Increased cognitive control after task conflict?

Investigating the N-3 effect in task switching

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Abstract

Task inhibition is considered to facilitate switching to a new task, and is assumed to decay slowly over time. Hence, more persisting inhibition needs to be overcome when returning to a task after one intermediary trial (ABA task sequence) than when returning after two or more intermediary trials (CBA task sequence). Schuch and Grange (2015) put forward the hypothesis that there is higher task conflict in ABA than CBA sequences, leading to increased cognitive control in the subsequent trial. They provided evidence that performance is better in trials following ABA than following CBA task sequences. Here, this effect of previous task sequence ("N-3 effect") is further investigated by varying the Cue–Stimulus Interval (CSI), allowing for short (100ms) or long (900ms) preparation time for the upcoming task. If increased cognitive control after ABA involves better preparation for the upcoming task, the N-3 effect should be larger with long than short CSI. The results clearly show that this is not the case. In Experiment 1, the N-3 effect was smaller with long than short CSI; in Experiment 2, the N-3 effect was not affected by CSI. Diffusion-model analysis confirmed previous results (regarding the effect of CSI and of the ABA-CBA difference); however, the N-3 effect was not unequivocally associated with any of the diffusion model parameters. In exploratory analysis we also tested the alternative hypothesis that the N-3 effect involves more effective task shielding, which would be reflected in reduced congruency effects in trials following ABA, relative to trials following CBA; congruency effects did not differ between these conditions. Taken together, we can rule out two potential explanations of the N-3 effect: Neither is this effect due to enhanced task preparation, nor to more effective task shielding. (286 words)

Keywords: N-2 task repetition costs, N-3 effect, CSI, cognitive control, task conflict

Public significance statement

The N-3 effect is a recently discovered sequential effect in task switching, and possibly reflects flexible recruitment of cognitive control. Here, we explored whether the N-3 effect involves improved preparation for an upcoming task, or more efficient shielding of the relevant task against the irrelevant tasks. The results show that the N-3 effect does not involve advance task preparation, and neither task shielding, but must be due to other cognitive mechanisms.

Introduction

Cognitive control refers to higher-order cognitive processes that enable goal-directed behavior; for instance, focusing on task-relevant information in the face of competing, irrelevant information (e.g., Grange & Houghton, 2014; Kiesel et al., 2010). A prominent theory proposes that the intensity of cognitive control processes is adjusted dynamically, with cognitive conflict triggering an increase in cognitive control (Botvinick, Braver, Barch, Carter & Cohen, 2001). Evidence in line with this theory so far has mainly been gathered in single-task paradigms where response conflict was manipulated. A standard finding is that cognitive processing is more selective in trials following high response conflict than in trials following low response conflict (see e.g., Duthoo, Abrahamse, Braem, Boehler, & Notebaert, 2014a, 2014b; Egner, 2007, 2017, for reviews).

In a recent paper, Schuch and Grange (2015) suggested that trial-to-trial adaptation of control can also be triggered by task conflict in a task-switching situation. They applied a N-2 task repetition cost paradigm, where task sequences of the type ABA (where the task performed in trial N is the same as the task performed in trial N-2) are compared to type CBA (where the task in trial N is not the same as in trial N-2). Performance is usually worse in ABA than CBA task sequences, presumably due to larger persisting inhibition of the previously inhibited task A in ABA sequences (Mayr & Keele, 2000; see Gade, Schuch, Druey, & Koch, 2014; Koch, Gade, Schuch, & Philipp, 2010; Mayr, 2007, for reviews). Schuch and Grange (2015) reasoned that, due to this persisting inhibition, ABA trials can be considered as trials with high task conflict relative to CBA trials, and this task conflict increases cognitive control in the trial *following* an ABA sequence. In line with this expectation, performance in trials *after* ABA sequences was found to be better than performance *after* CBA sequences; this effect was termed the "N-3 effect".

N-3 effect and task preparation

Here, we conducted two experiments further investigating this new N-3 effect. Assuming that the N-3 effect reflects increased cognitive control, one possibility is that it involves improved preparation for the upcoming task. Several authors have suggested that task preparation involves activation of the relevant attentional settings and task rules in working memory, and that task preparation builds up gradually over time (for reviews, see Kiesel et al., 2010; Koch, Poljac, Müller & Kiesel, 2018). A common method for investigating task preparation processes is to manipulate the time available for task preparation, by varying the interval between presentation of a task cue (indicating the upcoming task) and the imperative stimulus that needs to be processed according to the relevant task rules (Cue–Stimulus Interval, CSI).

