparation time in the S/L condition, and that a comparison between these two conditions would yield larger differences in the nondecision time parameter than the drift rate parameter.

Finally, we compared the two conditions that manipulated both conditions (S/S vs. L/L). Here, one would expect both effects on preparation inertia. Therefore, an examination of traditional RT switch cost measures would not be able to separate the two in either paradigm. As such, we were interested in this comparison primarily from a modeling perspective, as the model should be able to quantify preparation and inertia effects independently. Because these two conditions represent the shortest and longest RSI in the experiment, we expected this comparison to yield the largest effects on inertia (and therefore drift rate), such that there would be a greater inertia effect in the shorter RSI condition (S/S) compared to the longer RSI condition (L/L). We also expected that the longer CSI would result in better preparation between the two interval conditions. Finally, we expected that the L/L condition would yield reduced RT switch cost compared to the S/S condition.

Method

Participants

The sample consisted of undergraduate students who completed the study for course credit. Participants were randomly assigned to either the explicit task condition (*n* = 116) or the voluntary task condition (*n* = 114). Participants in the voluntary condition who switched tasks on greater than 80% of trials or less than 20% of trials were removed from analyses (*n* = 14). Age and gender characteristics of the final sample, split by condition, 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 by Task Condition

	Voluntary (*n* = 100)	Explicit (*n* = 116)
	Demographic Information	
Gender % (F/M/O)	60/40/0	61.20/37.93/0.86
Age	19.42 (1.52)	19.31 (1.52)
	Task Performance	
Accuracy (%)	94.15 (7.39)	92.56 (11.98)
Overall reaction time (ms)	866.40 (177.32)	853.51 (168.64)
Switch reaction time (ms)	975.59 (220.21)	903.49 (191.81)
Repeat reaction time (ms)	818.46 (151.55)	803.90 (152.69)
Switch Rate (%)	46.56 (13.21)	N/A

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

Paradigm

Participants performed a modified version of a number Stroop task. Each trial was composed of a task cue stimulus phase followed by a task stimulus phase. Task design is displayed in Figure 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 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 'j' and 'n' keys on a keyboard, where 'j' indicated the top number was chosen and 'n' indicated the bottom number was chosen. If participants responded incorrectly, a message that said 'Error' was displayed on the screen. If participants responded correctly, no feedback was presented.

The cue stimulus phase differed by condition. In the voluntary condition, the cue stimulus was always a '?' 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

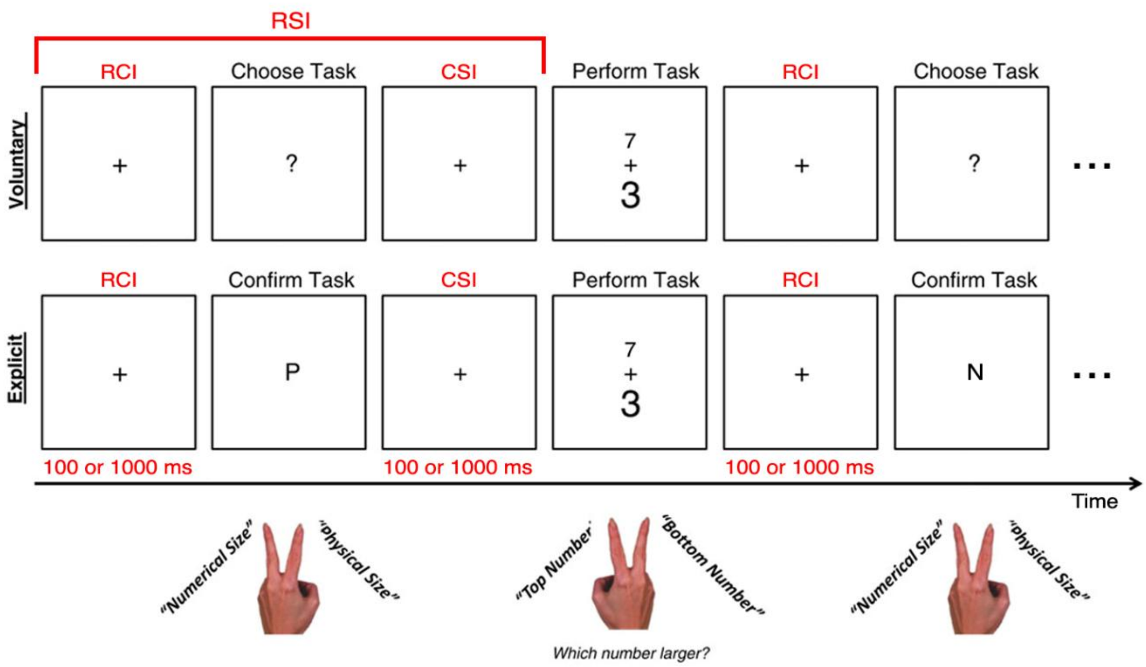

Figure 1. Depiction of task paradigms. Response-cue interval (RCI) and cue-stimulus interval (CSI) compose the response-stimulus interval (RSI).

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 explicit condition, participants were shown either an ‘N’ (indicating a numerical comparison trial) or a ‘P’ (a physical comparison trial). To ensure similarity between the conditions, participants in the explicit condition were asked to press either ‘d’ or ‘f’ (key mappings counterbalanced across participants) to confirm the task they were to perform. In both conditions, participants did not have a time limit to respond to the cue.

