Anticipatory reconfiguration elicited by fully and partially informative cues that validly predict a switch in task.

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Abstract

Task-switching studies show no behavioral benefit of partially informative cues. However,

ERP evidence of an early cue-locked positivity elicited by both fully and partially

informative cues, suggests that both cues trigger an anticipatory component of task-set

reconfiguration (Nicholson, Karayanidis, Davies & Michie, 2006b). We examined this

apparent discrepancy using a cued-trials task-switching paradigm with three tasks. The ERP

finding of an early cue-locked positivity was replicated for both *switch-to* cues, which validly

predicted an upcoming switch trial and specified the new task-set, and *switch-away* cues,

which validly predicted an upcoming switch trial but not the new task-set. This component

was not elicited by a *non-informative* cue that did not specify whether the task will switch or

repeat. *Switch-away* cues resulted in more accurate but not faster responding than *non-*

informative cues. Modelling of decision processes confirmed a speed-accuracy trade-off

between these conditions and a preparation benefit for both *switch-to* and *switch-away* cues.

These results indicate that both fully and partially informative cues elicit an early anticipatory

component of task-set reconfiguration which is reflected in the early cue-locked positivity.

We argue that the pattern of results is most consistent with a task-set inhibition account of

this early anticipatory component of task-set reconfiguration.

Acknowledgements

Task-switching paradigms require rapid alternation between two or more task-sets defined on the basis of distinct or partially overlapping target features. Typically, these paradigms produce 'switch costs' - longer reaction time (RT) and more errors when switching tasks as compared to repeating tasks (e.g., Rogers & Monsell, 1995). In cued-trials paradigms, increasing the cue-target interval reduces RT switch cost, but a significant residual switch cost remains even with long preparation intervals (Meiran, Chorev & Sapir, 2000). Recent behavioral (e.g., Arrington, Logan & Schneider, 2007) and electrophysiological (e.g., Karayanidis, Coltheart, Michie & Murphy, 2003) studies support multi-component models of task-switching with switch cost reflecting both active control processes (e.g., task-set reconfiguration, Rogers & Monsell) and passive target-driven processes (e.g., S-R priming, Wylie & Allport, 2000).

Although there is evidence of a role for inhibition in task-switching, it is unclear at what stage an inhibitory mechanism may be activated and whether it is a top-down process or a bottom-up process. Mayr and Keele (2000) argued that slower RT on the third trial of an ABA sequence as compared to a CBA sequence supports an inhibitory control process, albeit a rather low level one, as inhibition was not overcome with increasing preparation. Koch and colleagues argued that this inhibition is a by-product of response activation as studies have shown no backward inhibition (Schuch & Koch, 2003) or RT switch cost (Koch & Philipp, 2005) following no-go trials that require task-set preparation but no response execution. Driesbach, Haider and Kluwe (2002) compared subjective expectancy for partially informative cues, that signal an impending switch trial without identifying which specific task to prepare, and fully informative cues, that indicate which task to switch to. Unlike fully informative cues, partially informative cues did not produce subjective expectancy effects Thus, knowledge that the task would change without specification of which task would be performed did not produce the differential response benefit that would be expected if

inhibition of the previously active task set was required to switch tasks (see also Hubner,

Dreisbach, Haider & Kluwe, 2003).

In contrast, Nicholson, Karayanidis, Davies and Michie (2006b) found event-related

potential (ERP) evidence consistent with task-set inhibition during the cue-target interval.

ERPs are systematic fluctuations in brain electrical activity that are extracted from the

electroencephalogram (EEG) using signal averaging techniques (Andreassi, 2000), and have

been shown to provide a high temporal resolution window into the processes underlying task-

switching. In particular, ERP waveforms time-locked to cue onset consistently show a larger

parietal positivity for switch as compared with repeat trials (e.g. Kieffaber & Hetrick, 2005;

Miniussi, Marzi & Nobre, 2005; Nicholson, Karayanidis, Poboka, Heathcote & Michie, 2005;

Nicholson, Karayanidis, Bumak, Poboka & Michie, 2006a; Rushworth, Passingham & Nobre,

2005). This *differential switch positivity* (D-Pos) emerges as early as 200ms post-cue, and

with long preparation intervals peaks prior to target onset. After target onset, ERPs for switch

trials show a negative shift relative to repeat trials which emerges after 150ms and extends

more than 800ms after target onset. D-Pos has been mapped to processes associated with

task-set reconfiguration during the cue-target interval whereas the switch negativity has been

mapped to target dependent processes that cause residual switch cost (Karayanidis et al.,

2003; Nicholson et al., 2005; 2006a).

Nicholson et al.'s (2006b) ERP evidence for task-set inhibition came from a cued

trials task-switching paradigm in which participants randomly alternated between three tasks.

As is usual in task-switching paradigms, different cues signaled task repetition (*repeat* cue) or

a switch to a specified task (*switch-to* cue). A third partially informative cue signaled only

that the task would change (*switch-away* cue), with the actual task to be performed being

specified only upon target onset (see Figure 1a). An early cue-locked differential positivity

(D-Pos1) was found for both *switch-away* and *switch-to* trials relative to *repeat* trials (see

Figure 3b in Nicholson et al.). *Switch-to* trials also showed a second differential positivity which occurred later within the cue-target interval (D-Pos2), while for *switch-away* trials this component occurred after target onset. After target onset, both types of switch trials showed a differential negativity relative to *repeat* trials, but this was delayed until after D-Pos2 on *switch-away* trials.

Nicholson et al. (2006b) suggested that D-Pos2 reflects activation of the relevant task-set, which can occur prior to target onset for *switch-to* trials, but only after target onset for *switch-away* trials. As both *switch-to* and *switch-away* trials indicate that the previously active task-set will not be repeated, the D-Pos1 component, which was common to both of these trial types, was interpreted as reflecting inhibition of the now irrelevant task-set. However, D-Pos1 might also be attributed to differences in cue processing between *repeat* and both types of switch trials. In particular, both *switch-to* and *switch-away* trials involved a physical cue change between trials, which may have resulted in greater cue processing being required than for the cue on a *repeat* trial, where cue processing may have been primed by cue repetition.

Nicholson et al. (2006b) found that switch cost was larger on *switch-away* as compared to *switch-to* trials, and that increasing the cue-target interval reduced RT switch cost for *switch-to* but not *switch-away* trials. The length of the cue-target interval may have had no effect on *switch-away* trials because task-set inhibition was complete before the target appeared, even at the short cue-stimulus interval (200ms). However, it is also possible that there was no cue-target interval effect on *switch-away* trials simply because participants did not make any use of the *switch-away* cue. The equivalence of early ERP waveforms (D-Pos1) for *switch-to* and *switch-away* could then be attributed to participants undertaking the same cue encoding processes in both conditions. If a *switch-away* cue does allow partial preparation, it should cause a reduction in switch cost, even though this reduction would be

less than for *switch-to* cues. However, the behavioral benefits of the *switch-away* cue could not be established by Nicholson et al., as their design did not have a baseline condition.