We reasoned that if the N-3 effect is due to more intense preparation for the upcoming task (such as stronger activation of the task-relevant stimulus categories and task rules), then the more time there is for preparation, the larger the N-3 effect should become. To investigate this prediction, we manipulated the time for task preparation, with either short (100ms) or long (900ms) CSI. In Experiment 1, CSI varied from one experimental block to the next. In Experiment 2—in order to disentangle CSI in the current and previous trials—only every fourth trial had a short (100ms) or long (900ms) CSI (manipulated blockwise), while the three preceding trials had an intermediate CSI of 500ms. Thus, potential differences between the short and long CSI condition could be unambiguously traced back to CSI on the current trial, and could not be due to CSI on the three preceding trials (cf. Scheil & Kleinsorge, 2014).

We predicted that with long CSI, participants will engage in more task preparation than with short CSI, and hence performance will be better with long than short CSI. Importantly, if the N-3 effect involves improved task preparation, the N-3 effect should be more pronounced with long than with short CSI, because there is more time for task preparation. Speaking in statistical terms, we predicted an interaction of the factors “CSI (short versus long)” and “Previous Task Sequence (trials after ABA versus trials after CBA)”, as illustrated in Figure

1. (To explicate, we applied a three-factorial design with the factors CSI, Task Sequence, and Previous Task Sequence. The factor Previous Task Sequence denotes the N-3 effect (i.e., trials after ABA versus trials after CBA), and the factor Task Sequence (ABA versus CBA) denotes standard N-2 task repetition costs. Replicating previous research, we also predict main effects of Previous Task Sequence and of Task Sequence, cf. Schuch & Grange, 2015, as well as a main effect of CSI, see Kiesel et al., 2010, Koch et al., 2018, for reviews).

Diffusion modeling

In order to further investigate the cognitive processes underlying the N-3 effect, we also performed a diffusion model analysis on the data. Diffusion modeling is a valuable tool for complementing analyis of mean performance, because it makes more thorough use of the data, taking response time distributions of correct and incorrect responses into account (for reviews, see, e.g., Ratcliff & McKoon, 2008; Ratcliff, Smith, Brown & McKoon, 2016). The diffusion model is a process model, which models—and thererfore enumerates—core components of the response process. In a nutshell, diffusion models discriminate between the decision process and non-decisional processes in speeded choice RT tasks. Decisional processes comprise of the rate of evidence accumulation for a particular response, and the criterion for the amount of evidence required for a response. Non-decisional processes comprise perceptual encoding of stimuli and motoric proceses.

Previous research has allocated effects of a CSI manipulation in task switching to two parameters: non-decision time and drift rate. In task-switch trials, non-decision time was larger with short than long CSI (Karayanidis, Mansfield, Galloway, Smith, Provost, & Heathcote, 2009; Madden et al., 2009; Schmitz & Voss, 2012, 2014). This finding is in line with the idea that task-preparation processes occur prior to response-selection processes, and that with short CSI, more task preparation occurs after stimulus onset than with long CSI, where more task preparation can occur prior to stimulus onset. Moreover, drift rate was smaller in task-switch trials with short than long CSI in the studies by Schmitz and Voss

(2012, 2014). This latter effect could reflect how well the currently relevant task rules are implemented, with better implementation with long than short CSI, presumably as a result of more task preparation. Better implementation of the current task rules means that the cognitive representation of the currently relevant task rules is less noisy, leading to higher drift rates in trials with long than short CSI.

Regarding the N-3 effect, no diffusion model analysis has been conducted so far. We reasoned that if the N-3 effect involves more intense task preparation, this should be reflected by an interaction of the factors CSI and Previous Task Sequence in the diffusion-model parameters of non-decision time, drift rate, or both.

N-3 effect and task shielding

In a further exploratory analysis, we investigated an alternative hypothesis stating that the N-3 effect involves more efficient task shielding. In particular, the N-3 effect might reflect increased cognitive control after ABA (relative to after CBA) in the sense that the relevant task is shielded more efficiently against influences from the competing, currently unrelevant, tasks (e.g., Goschke, 2013; Goschke & Bolte, 2014). Such task shielding may be indicated by reduced congruency effects after ABA than after CBA. Congruency effects in task switching occur when different stimulus features relating to the relevant and irrelevant tasks trigger the same response (congruent trials) or different responses (incongruent trials). Performance is worse in incongruent than congruent trials (congruency effect; e.g., Bugg & Braver, 2016; Kiesel et al., 2010; Meiran, 2000; Rogers & Monsell, 1995; Sudevan & Taylor, 1987), indicating the currently irrelevant task is processed to some degree. The smaller the congruency effects, the more efficient the relevant task is shielded against the irrelevant task. Congruency effects also occur when switching between three different tasks (Longman, Lavric, Munteanu & Monsell, 2014; Schneider, 2014), and hence, can be analyzed in the present experiments as well. In order to test the hypothesis that the N-3 effect involves increased task shielding, we compared congruency effects after ABA versus after CBA

sequences. If the N-3 effect involves increased task shielding, congruency effects should be smaller after ABA than after CBA task sequences.