In both conditions, RCI (time between task response and cue stimulus on the next trial) and CSI (time between task choice response 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. Congruent trials (numerically larger number is also physically larger) and incongruent trials were also equally likely in both conditions, although congruence effects were not analyzed. In the explicit condition, switch trials and repeat trials were equally likely to occur. The full versions of both task conditions consisted of 6 blocks of 65 trials each.

Participants in both conditions completed practice versions of the task prior to the full versions, beginning with single task 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. In the voluntary condition, 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 split by condition are presented along with demographic information in Table 1.

RT Analyses

All RT analyses were conducted in R version 3.6.3 (R Core Team, 2020). 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 75,000 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.

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) using a random intercept for each subject. Explicit and voluntary conditions were examined separately, again to mirror the computational model analyses. 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 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, Sofer, & Frank, 2013) in Python 2.7. The first trial of each block was removed from analyses, as were reaction times of less than 200 ms or greater than 5000 ms (1.99% of voluntary trials and 2.00% of explicit trials). Note that we purposefully retained more upper outliers in this analysis than behavioral analyses, as the *HDDM* module allows for additional outlier trimming during model generation by specifying a percent of trials to be considered outliers.

To model our independent groups as separate populations, and to more intuitively examine effects of switching within interval conditions for each paradigm separately, independent models were generated for voluntary and explicit task paradigms. 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.

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; Cavanagh, Wiecki, Kochar, & Frank, 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.

We then examined how the effects of switching on RT, drift rate and nondecision time were affected by changes in CSI and RSI by comparing the pairs of intervals outlined in the hypotheses section of the Introduction. 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 'switch cost' on the parameter by examining the difference 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 'preparation cost' was switch nondecision time minus repeat nondecision time, as larger nondecision times mean worse preparation; for drift rate, the 'inertia cost' was repeat drift rate minus switch drift rate, as smaller drift rates mean worse processing. Then, we examined the differences in each of the three switch cost measures - RT cost, preparation cost, and inertia cost - across the interval comparisons of interest.

Results

Effects of Switching

Posterior probability distributions of the effects of switching on RT, drift rate and nondecision time in each interval combination are depicted in Figure 2. Relevant statistics for each comparison are listed in Tables 2 and 3. As expected, regressions revealed an effect of switching on RT for both paradigms in all interval conditions; log RT for switch trials was always significantly greater than log RT on repeats.

Table 2. Effects of switching on reaction time within interval conditions.

Task Condition	Interval (RCI/CSI)	Switch cost	95% CI of switch cost	Sig.
Voluntary	*S/S*	0.21	(.19, .22)	*
	S/L	0.13	(.12, .15)	*
	L/S	0.17	(.16, .19)	*
	L/L	0.11	(.09, .12)	*
Explicit	*S/S*	0.15	(.14, .17)	*
	S/L	0.11	(.10, .13)	*
	L/S	0.09	(.07, .10)	*
	L/L	0.08	(.07, .10)	*

Notes: *Switch costs are the estimated difference between log-transformed reaction times between switch and repeat trials. 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, Sig. = significance.*

Similarly, in all interval combinations in both paradigms, the posterior probability that drift rates on switches were worse than drift rates on repeats was greater than our significance threshold. Drift rates were always worse for switches than for repeats, indicating a substantial contribution of task set inertia to RT switch cost in all conditions.

For the explicit version of the task, nondecision times were not affected by switching in any interval combination, indicating that most switch-specific reconfiguration occurred prior to stimulus onset. For the voluntary version of the task, the expected effect of switching on nondecision times (longer nondecision times for switches than for repeats) was present for only the S/S interval condition, indicating a substantial contribution of increased preparation on switches to switch cost RT in this condition. For conditions in which CSIs were long (S/L and L/L), the reverse was true; nondecision times were *faster* for switches compared to repeats, possibly indicating that greater proactive control when participants decided to switch in these conditions lead to better preparation than for repeat trials (this interpretation is further supported by a reduction of preparation switch cost with lengthened preparatory intervals, analyzed below). For the L/S condition, nondecision time was equivalent for repeat and switch trials.

Table 3. Effects of switching on drift diffusion model parameters.

Task Condition	**Parameter**	**Interval (RCI/CSI)**	**Direction**	***P* of Switch Cost**	**Sig.**
Explicit	*Drift Rate*	*S/S*	Sw < Rep	100%	*
		S/L	Sw < Rep	100%	*
		L/S	Sw < Rep	99.92%	*
		L/L	Sw < Rep	99.40%	*
	Nondecision Time	*S/S*	Sw > Rep	39.43%	
		S/L	Sw > Rep	8.9%	
		L/S	Sw > Rep	50.74%	
		L/L	Sw > Rep	27.27%	
Voluntary	*Drift Rate*	*S/S*	Sw < Rep	100%	*
		S/L	Sw < Rep	100%	*
		L/S	Sw < Rep	100%	*
		L/L	Sw < Rep	100%	*
	Nondecision time	*S/S*	Sw > Rep	99.89%	*
		S/L	Sw < Rep	99.99%	*
		L/S	Sw > Rep	46.08%	
		L/L	Sw < Rep	100%	*

Notes: *Larger drift rates and smaller nondecision times indicate quicker performance. RCI = response-cue-interval, CSI = cue-response interval, S = short, L = long, Sw = switch, Rep = repeat, P = posterior probability, Sig. = significance, * = significant at 97.5% threshold.*