Experiment 1

The present study addresses these issues using an identical design to that of Nicholson et al. (2006b), with the exception of including an extra *non-informative* cue type. This cue signaled that the following trial may require a repeat *or* a switch in task (see Figure 1a). Like *switch-to* and *switch-away* cues, *non-informative* cues involved a physical shift in cue position. However, unlike *switch-to* and *switch-away* cues, *non-informative* cues did not indicate that the previously active task-set would be irrelevant on the next trial. In fact, they indicated that there was a 50% chance that the task would be repeated. Although inhibition of the previously active task-set is an efficient strategy for *switch-to* and *switch-away* cues, this is not the case for *non-informative* cues. Hence, if D-Pos1 represents processes associated with inhibition of the previously active but now irrelevant task-set, it should occur for *switch-to* and *switch-away* cues but not for *non-informative* cues. Alternatively, if D-Pos1 represents processing of the change in cue position, it should occur for *switch-to*, *switch-away* and *non-informative* cues.

The *non-informative* cue condition also acted as a baseline that allowed us to investigate whether *switch-away* cues provide some behavioral benefit (i.e., reduce switch cost) by allowing partial preparation for a task switch. Note that non-informative and switch-away cues were equally informative about which task would occur next. That is, both of these cue types ruled out exactly one of the three possible tasks. Hence a comparison of performance for these cue types controls for task uncertainty and specifically tests for benefits related to knowing that the previous task would not be repeated.

Methods

Participants

Twenty-three undergraduate students (18 females, 5 males) with mean age 21.3 years (*SD* = 3.51) were recruited from an introductory psychology course and participated for course credit.

Stimuli and Tasks

The paradigm was identical to that used by Nicholson et al. (2006b) with the exception of the additional non-informative cue. Briefly, participants viewed a circle (5° of visual angle) divided into six wedges with pairs of adjacent wedges grouped by thicker lines demarcating three task sections: digit, letter, and color (see Figure 1a). Each target was a pair of characters consisting of combinations of a letter, a digit or a non-alphanumeric symbol and was presented either in grey or in color. Each target (e.g., A4) consisted of three dimensions (see Figure 1b) – one relevant to the currently cued task (e.g., letter mapped to left hand response), one selected randomly from one of the two alternative tasks and incongruently mapped with the relevant task (e.g., digit mapped to right hand response) and one that was neutral (e.g., grey not mapped to any response). The same target could not appear on two successive trials. Response-target interval was 1400ms and included a 1000ms cue-target interval.

Four cue types (i.e., *repeat, switch-to, switch-away* and *non-informative*) were defined by cue location and were presented with equal probability in a pseudo-random sequence so that the same cue was not repeated on more than three consecutive trials. Non-informative cues resulted equiprobably in a switch or a repeat trial which was defined by the location of the target, thereby resulting in five trial types (i.e., *repeat, switch-to, switch-away, non-informative switch and non-informative repeat*). The target always appeared in one of the two segments highlighted by the cue.

Procedure

All participants attended two sessions scheduled 7-14 days apart. The first session included task training and practice (732 trials on each task alone and switching between tasks). The second session included further practice (another 732 trials) followed by the behavioral and EEG testing session. The testing session consisted of nine runs of 96 trials each. Participants were encouraged to respond as quickly and accurately as possible. Auditory feedback was provided after an incorrect response and behavioral feedback (mean RT and percentage correct) was displayed at the end of each run. EEG was continuously sampled at 2048 Hz/channel reference free from 64 scalp electrodes, the mastoids and nose using a Biosemi ActiView II system. Vertical electro-oculogram (EOG) was recorded from the supra-orbital and infra-orbital ridges of the left eye and horizontal EOG from the outer canthi of each eye.

Data Analysis

The first five trials of every run, trials associated with an incorrect response, trials immediately following an incorrect response and trials on which RT was faster than 200ms (0.005%) or slower than 3 standard deviations above the participant's mean RT (1.7%) were excluded. A 3 task (letter, digit, color) x 5 trial (*repeat, switch-to, switch-away, non-informative repeat and non-informative switch*) repeated measures ANOVA was performed. Critical values were adjusted using the Greenhouse–Geisser correction to avoid violating the assumption of sphericity (Vasey & Thayer, 1987) and simple comparisons for trial were corrected with family-wise error rate adjusted at α=.01(unless otherwise reported). For behavioral data, we compared *repeat* trials with each of *switch-to*, *switch-away* and *non-informative repeat* trials, and *switch-away* trials with each of *switch-to* and *non-informative switch* trials. Task did not interact with trial type for either RT (F=1.64) or error rate (F=2.43), so all behavioral and ERP analyses were averaged over task.

EEG data were analyzed using Brain Electrical Source Analysis (BESA v5.1). Scalp

electrodes were re-referenced offline to linked mastoids, and EOG artifact correction was applied using a regression algorithm (Ille, Berg and Scherg, 2002). Cue and target-locked EEG epochs were extracted from 300ms before to 1200ms after each cue and target (200ms pre-event baseline) and epochs with artifact exceeding a 100μV threshold were rejected. Averaged waveforms were created for each cue and target type, averaged over response hand and task. Both cue-locked and target-locked individual ERP waveforms included a mean of 130-140 trials, except for target-locked *non-informative switch* and *repeat* trials which included half that number. Target-locked data from two participants were excluded because there were less than 40 epochs contributing to one of the non-informative trial types. Therefore, cue-locked data is reported from 23 participants while target-locked data is from 21 participants.

Difference waveforms were calculated by subtracting the *repeat* waveform from each of the remaining waveforms and were visually inspected to determine time windows and scalp topography of maximal differentiation between cue types. For cue-locked waveforms, two mean amplitude windows were defined based on the positivity for *switch-to* relative to *repeat* waveforms (250-400ms, 450-700ms) and were analyzed at the parieto-occipital midline site (POz) using a one-way ANOVA with 4 levels of cue type. We compared *repeat* cues with each of the other three cues, and *switch-away* with *switch-to* and *non-informative* cues. For target-locked waveforms, two mean amplitude windows were used to define an early positivity that emerged around the peak of the P2 and a second later positivity around the latency of the N2 (180-250 and 300-370 ms, respectively) and were analyzed at F4 where the effects of trial were maximal. A third window (420-550ms) that targeted the negativity for *switch-to* relative to *repeat* trials was analyzed at Cz. Four contrasts were defined comparing *repeat* trials with each of the other three trial types. Where significant trial type differences emerged at these scalp sites, the scalp distribution of these differences was

analyzed using paired-samples t-tests at each electrode and are displayed as head maps in

Figures 2 and 3.

Results

Given that Nicholson et al's (2006b) argument that task-set reconfiguration involves

task-set inhibition as well as task-set activation was based on ERP data, we will discuss first

the ERP findings to establish replication of the original finding and present the outcomes for

the non-informative cue. Figures 2 and 3 show average cue-locked and target-locked

waveforms, respectively. Figure 4 shows average behavioral and ERP estimates and the

results of associated inferential tests.

Cue-locked waveforms

Cue-locked waveforms showed a sustained positivity over 100-800ms for all trial

types (Figure 2a, left). The main effect of cue was significant at POz for both early and late

positivities $F(3,66)=18.10$, $p<.001$; $F(3,66)=8.45$, $p<.001$, respectively. Difference

waveforms were derived between each cue type and the *repeat* waveform (Figure 2a, right).

A large broad positivity was evident over 150-800ms in the *switch-to* difference waveform.

This was also evident in the *switch-away* difference waveform but dissipated by 400ms. *Non-*

informative cues did not show any positivity relative to *repeat* cues.