Experiment 1

In Experiment 1, cue-based preparation time for the upcoming task was manipulated blockwise. Particpants alternated between blocks with short (100ms) and long (900ms) CSI.

Method

Participants. 32 participants were tested (18 women, 14 men; mean age: 27.7 years, SD= 4.7; range 20 to 36 years). The participants of Experiments 1 and 2 were recruited from the Aachen area and from the Psychology Students' Participant Panel and received either 8 Euros per hour or partial course credits for compensation. All participants had normal or corrected-to-normal vision and were naïve with respect to the purpose of the experiment. Informed consent was obtained from all individual participants included in the study. The study was in accordance with the ethical standards of the national research committee and with the 1964 Helsinki declaration and its later amendments.

The number of participants results from constraints of counterbalancing: The eight possible stimulus–response (S–R) mappings and CSI order were fully counterbalanced across participants, resulting in 16 different combinations. The achieved power with N=32 for detecting a 2x2 within-subjects interaction (i.e., interaction of the factors CSI and Previous Task Sequence) was .92 (as computed with G*Power 3; Faul, Erdfelder, Lang & Buchner, 2007; assuming a medium effect size of f=0.25 and a correlation of within-subject measurements of r=.50).

Tasks, Stimuli, and Responses. The same paradigm as in Schuch and Grange (2015, Experiment 1) was used (see also Schuch, Werheid & Koch, 2012). The stimuli were 40 different pictures of faces that had to be categorized as female or male (gender task), young or old (age task), or showing a happy or angry expression (emotion task). The pictures were 10.6 cm by 14.1 cm in size and were presented centrally on the computer screen; viewing distance

was about 50 cm. The tasks were indicated by the color of a frame that surrounded the facial pictures (blue frame color indicating the gender task, red indicating the age task, yellow indicating the emotion task). A left and right response key was used for responding (the "x" and "," keys on a QWERTZ keyboard, which are located just above the left and right end of the space bar, respectively). Subjects used their left and right index fingers for responding.

Procedure. Participants performed two short blocks of practice with 12 trials each to familiarize themselves with the tasks. Each practice block included four trials of each task, presented in pseudorandom order; immediate task repetitions could not occur. Then, participants proceeded with eight blocks of 120 trials each, which were separated by self-paced breaks. The experiment took about 1 hour in total.

In all blocks, task cues (i.e. colored frames) and stimuli (i.e., facial pictures) occurred in pseudorandom order, with the following constraints: (1) immediate task repetitions were not allowed; (2) each task–stimulus combination occurred once per block (i.e., each of the three tasks occurred 40 times per block, and each of the 40 stimuli occurred equally often in the context of each task); and (3) there was a roughly equal number of trials for each cell of the 2x2 matrix of Task Sequence (ABA, CBA) and Previous Task Sequence (previous ABA, previous CBA); range 28 to 32 trials per cell per block. The person presented in the stimulus image on a particular trial n was never the same as the persons presented in trials n–1 and n–2. Moreover, it was controlled that ABA sequences included a roughly equal number of response repetitions and response switches from trial n-2 to n (7 to 12 response repetitions from n-2 to n in ABA sequences per task per block). In CBA sequences, the number of n-2 response repetitions depended on the particular S-R mapping; S-R mappings were fully counterbalanced across participants (see above).

The trial procedure was as follows. Every trial started with the presentation of a red, blue, or yellow frame for either 100ms or 900ms (depending on CSI condition), followed by the presentation of a picture inside the frame. Frame and picture stayed on the screen until the left

or right response key was pressed. Then the screen turned black for 1,400ms or 600ms (depending on CSI condition). If the wrong key was pressed, an error feedback occurred after 500ms of blank screen and lasted for 1,000ms, after which the screen turned black again for another 900ms or 100ms (depending on CSI condition). That is, the interval between the response in the previous trial and the stimulus in the current trial (response-stimulus interval, RSI) was constant across CSI conditions (1,500ms after correct responses; 2,500ms after incorrect responses).