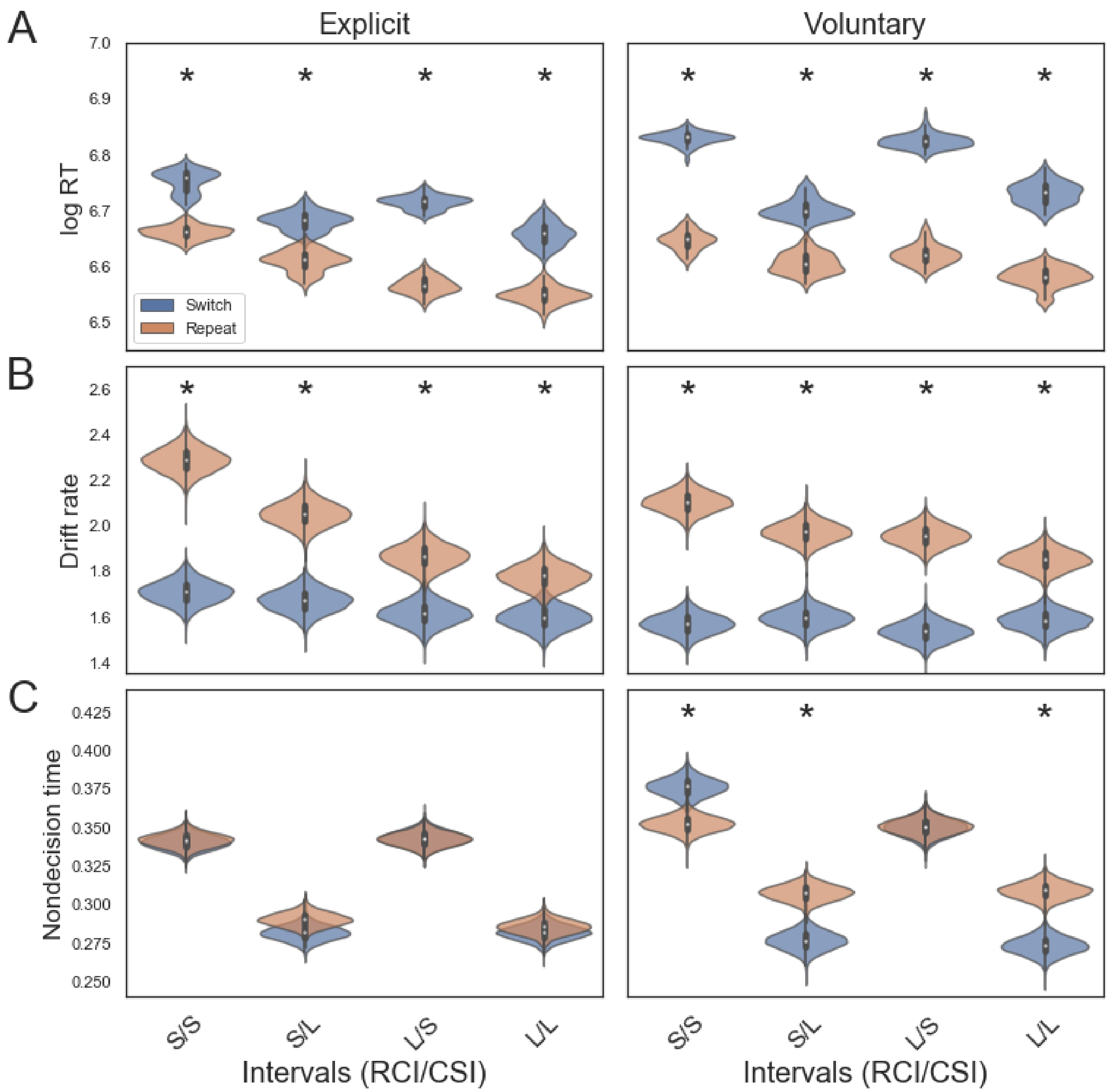

Figure 2. *Violin plots of posterior probability distributions of task performance and modeling parameters. Results from the explicit paradigm are shown in the left column, and results from the voluntary paradigm are shown in the right column. Row A depicts group estimates for log-transformed reaction times (log RT). Row B depicts posterior probability distributions of drift rates. Row C depicts posterior probability distributions of nondecision times. An asterisk (*) denotes a significant difference between switches and repeats. RCI = response-cue interval, CSI = cue-stimulus interval.*

Effects of CSI manipulation

Posterior probability distributions of RT switch costs, inertia switch costs, and preparation switch costs 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 Table 4 (for model parameters). A comparison of conditions that represent different CSIs while RSI was held constant (S/L vs. L/S) revealed a larger RT switch cost in short CSI conditions for the voluntary version of the task. The difference between switch and repeat RT was greater for the L/S condition compared to the S/L condition. As expected, this comparison yielded a significant increase in preparation switch cost for the L/S condition compared to the S/L condition, but no effect on inertia switch cost, indicating that the change in switch cost due to CSI manipulations while RSI was held constant can be attributed to changes in task set preparation rather than task set inertia in the voluntary version of the task.

For the explicit version of the task, manipulating CSI while RSI was held constant did not significantly affect switch cost RT, although the effect was in the expected direction. Comparisons across these conditions in the explicit version also did not yield significant differences in preparation switch cost or inertia switch cost, indicating that manipulating the CSI while holding the RSI constant did not affect any measure of switch cost in the current paradigm.