The early positivity was significantly larger for both *switch-to* and *switch-away* cues

as compared to *repeat* cues, $F(1,22)=39.30$, $p<.001$; $F(1,22)=31.68$, $p<.001$, respectively

(Figure 4b). This differential positivity for *switch-to* and *switch-away* relative to *repeat* cues

emerged at central sites but was stronger at parietal and occipital sites, also reflected at

frontopolar locations (Figure 2b). Importantly, this early positivity was also larger for *switch-*

away as compared to *non-informative cues*, $F(1,22)=17.89$, $p<.001$, across most parietal-

occipital sites (Figure 2b) and did not differ in amplitude between *repeat* and *non-informative*

cues at any site. The later positivity was larger for *switch-to* as compared to both *repeat* cues

and *switch-away* cues at POz $F(1,22)=9.31$, $p=.006$, $F(1,22)=12.65$, $p=.002$, respectively (Figure 4b), an effect that was distributed over the parietal-occipital scalp (Figure 2b). There was no difference between the other cue types in this latency range.

Target-locked waveforms

Target-locked waveforms showed an early N1 and large fronto-central P2 followed by an N2 and LPC complex (Figure 3a, left). *Switch-to* minus *repeat* difference waveforms showed a broad negative shift spreading over 200-800ms after target onset that was largest at Cz (Figure 3a, right). All other difference waveforms show a right frontally maximal positivity over 200-400ms, followed by a broad centrally maximal negativity.

Target-locked difference waveforms for *switch-away*, *non-informative repeat* and *non-informative switch* targets showed two positive peaks: one within the latency range of the frontal P2 (180-250ms) and the other around 100ms later (300-370ms; Figure 3a, right). Both windows showed a significant main effect of trial type at F4, $F(4,80)=3.30$, $p=.043$, $\varepsilon=.538$; $F(4,80)=7.37$, $p<.001$. The early positivity (180-250 ms; Figure 4c) was larger for both *switch-away* and *non-informative repeat* targets as compared to *repeat* targets, $F(1,20)=8.45$, $p=.009$; $F(1,20)=11.85$, $p=.003$, respectively. This early target-locked differential positivity was more widespread over frontocentral sites for *non-informative repeat* cues, but fairly localized over the right frontal scalp for *switch-away* cues (Figure 3b). The later positivity (300-370ms) was larger for both *non-informative repeat* and *non-informative switch* targets as compared to *repeat* targets ($F(1,20)=10.77$, $p=.004$, $F(1,20)=9.03$, $p=.007$, respectively; Figure 4c), over both right frontocentral and left centroparietal sites (Figure 3b). This positivity was again evident for *switch-away* cues, but was only marginally significant over the right frontal scalp ($F(1,20)=4.77$, $p=.041$).

Mean amplitude over 420-550ms in the target-locked waveforms produced a significant main effect of trial at Cz ($F(4,80)=6.38$, $p=.002$; Figure 3a) reflecting a significant

negative deflection for all trial types relative to *repeat* targets (Figure 4c; *switch-to*: $F(1,20)=16.65$, $p=.001$; *switch-away* $F(1,20)=19.45$, $p<.001$; *non-informative switch*: $F(1,20)=8.37$, $p=.009$; *non-informative repeat*; $F(1,20)=10.03$, $p=.005$). This post-target switch negativity showed a broad scalp distribution for *switch-to* and *switch-away* targets, especially over centroparietal sites (Figure 3b), whereas the effect was restricted over the frontocentral midline for both *non-informative switch* and *non-informative repeat* targets.

Accuracy and Mean RT

Mean RT showed a significant effect of trial type, $F(4,88)=38.62$, $p<.001$, $\varepsilon=.320$ (Figure 4a). Responses for *repeat* trials were significantly faster than for *non-informative repeat*, $F(1,22)=61.49$, $p<.001$, *switch-to*, $F(1,22)=32.29$, $p<.001$, and *switch-away* trials, $F(1,22)=51.59$, $p<.001$. RT for *switch-away* trials was slower than for *switch-to* trials, $F(1,22)=37.36$, $p<.001$, but not significantly faster than for *non-informative switch* trials.

Although error rate was quite low (2.8-5.5%; Figure 4a), the main effect of trial type was significant, $F(4,88)=10.76$, $p<.001$, $\varepsilon=.673$. Repeat trials produced fewer errors than all other trial types (*switch-to*: $F(1,22)=16.87$, $p<.001$; *switch away*: $F(1,22)=9.45$, $p=.006$; *non-informative repeat*: $F(1,22)=21.27$, $p<.001$). Error rates were also higher for *non-informative switch* than *switch-away* trials, $F(1,22)=9.53$, $p=.005$.

We examined whether the amplitude of the early cue-locked positivity was associated with improved behavioral performance using one-tailed Pearson correlations for *switch-to* and *switch-away* cues which showed clear and measurable D-Pos1. Larger positivity was associated with faster RT for *switch-to* trials ($r=-.691$, $p<.001$, n=23) and less strongly for *switch away* trials ($r=-.367$, $p<.05$, n=23) but showed no relationship with error rate.

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Discussion

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ERP data replicated Nicholson et al.'s (2006b) finding of an early posterior cue-locked differential switch positivity (D-Pos1) for both *switch-to* and *switch-away* cues

followed by a second differential switch positivity (D-Pos2) that was cue-locked for *switch-to*

trials and target-locked for *switch-away* trials. Both *switch-to* and *switch-away* trials elicited a

large post-target switch negativity compared to *repeat* trials, and the onset of this negativity

was delayed until after resolution of the earlier positivity for *switch-away* trials, again

suggesting that it reflects target-triggered processes such as completion of task-set

reconfiguration or S-R priming.

Notably, within the cue-target interval, *non-informative* cues showed no evidence of

any differential switch positivity relative to repeat cues. However, after the onset of the target

that defined the currently active task-set, both *non-informative repeat* and *non-informative*

switch trials showed a significant differential positivity relative to *repeat* trials. The finding

that, unlike *switch-to* and *switch-away* cues, *non-informative* cues did not elicit the early

switch positivity (D-Pos1) within the cue-target interval indicates that this component does

not reflect processing of a change in the physical position of the cue. It could be argued that

although non-informative cues involved some spatial displacement, the degree of

displacement differed between cue types (i.e., 60° for *non-informative*, 120° for *switch-to*

and180° for *switch-away* cues). However, if the cue-locked positivity is affected by degree of

cue displacement, there should be correspondence between the angular displacement of the

cue and D-Pos1 amplitude (i.e., *non-informative* < *switch-to* < *switch-away*). This was not the

case in the current data.

Therefore, the D-Pos1 component appears to reflect a process that is activated by cues

which validly signal that the previously active task-set will not be relevant to the next target

and consequently that there will definitely be a switch in task on the next target (i.e., *switch-*

to and *switch-away* cues), even when the cues do not specify which task will be relevant.

Importantly, the process reflected by the D-Pos1 is not activated by cues which signal that the

previously active task-set may (i.e., *non-informative* cues) or will (*repeat*) be relevant to the

next target. This finding supports the contention that partially informative cues trigger some anticipatory reconfiguration process.

Replicating Nicholson et al.'s (2006b) finding, *switch-away* trials resulted in longer RT than *switch-to* trials. This indicates that the additional information regarding the identity of the upcoming task afforded by *switch-to* cues led to greater anticipatory reconfiguration than on *switch-away* cues. However, mean RT did not differ between *switch-away* and *non-informative switch* trials. This result appears to contradict the idea that participants use *switch-away* cues to partially prepare for a switch trial. If preparation is a time-consuming process, then it should take longer to complete on *non-informative switch* trials than on the partially informative *switch-away* trials, and hence mean RT should be less in the latter condition.

This argument fails to take account of the fact that the *non-informative switch* trials had a reliably higher error rate than *switch-away* trials. The error difference raises the possibility that participants used the information provided by *switch-away* cues to engage in a speed-accuracy tradeoff. That is, because *switch-away* cues provide certainty that the upcoming trial will require a switch in task, and hence will be more difficult and potentially error prone, participants may have required a higher standard of evidence before making a decision in order to reduce the possibility of making an error. If that were the case, the same higher standard of evidence would be expected to be applied on *switch-to* trials. Mean RT in the *switch-to* condition could still be less than in the *non-informative switch* condition if the extra time required to make a decision using a higher standard of evidence on *switch-to* trials was less than the time saved by being able to complete reconfiguration in the cue-target interval. In the *switch-away* condition, in contrast, the lesser amount of time saved by partial reconfiguration could be cancelled out by the extra time taken to make a decision, so that overall mean RT in the *switch-away* and *non-informative switch* conditions is equal.

Fortunately, as we describe next, it is possible to directly test our speculation about speed-accuracy tradeoff differences between cue conditions. Speed-accuracy tradeoff is a pervasive phenomenon in choice tasks ranging from simple stimulus categorization to recognition memory (for a summary, see Luce, 1986, pp. 237–245). It has been intensively studied and it is now almost universally agreed that it can be explained in detail by evidence accumulation models. Evidence accumulation models of the decision process provide a detailed account of the mechanism by which speed-accuracy tradeoffs is accomplished. They also predict that a speed-accuracy tradeoff will have a quite specific effect on aspects of the RT distribution, such as RT variance, which are neglected by an analysis of mean RT alone. Hence, by fitting an evidence accumulation model to our data we are able to provide a rigorous test of whether the lack of a mean RT difference between *non-informative* and *switch-away* trials is a by-product of speed-accuracy tradeoff.

Evidence Accumulation Model Analysis

Evidence accumulation models fractionate mean RT within 2-choice response tasks into two independent components: decision time and non-decision time. Decision time includes processes directly involved in choosing a response to the current stimulus i.e., stimulus categorization and response selection. Non-decision time includes the time to complete processes that do not directly contribute to the decision, typically including processes such as stimulus encoding and response activation/execution. Evidence accumulation models assume that a decision is reached by accumulating (i.e., repeatedly sampling and combining) stimulus information about a choice until the evidence favoring one choice exceeds the evidence favoring other choices by a criterion amount. Decision time, therefore, is determined by the conservativeness of the evidence criterion and the rate of evidence accumulation. A speed-accuracy tradeoff occurs when participants differ between

conditions in conservativeness (i.e., maintain a different evidence criterion).

Wagenmakers, van der Maas and Grasman (2007) advocated the use of parameter estimates from a particular type of evidence accumulation model, a diffusion model, to account for speed-accuracy tradeoff. Their "EZ" diffusion method estimates three parameters. The evidence accumulation or "drift" rate (v) and the evidence criterion (a) parameters together determine decision time (dt). The remaining portion of the RT that is due to non-decision processes is determined by the *Ter* parameter. We applied a more recent development of this approach, the EZ2 method (Grasman, Wagenmakers & van der Maas, in press), which also estimates a decision bias parameter, although this parameter is not of substantive interest in the present application.

Within task-switching paradigms, when reconfiguration is completed before target onset (i.e., anticipatory reconfiguration with predictable switch cues and long CSI), there is no effect of reconfiguration on RT and any residual RT switch cost is assumed to reflect post-target processes related to S-R priming. However, if reconfiguration is not completed before target onset (i.e., very short CSI and/or unpredictable switch trials), RT would increase by the amount of time required to complete reconfiguration, as the initiation of decision processing will be delayed. Such delays would increase estimates of the non-decision time (*Ter*) parameter. In our paradigm, *switch-to* trials allow complete reconfiguration before target onset and so there should be little or no contribution by reconfiguration to non-decision time. In contrast, on *non-informative switch* trials, reconfiguration should make a large contribution to non-decision time. If *switch-away* trials involve partial reconfiguration, non-decision time should be less in *switch-away* than *non-informative switch* trials.

In summary, we predict that non-decision time should be shortest for *switch-to* trials, intermediate for *switch-away* trials, and longest for unprepared *non-informative switch* trials, as the amount of reconfiguration that can be completed in the cue-target interval decreases

across these conditions. Predictions related to non-decision time for the *repeat* cue trials are less constrained because the reconfiguration process itself may be primed in this condition. Generally, we would expect *repeat* trials to have a shorter non-decision time than all other trial types, because they require no reconfiguration, or at least minimal reconfiguration. *Switch-to* trials may be an exception, as the relatively long cue-target interval may have been sufficient to complete preparation to the same level as *repeat* trials.

Decision time is determined by criterion and drift rate; a longer decision time may result from a high response criterion, a lower drift rate or a combination of both. Hence, if, as we suggested, participants use a more cautious (larger) evidence criterion in the *switch-away* than the *non-informative switch* condition, a longer decision time would be predicted in the former condition. We argue that it is the fact that these two conditions have opposite effects on non-decision and decision time that can account for our finding of no difference between them in mean RT. As both *switch-to* and *switch-away* cues certainly indicate the next trial will be a switch, no difference in criterion or decision time is predicted between these conditions. However, we predict that *switch-to* trials will have a shorter mean RT because of their shorter non-decision time.

Methods

Wagenmakers et al.'s (2007) EZ diffusion method estimates three separate parameters for each response to a task, the evidence accumulation or "drift" rate (v), the evidence criterion (a), which together determine mean decision time (dt), and a parameter for the remaining portion of mean RT, non-decision time (Ter). These three parameters are estimated analytically based on three aspects of the data for each response, accuracy and the mean and variance of RT for correct decisions. The EZ method assumes that decisions are unbiased, whereas the more recently developed EZ2 method (Grasman et al., in press) does not need to make this assumption as parameter estimates are obtained for the entire task rather than for

each response separately. These parameters are: two drift rate and two non-decision time parameters (one for each response), the criterion for one of the responses (*a*; the criterion for the other response is assumed to be zero without loss of generality) and the starting point for evidence accumulation (*z*). These size parameters are estimated based on six data points, accuracy and the mean and variance of correct RT for each response.

Hence, as is the case for EZ, the number of parameters estimated equals the number of data points, but for EZ2 the equation relating the two cannot be solved analytically. However, the EZ2 equation implicitly defines a unique solution which can be easily and reliably found by numerical methods using programs provided by Grasman et al. (in press). Our use of EZ2 was not so much motivated by its affording an estimate of response bias (which we do not report as there was no evidence of bias or differences in bias across conditions) as by the fact that it requires less assumptions and is in our experience more robust and efficient than EZ estimation, and because it corresponds more directly to the diffusion model's assumption that one evidence accumulation process is responsible for both choices.

In our experiment mean RT showed a reliable difference between tasks and a reliable interaction between task and response hand. As EZ2 analysis depends on variance estimates, and these can be distorted by pooling over conditions that differ in their mean, we applied the diffusion analysis to data broken down by task and response as well as trial type. This resulted in small sample sizes for correct responses (less than 20) for some conditions in some subjects.