Table 4. Comparisons of switch effects on model parameters across interval pairs of interest.

Task Condition	**Parameter Cost**	**Interval Comparison (RCI/CSI)**	***P* of Switch Cost Difference**	Sig.
Explicit	*Inertia Cost*	*S/L < L/S*	10.56%	
		*L/*S < S/S	99.90%	*
		L/L < L/S	97.5%	#
		L/L < S/S	100%	*
	Preparation Cost	*S/L < L/S*	84.62%	
		*L/*S < S/S	41.99%	
		L/L < L/S	29.45%	
		L/L < S/S	59.58%	
Voluntary	*Inertia Cost*	*S/L < L/S*	68.40%	
		*L/*S < S/S	90.13%	
		L/L < L/S	90.38%	
		L/L < S/S	99.87%	*
	Preparation Cost	*S/L < L/S*	99.80%	*
		*L/*S < S/S	99.04%	*
		L/L < L/S	67.21%	
		L/L < S/S	100%	*

Notes: *Larger inertia costs indicate worse drift rates for switches than repeats. Larger preparation costs indicate worse nondecision times for switches than repeats. RCI = response-cue-interval, CSI = cue-response interval, S = short, L = long, Sw = switch, Rep = repeat, P = posterior probability, Sig. = significance, * = significant at 97.5% threshold, # = significant at 95% threshold.*

Effects of RSI manipulations

Increasing RSI while holding CSI constant at a short interval (L/S vs. S/S) reduced RT switch cost in the explicit condition. As expected, shorter RSIs (S/S) yielded larger RT switch costs compared to longer RSIs (L/S). As expected, model results indicated that the effect of this manipulation on switch costs was not attributable to changes in preparation switch costs but instead to a reduction of inertia switch costs with increased RSI lengths.

In the voluntary version, the effect of RSI manipulations while CSI was short also yielded the expected effect on RT switch cost such that shorter RSIs (S/S) meant larger RT switch costs than longer RSIs (L/S). However, unlike in the explicit version, model parameters in the voluntary paradigm indicated that the effect on switch cost was largely attributable to differences in preparation switch cost; The effect of increasing RSI on inertia switch cost was in the expected direction but nonsignificant, possibly due to a reduction in the effect of inertia resulting from increased preparation. Taken together, these results indicate that participants in the voluntary version used longer RSIs to prepare for the upcoming trial, while participants in the explicit condition did not. This difference across task versions was only detectable using model parameters, as the manipulation similarly affected RT switch cost in both.

While switch cost RTs were qualitatively larger for the S/L compared to the L/L condition in both the voluntary and explicit versions, the difference did not reach significance in either. Similarly, lengthening RSIs while holding CSI long did not affect preparation cost in either paradigm. Longer RSIs also did not result in a significant change in inertia switch cost for the voluntary version, although the direction of the effect was in the expected direction. In the explicit version, longer RSIs reduced inertia switch cost enough to be considered a significant change using the 95% threshold often adopted when examining Bayesian models (Cavanagh et al., 2011, 2014), but not enough to meet the 97.5% threshold adopted here. In sum, lengthening RSI while holding CSI constant at a long interval yielded reductions in switch cost and inertia in the expected directions, but not large enough to reach significance.