In order to make mean and variance estimates robust we based them on fits of the Ex-Gaussian distribution to correct RT deciles (Heathcote, Brown & Mewhort, 2002; see Wagenmakers, van der Maas, Dolan & Grasman, 2008, for a related approach to EZ estimation). We also based EZ2 estimates on the robust accuracy measure recommended by

Snodgrass and Corwin (1988). In a few cases (<1%), estimates of *Ter* estimates were too

small to be plausible (<100ms). In such cases, we obtained parameter estimates by solving

the EZ2 equations under the constraint that *Ter*>100ms. Note that without constraint EZ2

parameters produce a perfectly accurate account of accuracy and correct RT mean and

variance. Although this is not necessarily the case when a constraint is imposed, the effect of

the constraint used on our data was negligible, so that the account of these measures remained

essentially perfect.

As the Ex-Gaussian usually provides an excellent descriptive account of RT

distribution, our methods also provided a gold standard against which to compare the

diffusion model's account of the data, thus addressing concerns raised by Ratcliff (in press)

about EZ estimation. A qualitative check provided by inspecting Figure 5 shows that for our

data, EZ2 estimation produced an accurate account of the full distribution of correct RT,

which was only slightly inferior to that of the Ex-Gaussian. A small disadvantage is to be

expected given the diffusion model accounts for accuracy as well as RT using the same

number of parameters as the Ex-Gaussian, which only accounts for RT.

Results

EZ2 parameter estimates were derived for each of the 23 participants from

Experiment 1. Mean RT, RT variance and error rate were used to estimate the non-decision

time, evidence criterion and drift rate parameters at each level of task and trial type. These

parameter estimates were analyzed using 3 task (letter, digit, color) x 5 trial type (*repeat,*

switch-to, switch-away, non-informative repeat and non-informative switch) repeated

measures ANOVA followed by five simple comparisons for trial with family-wise error rate

adjusted at α=.01. As well as the drift rate, criterion and non-decision time parameters, we

analyzed decision time. We present result for all four measures for clarity, but it is important

to keep in mind that these measures are related, as decision time is a function of the drift rate

and criterion, and decision time and non-decision time sum to mean RT. Task did not interact with trial type in any of these analyses so we report results averaged over task (Figure 6). As in earlier analyses, five planned contrasts compared *repeat* trials with *switch-to*, *switch-away* and *non-informative repeat* trials, and *switch-away* trials with *switch-to* and *non-informative switch* trials. We also report correlations between EZ2 parameters and the early cue-locked switch positivity.

Figure 6a shows that non-decision time varied from 370ms for *repeat* trials to 650ms for *non-informative switch* trials (trial $F(4,88)=71.06$, $p<.001$, $\varepsilon=.673$). Non-decision time was significantly faster for *repeat* trials as compared with *switch-away* and *non-informative repeat* $F(1,22)=71.41$, $p<.001$, $F(1,22)=59.69$, $p<.001$, respectively (although not part of the planned set, note that the *repeat* and *non-informative switch* trials comparison was also highly significant $F(1,22)=213.78$, $p<.001$). Non-decision time did not differ between *repeat* trials and *switch-to* trials ($F<1.5$), but *switch-away* trials had a significantly shorter non-decision time compared with *non-informative switch* trials, $F(1,22)=28.49$, $p<.001$, and a longer non-decision time compared with *switch-to* trials, $F(1,22)=112.8$, $p<.001$. Larger cue-locked positivity was associated with faster non-decision time for *switch-to* cues ($r=-.397$, $p<.05$) and marginally for *switch-away* ($r=-.349$, $p=.051$) cues.

As shown in Figure 6d, response criteria were low on *repeat* and both types of *non-informative* cue trials. However, criteria were significantly higher for both *switch-to* and *switch-away* trials (trial, $F(4,88)=14.74$, $p<.001$, $\varepsilon=.465$; *repeat* vs. *switch-to*, $F(1,22)=14.07$, $p=.001$; *repeat* vs. *switch-away*, $F(1,22)=9.73$, $p=.005$). Decision time was also significantly affected by trial type, $F(4,88)=11.71$, $p=.001$, $\varepsilon=.341$ (Figure 6b). Both *switch-to* and *switch-away* trials had significantly longer decision time than *repeat* trials, $F(1,22)=18.32$, $p<.001$, $F(1,22)=9.14$, $p=.006$, respectively. Decision time was also lower for *non-informative switch* as compared to *switch-away* trials, $F(1,22)=16.76$, $p<.001$. This can be accounted for by

differences in response criterion, $F(1,22)=44.06$, $p<.001$, but not drift rate, $F<1$ (Figure 6c).

Drift rate for *repeat* trials was significantly higher than for all other trial types (*switch-to*:

$F(1,22)=62.05$, $p<.001$; *switch-away*: $F(1,22)=27.67$, $p<.001$; *non-informative repeat*:

$F(1,22)=13.36$, $p=.001$). Larger cue-locked positivity on *switch-to* trials was associated with

faster decision time ($r=-.414$, $p<.05$), lower criterion ($r=-.425$, $p<.05$) and faster drift rate

($r=.366$, $p<.05$). *Switch-away* cues showed no significant correlations between cue-locked

positivity and these diffusion measures.

Discussion

The non-decision time findings are consistent with predictions based on our

assumption that the cues preceding *non-informative switch, switch-away and switch-to* trials

results in differential degree of activation of an anticipatory reconfiguration process. Partially

informative *switch-away* cues, which provided certainty about an upcoming task switch

without indicating which task will be active, offered a reliable behavioral advantage over

non-informative cues that were equally likely to be followed by a switch or repeat trial. In

particular, this advantage was evident in non-decision time[1], a latent measure which in the

context of cued task-switching is affected by the degree of anticipatory reconfiguration

afforded by the cue. In the current paradigm, the only common information provided by

switch-to and *switch-away* cues and not afforded by *non-informative* cues is that the task that

was relevant on the previous trial *will not* be repeated. The finding that this information

resulted in a reduction in non-decision time suggests that both *switch-away* and *switch-to*

cues elicit some degree of anticipatory reconfiguration and that this partial preparation results

in a behavioral advantage over *non-informative* cues that are equally likely to result in a

switch or repeat trial.

Just as predicted by our speed-accuracy tradeoff account, response criterion

adjustment occurred only for cues validly predicting a change in task (*switch-to, switch-*

away), but not for cues signaling that the task may repeat (*non-informative*)[2]. This criterion adjustment caused decision time to be greater in the *switch-to* and *switch-away* conditions than the *non-informative switch* condition. The decision time difference between *switch-away* and *non-informative* cues masked the non-decision time advantage that partial preparation afforded to *switch-away* cues over *non-informative switch* cues, resulting in no observable difference in mean RT.

This pattern of reduced non-decision time and increased response criterion in the *switch-away* and *switch-to* conditions may appear counterintuitive. It suggests that anticipatory reconfiguration (reflected in reduced non-decision time) resulted in slower rather than faster decision time – a disadvantage rather than an advantage of preparation. However, seeing this effect as only a disadvantage fails to appreciate the full range of behavior displayed by participants, and the task demands which they must satisfy in terms of accuracy as well as speed. The increase in response criterion had the advantage of decreasing the probability of an error, which explains why accuracy was higher in the *switch-away* and *switch-to* conditions than the *non-informative switch* condition even though the quality of the evidence (drift rate) was the same in all three conditions. By setting the criterion as they did, participants were able to achieve greater accuracy in the *switch-to* condition without sacrificing speed relative to the *non-informative* conditions, as the increased decision time cost was cancelled by the non-decision time advantage afforded by partial preparation.

General Discussion

Nicholson et al. (2006b) reported an early cue-locked differential switch positivity for both fully informative (*switch-to*) and partially informative (*switch-away*) cues, suggesting a common anticipatory reconfiguration process. They argued that, as the only common information provided by these cues was that the previously active task would not be repeated,

this switch positivity could reflect suppression or disengagement of the now irrelevant task-set. However, the absence of a demonstrated behavioral benefit afforded by *switch-away* cues, and the fact that both *switch-to* and *switch-away*, but not *repeat*, cues involved a change in spatial position suggested another interpretation – that the early switch positivity reflects processing of the change in the spatial position of the cue or repetition priming for the *repeat* cue. In the present study, we tested this alternative explanation by including *non-informative* cues that, like *switch-to* and *switch-away* cues, involve a change in spatial position (and therefore do not involve cue identity repetition) but, unlike *switch-to* and *switch-away* cues, are not associated with any strategic benefit in suppressing the previously active task-set. The ERP data showed that the early posterior cue-locked differential switch positivity (D-Pos1) was elicited for both *switch-to* and *switch-away* cues but not for *non-informative* cues. Therefore, D-Pos1 does not simply reflect processing of a change in cue position.

These results indicate that partially informative cues trigger a subcomponent of an anticipatory reconfiguration process represented by the early differential positivity (D-Pos1) to both *switch-to* and *switch-away* cues. Surprisingly, *switch-away* cues signaling that the upcoming trial requires a change in task-set, without specific information about which task-set to prepare, did not appear to provide any advantage in speed relative to non-informative cues signaling that a change may or may not be necessary. However, error scores provided evidence that the failure to find a *switch-to* advantage in mean RT was due to a speed-accuracy tradeoff.

We examined the issue of speed-accuracy tradeoff by using the EZ2 analysis method (Grasman et al., in press), which combines measurements of response accuracy with measurements of response speed and variability in order to fit an evidence accumulation model of the task decision process. Critically for our purposes, this model produces estimates of the criterion amount of evidence required to make a decision and of the mean time to

complete non-decision and decision processes. Diffusion model analyses provided evidence

of a behavioral effect on RT of the partial information provided by *switch-away* cues.

Specifically, non-decision time, a latent measure that includes the time to complete

reconfiguration after target onset, did not differ between *repeat* and *switch-to* cues, but

increased progressively across *switch-to, switch-away* and *non-informative* cues. Hence, cues

that allowed full reconfiguration showed no effect of reconfiguration on non-decision time,

whereas cued that allowed partial reconfiguration provided a non-decision time advantage

over cues providing no information about the likelihood of a switch trial.

  These results are consistent with the idea that the partial preparation afforded by the

information that the previously active task-set will not be repeated is a time consuming part

of the reconfiguration process. Non-decision time was negatively correlated with the

amplitude of the early cue positivity, suggesting that activation of the processes reflected in

this early switch positivity resulted in greater anticipatory reconfiguration. Importantly, the

diffusion analysis demonstrates that behavioral results are consistent with the interpretation

of D-Pos1 as being representative of preparation for an upcoming change in task-set. These

data provide a crucial link between behavioral and ERP data which does not exist when only

mean RT is considered.

  Although these findings strongly support the contention that partially informative cues

trigger some anticipatory reconfiguration process, there are at least two possible

interpretations about the precise nature of this process. One possibility is inhibition of the

previously relevant task-set, which both *switch-to* and *switch-away* cues indicate will not be

relevant on the current trial (Nicholson et al., 2006b). Another is activation of one or more

task-sets which the cues indicate are likely to be relevant for the following target[3]. In the

latter case, *switch-away* cues could either activate both possible task-sets or randomly

activate one of the two possible task-sets. If both possible task-sets are activated, it seems

likely that cue-locked waveforms would reflect greater processing for *switch-away* trials than *switch-to* trials. Hence, cue-locked differentiation between *repeat* and switch trials (i.e., D-Pos1) should be larger or more prolonged for *switch-away* cues than for *switch-to* cues (i.e., *switch-to* trials = one task-set activation, *switch-away* trials = two task-set activations). Furthermore, *non-informative* cues are also likely to activate the non-repeat task-set. Therefore, the cue-locked positivity should show amplitude changes so that *repeat<switch-to=non-informative< switch-away*. This order is not compatible with the pattern of differences observed in cue-locked waveforms.

If *switch-away* cues activate only one of the two cued task-sets in a random or semi-random fashion, the behavioural advantages which we found for *switch-away* over *non-informative* cues are difficult to understand. As both types of cues afford the same level of uncertainty reduction about the nature of the upcoming task, it seems likely that both would be used to activate the corresponding task-sets in the same way. If this were the case then there should be no behavioural advantage for *switch-away* trials over *non-informative* trials, which is not what was observed. It remains possible, however, that the task-set activation account is correct if participants only, or more efficiently, use *switch-away* cues for task-set activation, although it is unclear why this might be the case.

The alternative interpretation (Nicholson et al., 2006b) is that anticipatory task-set reconfiguration is a multi-component process that encompasses both inhibition of the previously active task-set, reflected in the early D-Pos1, and activation of the now relevant task-set, reflected in the later D-Pos2. Variation across *switch-to*, *switch-away* and *non-informative* cues in both D-Pos1 and non-decision time is compatible with a process of suppression or inhibition of the previously active task-set, which may be conceptualized as being similar to the idea of disengagement of attention to spatial location invoked in cued spatial attention tasks (e.g., Posner, 1980 but see Cohen, Romero, Servan-Schreiber, & Farah,

1994). This interpretation is strengthened by the finding that the amplitude of the early cue-locked positivity for both *switch-to* and *switch-away* cues was inversely related to mean RT and non-decision time, suggesting that greater anticipatory reconfiguration, which we argue involves inhibition of the irrelevant task-set, leads to faster RT by reducing non-decision time.

The evidence accumulation (diffusion) model analysis not only provided evidence for a behavioral benefit arising as a result of task-set inhibition but also a plausible explanation of why this behavioral benefit is not evident in mean RT measures. Specifically, model parameters indicated that the non-decision time advantage offered by this partial preparation was not evident in mean RT because it was counteracted by another process which was also activated by cues that provided certainty of an upcoming switch in task, and which resulted in an increase in the decision time component of RT. Estimates of the criterion amount of evidence required to make a decision indicated that participants responded to cues that provided certainty of an upcoming switch in task (i.e., *switch-away* and *switch-to* cues) by requiring a higher standard of evidence, resulting in slower but more accurate decision for *switch-away* relative to the *non-informative switch* trials.

This more fine grained analysis of the behavioral data produced results that, in contrast to traditional approaches, are able to provide a unified explanation of both accuracy and speed. The fact that *switch-to* and *switch-away* cues were associated with both a reduction in non-decision time and an increase in evidence criterion suggests third interpretation of the anticipatory preparation process reflected in the early cue-locked positivity. Specifically, it is possible that D-Pos1 reflects the process of increasing the evidence criterion and that this is a time-consuming process that contributes to non-decision time. When this process can be completed before target onset, D-Pos1 is elicited in the cue-stimulus interval and non-decision time is reduced. When it is completed after target onset,

D-Pos1 is elicited after target onset and non-decision time is higher. Although this explanation is compatible with most of our results, it predicts that evidence criterion should be higher for all switch trials, but this was not the case for *non-informative switch* trials. This account is also not easily reconciled with the fact the target-locked positivity was elicited for both *non-informative switch* and *non-informative repeat* trials, even though neither showed an increase in evidence criterion. Furthermore, it would predict that the amplitude of the early cue positivity will be associated with a higher evidence criterion for both *switch-to* and *switch-away* cues. However, a larger early cue positivity was associated with faster non-decision time and *lower* evidence criterion, the latter being significant only for *switch-to* cues.