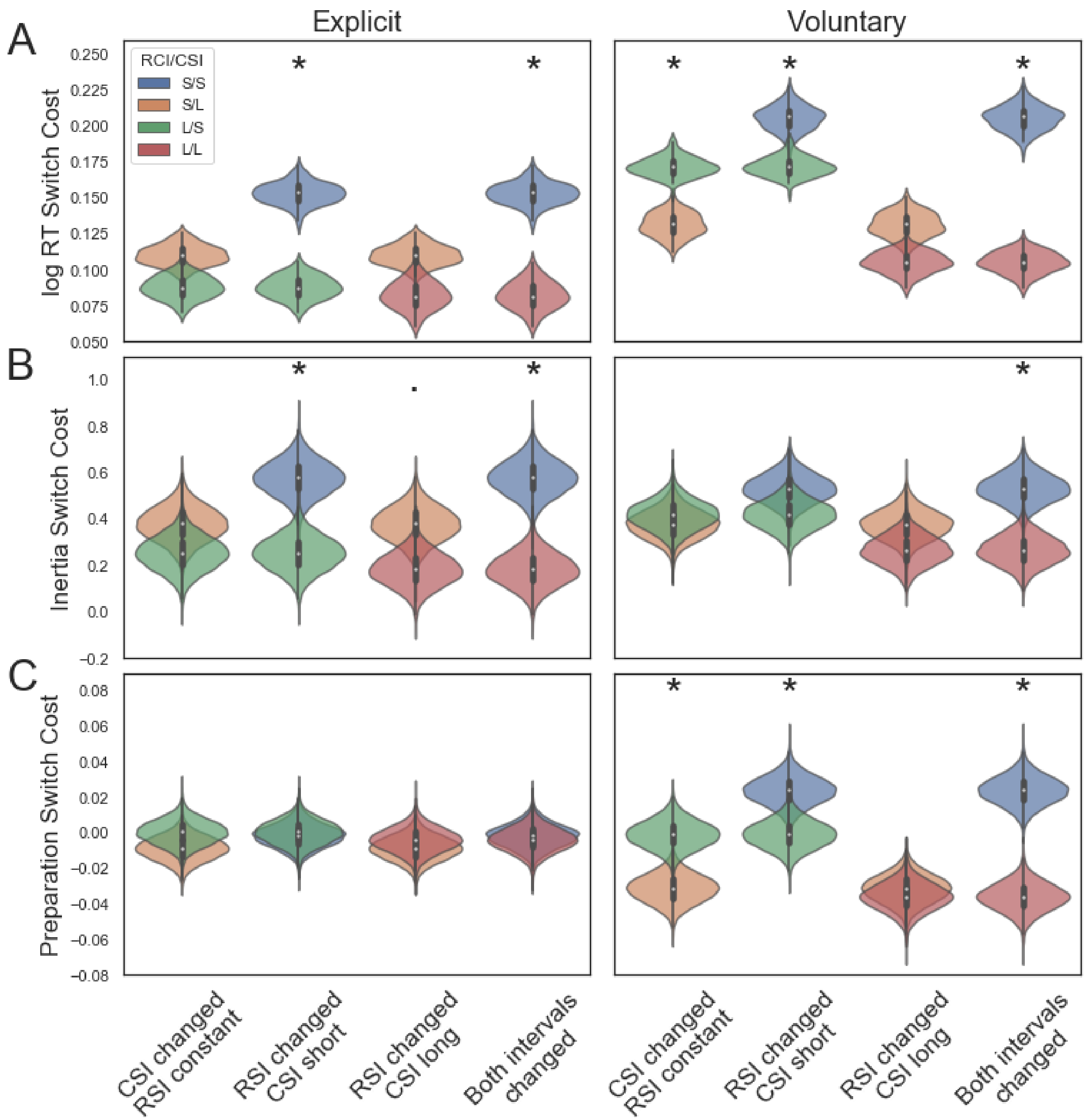

Figure 3. Effects of switching (switch cost) on reaction time, drift rate, and nondecision time across interval pairs of interest. Larger switch costs in all graphs indicate worse performance on switch trials relative to repeat trials. Asterisk (*) denotes a significant difference between the pair of interval conditions. Period (·) indicates a significant difference at a commonly used, less stringent significance threshold. Row A depicts posterior probability distributions of the difference in log-transformed reaction time between switches and repeats (log RT switch cost). Row B depicts posterior probability distributions of the difference in drift rates between switches and repeats (inertia switch cost). Row C depicts posterior probability distributions of the difference in nondecision times between switches and repeats (preparation switch cost). CSI = cue-stimulus interval, RCI = response-cue interval, RSI = response-stimulus interval.

Effects of manipulating both RSI and CSI

We expected that increasing both the RSI and the CSI (S/S vs. L/L) would reduce RT switch cost. This was true for both the voluntary and the explicit versions of the task. For the explicit version, the comparison of these intervals revealed that increasing both intervals significantly reduced inertia switch cost, but not preparation switch cost. However, in the voluntary version, increasing both intervals yielded a significant reduction in both inertia switch cost and preparation switch cost. Again, while the comparison revealed similar effects on RT switch cost across the two paradigms, model parameters revealed an effect on task preparation cost for only the voluntary paradigm.

Effects of interval manipulations within switch and repeat trials

While our hypotheses (and the majority of previous literature) were focused on the effects of interval manipulations on switch costs (the difference between switches and repeats), we subsequently noticed patterns in the data that suggested the effects of preparation and inertia manipulations affected switch and repeat trials differently. Namely, it appeared that inertia manipulations primarily affected repeat trials and not switch trials (see Fig. 1B) while preparation manipulations seemed to affect both switches and repeats (see Fig. 1C). To test these observations statistically, we conducted additional analyses examining the same pairwise interval comparisons outlined in the initial hypotheses on RTs and parameters in switch and repeat trials separately. Relevant statistics can be found in Tables 5 and 6.

Increasing CSI while holding RSI constant (S/L vs. L/S) significantly affected reaction time for both switch and repeat trials in both the voluntary and explicit versions of the task such that longer CSIs were associated with faster responses. Nondecision time also differed across the S/L and L/S conditions on both switch and repeat trials in both versions of the paradigm such that longer CSIs meant better preparation on both switches and repeats. This pattern of results suggested that longer CSIs increased preparation for all trial types, not just reconfiguration for switch trials. Drift rates were better for voluntary repeats when CSI was longer, possibly reflecting a reduction in inertia due to improved preparation, but drift rate was unaffected by the CSI manipulation in all other conditions.

Table 5. Comparisons of reaction times by trial type across interval pairs of interest.