In conclusion, we have replicated evidence for an early cue-locked positivity which is elicited by cues that provide certainty of an upcoming switch in task. We provided strong evidence that this positivity is associated with an anticipatory component of the task-set reconfiguration process and with a behavioral benefit in the non-decision component of RT. We have identified a number of alternative interpretations of this process and have shown that most fail to explain the full set of behavioral and ERP data. It seems to us arguable, therefore, that although the data do not provide *direct* evidence for task-set inhibition as a component of anticipatory task-set reconfiguration, this interpretation provides the most plausible and comprehensive account of the data.

More broadly, the finding that simple behavioral measures and ERP measures may lead to theoretically opposed interpretations of the underlying cognitive processes suggests that such simple behavioral measures alone may be limited. We argue instead, that more sophisticated model-based analyses of behavior, combined with ERP and other neuroimaging measures, are likely to be more successful in providing a full account of all relevant processes (see also Forstmann et al., in press).

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Figure Legends

Figure 1. Example of task-position mapping (top, left). The four types of cues used to indicate the requirements of the next trial (repeat, switch-to switch-away and non-informative). Each cue type was presented on 25% of trials. Bottom: Stimulus-response mappings with the four possible stimuli associated with each response. These were counterbalanced across participants.

Figure 2. A. Cue-locked ERP and difference waveforms for each trial type at POz. Grey bars indicating mean amplitude windows used in analyses. B. Head maps showing sites of significant deviation between different trial types over 250-400ms and 450-700ms. Open squares: α =.05; filled squares: α =.01. Over 250-400 ms, the *switch-to* vs. *repeat* contrast was most significant over parieto-occipital sites ($p=2.6^{-6}$ - 0.005). The *switch-away* vs. *repeat* contrast was most significant over frontal and parieto-occipital electrodes ($p=2.5^{-8}$ - 0.01). The *non-informative* vs. *switch-away* contrast was most significant over parieto-occipital electrodes ($p=5.1^{-5}$ - 0.01). Over 450-700 ms, the *switch-to* vs. *repeat* contrast was most significant at POz ($p=0.009$). The *switch-to* vs. *switch-away* contrast was most significant at parieto-occipital sites ($p=.0009$ - 0.01).

Figure 3. A. Target-locked ERP and difference waveforms at F4 and Cz. Grey bars indicating the respective mean amplitude windows used in analysis. B. Head maps showing sites of significant positive deviation relative to repeat trials over 180-250ms, 300-370ms and 420-550ms. Open squares: $\alpha=0.05$; filled squares: α =0.01. Over 180-250ms, the *switch-away* vs. *repeat* contrast was most significant at F4 ($p=0.009$). The *non-informative repeat* vs. *repeat* contrast was most significant over frontal sites ($p=0.002$ - 0.01). Over 300-370ms, the

switch-away vs. *repeat* contrast was most significant electrode at F8 (*p*=0.02). The *non-informative repeat* vs. *repeat* contrast was most significant over left centro-parietal sites (*p*=0.0009 - 0.01). The *non-informative switch* vs. *repeat* contrast was most significant at F4 (*p*=0.007). Over 420-550ms, the *switch-to* vs. *repeat* contrast and the *switch-away* vs. *repeat* contrast were most significant over centro-parieto- occipital electrodes (*p*=0.0001 -0.009; *p*=0.0003 - 0.009, respectively). The *non-informative repeat* vs. *repeat* contrast was most significant at Cz (*p*=0.005) and the *non-informative switch* vs. *repeat* contrast was most significant over fronto-central sites (*p*=0.004 - 0.009).

Figure 4. A. Mean RT and error proportion for each trial type. B. Cue-locked ERPs: mean amplitude over 250-400ms and 450-700ms at POz. C. Target-locked ERPs: mean amplitude over 180-250ms and 300-370ms at F4 (left, middle) and over 420-550ms at Cz (right). R = Repeat, NI-R = Non-informative Repeat, S-To = Switch To, S-Aw = Switch Away, NI-S = Non-informative Switch. Significant differences between conditions are shown by solid lines at p<.01 and broken lines at p<.05.

Figure 5. Cumulative distribution functions created by averaging data deciles over participants and conditions, and similarly averaged deciles produced by Ex-Gaussian and EZ2 fits.
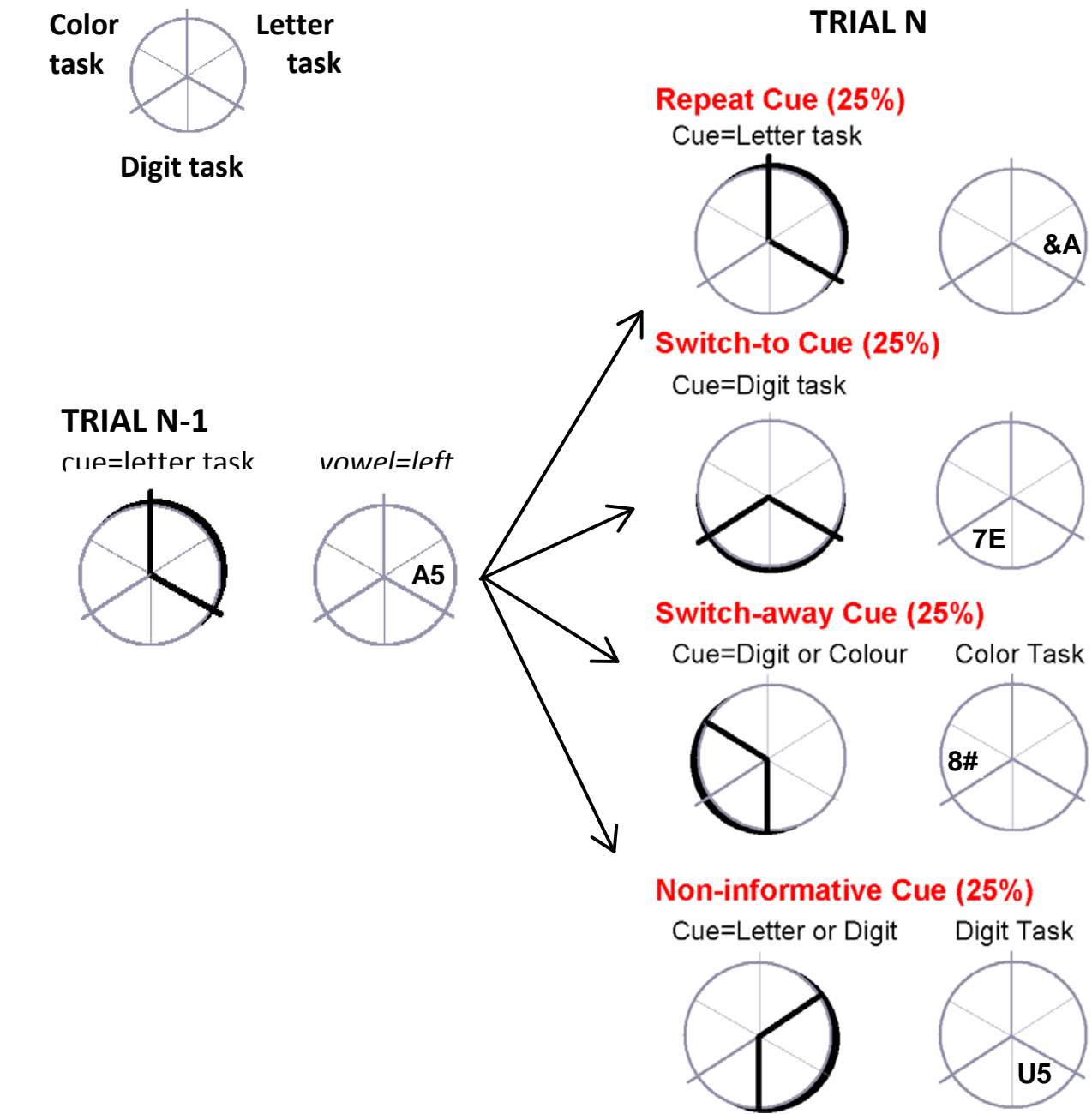
Figure 6. Diffusion model parameters R = Repeat, NI-R = Non-informative Repeat, S-To = Switch To, S-Aw = Switch Away, NI-S = Non-informative Switch. Significant differences between conditions are shown by solid lines at *p*<.01.