Task Condition	Trial Type	Interval Comparison (RCI/CSI)	Log RT difference	95% CI of difference	Sig.
Voluntary	*Switch*	*S/L - L/S*	-.11	(-.12, -.09)	*
		L/S - S/S	-.01	(-.02, .01)	
		L/L - S/L	0.00	(-.02, .02)	
		L/L - S/S	-.11	(-.13, -.09)	*
	Repeat	*S/L - L/S*	-.07	(-.08, -.05)	*
		L/S - S/S	.03	(.02, .04)	*
		L/L - S/L	.03	(.02, .05)	*
		L/L - S/S	0.00	(-.02, .01)	
Explicit	*Switch*	*S/L - L/S*	-.09	(-.11, -.08)	*
		L/S - S/S	.03	(.02, .04)	*
		L/L - S/L	.03	(.02, .05)	*
		L/L - S/S	-.04	(-.05, -.02)	*
	Repeat	*S/L - L/S*	-.12	(-.13, -.10)	*
		L/S - S/S	.10	(.08, .11)	*
		L/L - S/L	.06	(.04, .07)	*
		L/L - S/S	.04	(.02, .05)	*

Notes: *RCI = response-cue-interval, CSI = cue-response interval, S = short, L = long, CI = credible interval, Sig. = significance.*

Manipulating RCI & RSI while holding CSI short (L/S vs. S/S) did not affect reaction times on switch trials in the voluntary condition, but increased reaction time for voluntary repeat trials. In the explicit version, longer RSIs resulted in a significant increase in switch RTs, but a significantly larger increase in repeat RTs. Similarly, longer RSIs holding CSI short did not affect drift rates in voluntary switch or explicit switch trials. However, lengthening RSI significantly decreased drift rates (worse performance) on repeat trials in both the voluntary and explicit versions, indicating that more time for previous task sets to dissipate harmed repeat trial performance rather than facilitating switch trial performance. Further, longer RSIs meant better preparation on voluntary switch trials, but not voluntary repeats or on either trial type in the explicit paradigm, indicating that participants in the voluntary paradigm used longer RSIs to proactively prepare for upcoming switches.

As was the case for short CSIs, increasing RSI when CSI was long resulted in no change to voluntary switch RT but an increase in voluntary repeat RT. In explicit trials, longer RSIs again increased RT during switch trials, but had a more pronounced slowing effect on repeat trials. Manipulating RSI while holding CSI long also decreased drift rates on switches for both the explicit and voluntary versions.

The RSI manipulation did not affect drift rates on switch trials, nor did it affect nondecision times in any trial type. In sum, RSI manipulations did indeed seem to affect switch costs primarily by impairing performance on repeat trials, an effect best accounted for by model parameters affected by inertia rather than preparation.

Finally, increasing both intervals significantly reduced nondecision time on all trial types as well as reduced drift rates on repeat trials in both paradigm versions, while not significantly affecting drift rates for switch trials in either; effects here were consistent with better preparation on all trial types and a selective (detrimental) effect of decreased inertia on repeats. Reaction times on switch trials were better for L/L compared to S/S trials for both the voluntary and explicit versions. While reaction times for voluntary repeats did not differ across S/S and L/L trial types, reaction times for explicit repeats were worse for L/L trials compared to S/S trials.

Table 6. Comparison of model parameters by trial type across interval pairs of interest.

Task Condition	Trial Condition	Parameter	Interval Comparison (RCI/CSI)	P of Difference	Sig.
Voluntary	*Switch*	*Drift Rate*	S/L > L/S	83.92%	
			L/S < S/S	71.82%	
			L/L < S/L	57.03%	
			L/L < S/S	41.02%	
		Nondecision Time	S/L < L/S	100%	*
			L/S < S/S	99.97%	*
			L/L < S/L	66.18%	
			L/L < S/S	100%	*
	Repeat	*Drift Rate*	S/L > L/S	62.36%	
			L/S < S/S	99.12%	*
			L/L < S/L	97.84%	*
			L/L < S/S	99.99%	*
		Nondecision time	S/L < L/S	100%	*
			L/S < S/S	58.51%	
			L/L < S/L	42.47%	
			L/L < S/S	100%	*
Explicit	*Switch*	*Drift Rate*	S/L > L/S	78.56%	
			L/S < S/S	91.10%	
			L/L < S/L	84.18%	
			L/L < S/S	94.01%	
		Nondecision Time	S/L < L/S	100%	*
			L/S < S/S	35.26 %	
			L/L < S/L	48.69%	
			L/L < S/S	100%	*
	Repeat	*Drift Rate*	S/L > L/S	99.42%	*
			L/S < S/S	100%	*
			L/L < S/L	100%	*
			L/L < S/S	100%	*
		Nondecision time	S/L < L/S	100%	*
			L/S < S/S	46.30%	
			L/L < S/L	76.76%	
			L/L < S/S	100%	*

Notes: *Larger drift rates and smaller nondecision times indicate quicker performance. RCI = response-cue-interval, CSI = cue-response interval, S = short, L = long, P = posterior probability, Sig. = significance, * = significant at 97.5% threshold.*

Discussion

The current study sought to dissociate the contributions of task set preparation and task set inertia on voluntary task switching. To this end, we tested the effects of CSI and RSI manipulations on switch cost RT as well as on drift diffusion parameters thought to index task set preparation and task set inertia. In line with hypotheses, reducing the CSI increased switch cost during a voluntary task switching paradigm, and this increase was attributable to reduced task set preparation rather than an effect on task set inertia. However, contrary to hypotheses and the previous literature, these same effects of CSI manipulations were not present in an explicit task switching paradigm. Manipulating the RSI while holding CSI short affected switch cost; however, RSI manipulations holding CSI long did not affect switch cost, also in line with hypotheses. Further, RSI manipulations were found to effect preparation in the voluntary, but not the explicit, paradigm. This pattern supports the idea that drift diffusion models might help quantify task set preparation occurring prior to task cue presentation in voluntary paradigms, which has traditionally been difficult to quantify. Finally, manipulating the RSI and CSI concurrently affected switch cost RT in both paradigms, but the effects of the manipulation on DDM parameters differed depending on the paradigm.

A series of post-hoc analyses revealed that, although CSI manipulations only affected switch cost RT in the voluntary paradigm, longer CSIs resulted in quicker reaction times for both switches and repeats in~~for~~ both paradigms. Further, this effect was associated with a facilitation of task set preparation on both paradigms, indicating that CSI manipulations might help preparation on all trials rather than having a switch-specific effect on preparation. RSI manipulations, however, primarily affected switch cost RT by slowing RT on repeat trials. The increase in RT was attributed to task set inertia for both paradigms, as well as a reduction in preparation for the voluntary paradigm – this difference in effects across paradigms was only detectable by examining DDM parameters.

Effects of switching on preparation

While switch costs were present in RT measures in all interval combinations for both versions of the task, model results indicated that the effects of switching on task set preparation differed across task conditions.

For the explicit version, there was no effect of switching on nondecision time (preparation) in any interval condition. Importantly, the drift diffusion model would only capture preparation occurring after stimulus onset. Previous work has indeed found that nondecision time does not differ between switch and repeat trials for longer RSIs (Schmitz & Voss, 2012), presumably because longer RSIs allow for the preparation time unique to explicit switches to occur prior to stimulus onset. Here, the additional requirement of having participants respond to a task cue might have exacerbated this. This examination of the difference in preparation between switches and repeats serves to highlight preparatory processes specific to switches; however, EEG studies suggest that there are two separable switch-specific preparation and general task set preparation processes (Karayanidis & Jamadar, 2015; Karayanidis et al., 2009; Karayanidis, Provost, Brown, Paton, & Heathcote, 2011). In a double registrant paradigm such as this one, switch-specific preparation might primarily occur during the CSI rather than after stimulus onset, making the switch-specific process hard to detect with a DDM of task stimulus responses. Instead, the model employed here might be better suited for quantification of a general task preparation as it occurs later. A general preparation process is better addressed by our later examinations of switch and repeat trials separately rather than the difference between the two.

For the voluntary version, the expected effects of longer preparation for switches were only present during the shortest RSI condition (S/S). It is possible that this effect was present for S/S trials for the voluntary version—but not the explicit version—due to the difference in task cue RT across the two versions. Task cue RTs were quicker on average in the voluntary version by about 100 ms on average ($p < .001$); because the CSI here was defined as the time between task cue *response* and stimulus onset, the longer RTs in the explicit version might have lengthened the time between cue presentation and stimulus presentation enough to eliminate differences in preparation detectable after the stimulus onset. This explanation is supported by previous work which has found that, in an explicit paradigm, the difference in switch vs. repeat preparation is not detectable in explicit paradigms if the time between cue and response is as short as 600 ms (Schmitz & Voss, 2012). Here, the time between cue and response onsets was longer due to the requirement to respond to task cues, meant to make the explicit and voluntary paradigms more comparable.

Interestingly, for conditions on which CSI was long, nondecision times in the voluntary paradigm were *better* for switches than for repeats. This pattern might suggest that participants are engaging in a more proactive strategy when choosing to switch compared to when choosing to repeat – when given enough time prior to stimulus onset, preparation for switches is actually more efficient than for repeats. Notably, this was not the case when participants were told which task to perform, suggesting that any relationship between a proactive mindset and switch trials specifically depends upon voluntary choice. Indeed, previous work has suggested that proactive control plays an important role in task switching behavior (Karayanidis & Jamadar, 2015; Orr & Banich, 2014). This explanation would reconcile the effects in voluntary paradigm and the lack of effects in the explicit paradigm; a more generally proactive mindset has been found to result in both more efficient switch-specific preparation *and* more efficient general task preparation (Karayanidis et al., 2011). However, the fact that switching increased nondecision time for short CSI trials in the voluntary task would suggest that the benefit of a proactive strategy is most visible when given more time to prepare before stimulus onset.

Effects of switching on task set inertia

As expected, drift diffusion models indicated a significant contribution of inertia to switch cost RT (worse drift rates for switches than repeats) in all conditions for both task versions, consistent with previous work (Karayanidis et al., 2009; Schmitz & Voss, 2012, 2014). These results suggest that, even when participants are able to prepare for switches more effectively than for repeats (as was the case in some voluntary conditions), task set inertia is not eliminated and contributes to switch cost RT.

An alternative (or perhaps additional) explanation might be that the difference in drift rates between switches and repeats quantifies more than just task set inertia. The fact that RSI manipulations consistently reduce the effect of switching on drift rates provide strong support for the idea that the effect does capture inertia. However, the presence of a residual switch cost – a switch cost RT that remains even with very long intervals between trials – is well documented, but not well-accounted for by a unified cognitive theory (Nieuwenhuis & Monsel, 2002; Verbruggen, Liefooghe, Vandierendonck, & Demanet, 2007; Whitson et al., 2014). Meanwhile, the current work – replicating previous work (Schmitz & Voss, 2012) – indicates that the effect of switching on drift rate is not entirely eliminated in any interval condition. It is possible that the persistent effect of switching on drift rate might be related to this residual switch cost rather than simply a persistent effect of task set inertia. The drift rate parameter itself is often described as a 'signal-to noise ratio during decision making' across a variety of cognitive tasks (Bogacz, Hu, Holmes, & Cohen, 2010; Maldonado et al., 2019; Sun & Landy, 2016), making it a reasonable candidate for quantifying residual switch cost in the model. Quantifying a residual switch cost with a model parameter would provide a new avenue by which to explore the residual switch cost effect. However, it might also represent a limitation of the drift diffusion model as applied here, as switch effects on drift rate could not be universally be attributed to task set inertia or a residual component. Future research should explore this possibility, perhaps through modifications of the drift diffusion model or through the use of other decision-making models that might separate the effects of inertia and a residual switch cost.