FOOTNOTES

[1] For readers concerned that this behavioural effect is entirely dependent on the diffusion model being correct, it is important to note that differences in *Ter* between conditions equal differences in the fastest RTs for those conditions. Hence, an interpretation of these results purely in terms of observed behaviour is that *switch-away* cues reliably speed up the fastest responses relative to *non-informative* cues.

[2] As with non-decision time effects, criterion differences correspond to an observable behavioural difference. In the case of criterion effects this is RT variance. When drift rate (which also affects RT variance) is the same between two conditions (e.g., *switch-to* and *non-informative* in our data) but one condition has a larger criterion (e.g., *switch-to* has a greater criterion than *non-informative* in our data) it will also have a larger variance.

[3] We thank an anonymous reviewer for this suggestion.

Color task / Letter task / Digit task

TRIAL N-1
cue=letter task   vowel=left

A5

TRIAL N

Repeat Cue (25%)
Cue=Letter task
&A

Switch-to Cue (25%)
Cue=Digit task
7E

Switch-away Cue (25%)
Cue=Digit or Colour   Color Task
8#

Non-informative Cue (25%)
Cue=Letter or Digit   Digit Task
U5

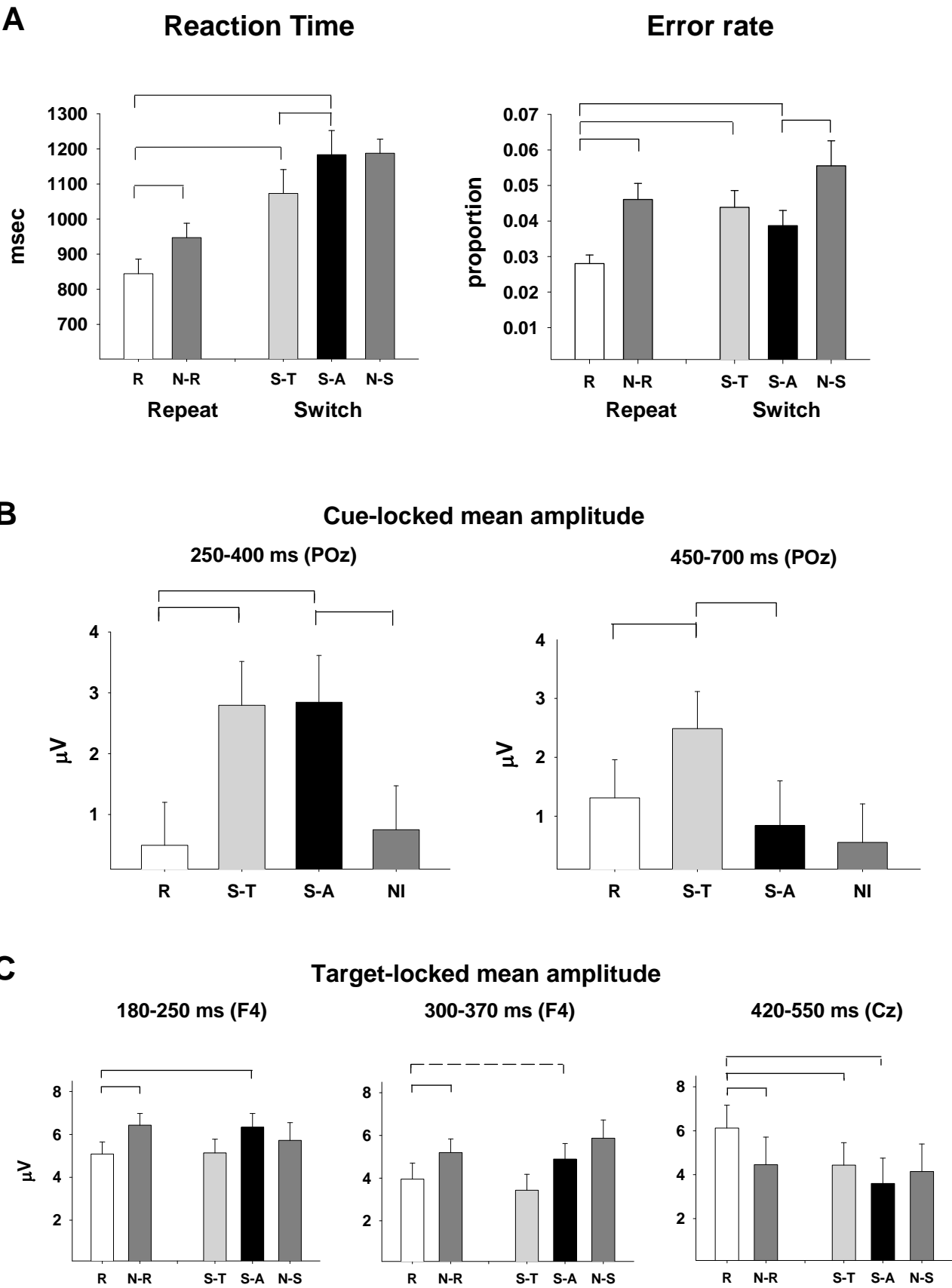| Example of S-R mapping	Left hand response	Right hand response
Letter Task	Vowel (A, E, I, U)	Consonant (G, K, M, R)
Digit Task	Even (2, 4, 6, 8)	Odd (3, 5, 7, 9)
Color Task	Cold (forest green, lime green, sky blue, turquoise)	Hot (red, pink, orange, yellow)

FIGURE 2

A.

Target-locked ERP waveforms

Difference waveforms

-2μV

-1μV

F4

Cz

	Rpt
	N-R
	S-T
	N-S
	S-A

	N-R - Rpt
	S-T - Rpt
	N-S - Rpt
	S-A - Rpt

-200 0   200 400 600 800 1000

B.

180-250 ms

S-A vs. Rpt   N-R vs. Rpt

300-370 ms

S-Aw vs. Rpt   N-R vs. Rpt   N-S vs. Rpt

420-550 ms

S-T vs. Rpt   S-A vs. Rpt   N-R vs. Rpt   N-S vs. Rpt