Effects of RSI manipulations

As hypothesized, increasing RSI while holding CSI short reduced switch cost RT in both versions of the task. Replicating previous work (Schmitz & Voss, 2012), the effect in the explicit version was best explained by the model by a reduction in inertia switch cost. However, as predicted for the voluntary task, modeling results indicated that participants used the longer RSIs to facilitate preparation. This pattern suggests that drift diffusion models might indeed capture task set preparation that occurs outside the preparatory interval in voluntary paradigms, which could prove useful in future work.

The RSI manipulation did not reduce inertia switch cost for the voluntary paradigm, although the results were in the expected direction – this might be due to the fact that increased preparation might have reduced the effects of inertia on switching to the point where it was no longer statistically significant. This explanation would be in line with hypotheses and previous work that found better preparation to reduce inertia in explicit task switching (Karayanidis et al., 2010; Yeung & Monsell, 2003a). Similarly, for long preparatory intervals, there were no significant effects of RSI manipulations for either paradigm. Again, however, the effects were in expected directions. The lack of significant differences in these comparisons also supports the idea that better preparation might reduce task set inertia; The increased preparation afforded to participants by longer CSIs might have reduced the effects of the RSI manipulation on task set inertia.

Interestingly, for both versions of the tasks, the effects of RSI manipulations seemed to primarily impair drift rates and RTs for repeat trials rather than primarily switch trials. This pattern indicates that, for both versions of the task, reducing task set inertia effects on switch cost by reducing the advantage participants normally experience on repeat trials rather than facilitating participants' ability to switch tasks. Future work should attempt to replicate these results, as this pattern challenges classical conceptions of task set inertia as primarily affecting switch trials (Meiran et al., 2000).

Effects of CSI manipulation

Manipulating the CSI, generally thought to allow for better preparation and thus a reduction of switch cost, only reduced switch cost RT for the voluntary task. Model results were as expected within the voluntary task – the manipulation reduced the preparation switch cost, but not the inertia switch cost. For the explicit version, there were no effects of CSI length on nondecision time or switch cost. As discussed earlier, this discrepancy might be due to the confound of a difference in task cue RT across the two tasks. The longer responses to cues for the explicit version might have lengthened the short CSI condition to the point where any switch-specific preparation occurred prior to stimulus onset. Importantly, however, previous work has indicated that there are two preparatory components in task switching – a switch-specific preparation process followed by a more general task preparation process (Karayanidis et al., 2011).

Because the drift diffusion model was applied here to decompose reaction times following stimuli, it is possible that the nondecision time parameter in the model is better suited to capture the general task preparation component rather than the switch-specific preparation, as the general preparation occurs about 200 ms later (Karayanidis et al., 2011). In other words, the 'short' CSI condition in the explicit paradigm might have been too long to delay the switch-specific preparation beyond stimulus onset. However, it could have been short enough to delay the general preparation process beyond stimulus onset, allowing it to be captured by modeling stimulus response RTs.

Supporting this account, longer CSIs universally facilitated RTs on switch trials *and* repeat trials individually for both versions of the task, an effect which was attributed to more efficient nondecision times. This pattern not only indicates that CSI manipulations allow for more efficient general task preparation, as the effect was visible for both switches and repeats, but also that the drift diffusion model reliably quantifies this effect.

Conclusions

Supporting our primary hypothesis, the current work indicates that drift diffusion models are able to effectively quantify preparation that occurs outside of the CSI. The results also represent the first evidence that, for voluntary choices, participants might prepare more efficiently for switches than for repeats, supporting previous work which suggests that proactive control plays a vital role in task switching behavior (Karayanidis & Jamadar, 2015; Orr & Banich, 2014). Our results also indicate that, for double registrant task switching paradigms, reducing task set inertia slows repeat responses rather than facilitating switch performance. However, manipulations of task set preparation affected both types of trials, suggesting that these manipulations might affect a general preparatory process rather than a switch-specific process.

Limitations & Future directions

The main limitation of the current work is that it only used a double-registrant version of explicit task switching. While this allowed the explicit version to be more comparable to the voluntary version, an additional single-registrant condition might have accounted for the additional time spent responding to task cues that lengthened the interval between cue and stimulus onsets. This additional condition could provide more insight into the lack of switching effects on nondecision time in the double-registrant explicit paradigm.

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 and examining how each might relate to nondecision time in double-registrant tasks would help corroborate the explanations proposed in the current study. Future work might additionally attempt to replicate our finding that RSI manipulations primarily affect repeat trials rather than switch trials, or examine whether other manipulations of task set inertia (such as stimulus priming) also primarily affect repeat trials. Finally, future work might wish to manipulate the degree to which participants engage in proactive strategies to examine whether the manipulation might affect how often or how effectively participants switch tasks in a voluntary paradigm.

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