The cue-stimulus interval varied blockwise, with half of the participants starting with short CSI, the other half with long CSI. The instructions encouraged participants to prepare for the upcoming task as soon as the task cue was presented, and it was mentioned that preparation time was very short in some blocks and longer in other blocks.

Design

A 2x2x2 within-subjects design with the independent variables CSI (100ms vs 900ms), Task Sequence (ABA vs CBA), and Previous Task Sequence (Previous ABA, Previous CBA) was applied. The dependent variables were RT and Error Rates.

Results

Data filtering. After visual inspection of the RT distribution, RTs above 10,000ms and premature responses (that occurred before stimulus onset) were excluded from further analysis (0.04% of the data), as were the first three trials of each experimental block. Then outliers were identified as RTs above or below 2.5 *SDs* of each participant's mean per condition (2.8% of the data). Outliers and the three trials following an error were removed for analysis of both RT and error data; for RT analysis, error trials were removed as well. The mean number of trials per condition and particpant for analysis of error rates was 101 (SD 10, min 53, max 119); for analysis of RT, it was 97 (SD 12, min 42, max 119). Three-way within-subjects ANOVAs with the independent variables CSI, Task Sequence, Previous Task Sequence were computed separately on mean RTs and mean Error Rates.

To match with the analysis reported in Schuch and Grange (2015), we also checked for slow participants in the sample. There were four participants whose overall mean RT (1,822ms, 1,893ms, 1,986ms, and 2,177ms, respectively) was more than 2.5 SDs above the mean RT of all other participants (1,065ms, *SD*=237ms). The analyses were computed with and without these four slow participants. The patterns of significant effects in the ANOVAs remained the same, unless reported otherwise.

Mean RTs. See Figure 2. The ANOVA on mean RTs revealed a trend for a main effect of CSI, $F(1,31)=3.26$, $p=.08$, $\eta^2_p=.10$ [significant main effect of CSI without the slow participants, $F(1,27)=5.18$, $p<.05$, $\eta^2_p=.16$], indicating faster RT with longer CSI. A main effect of Task Sequence was obtained, $F(1,31)=62.58$, $p<.01$, $\eta^2_p=.67$, indicating persisting task inhibition in ABA relative to CBA sequences. There was also a significant main effect of Previous Task Sequence, $F(1,31)=10.97$, $p<.01$, $\eta^2_p=.26$, indicating the N-3 effect (i.e., shorter RT when the Previous Task Sequence was ABA than when it was CBA).

An interaction between CSI and Previous Task Sequence was obtained, $F(1,31)=5.15$, $p<.05$, $\eta^2_p=.14$, indicating that for short CSI, performance was faster after ABA than after CBA trials (i.e., the N-3 effect), whereas for the long CSI, this was not the case (i.e., no N-3 effect). Moreover, there was a trend for an interaction of Task Sequence and Previous Task Sequence, $F(1,31)=3.48$, $p=.07$, $\eta^2_p=.10$, indicating a smaller effect of Previous Task Sequence in ABA than CBA trials. The interaction between CSI and Task Sequence was not significant, $F(1,31)=2.11$, $p=.16$, $\eta^2_p=.06$, and neither was the three-way interaction, $F(1,31)=2.53$, $p=.12$, $\eta^2_p=.08$.

Mean Error Rates. See Figure 2. The corresponding ANOVA on mean error rates yielded a trend for a main effect of CSI, $F(1,31)=3.48$, $p=.07$, $\eta^2_p=.10$, (significant main effect of CSI without the slow participants, $F(1,27)=4.15$, $p=.05$, $\eta^2_p=.13$), indicating less mistakes with longer CSI. No significant main effects were found for Task Sequence, or Previous Task Sequence, Fs<1.

The ANOVA showed a significant interaction of CSI and Previous Task Sequence, $F(1,31)=4.37$, $p<.05$, $\eta^2_p=.12$, indicating less mistakes after ABA than after CBA with short CSI (i.e., N-3 effect with short CSI), but more *more* mistakes after ABA than CBA with long CSI (i.e., *reversed* N-3 effect with long CSI). No other effects were significant ($F(1,31)=2.30$, $p=.14$, $\eta^2_p=.07$, for the interaction of Task Sequence and Previous Task Sequence; all other Fs<1).

Discussion

As expected, performance was better with long than short preparation time (marginally better when all participants were considered; significantly better when the very slow participants were excluded), suggesting that participants engaged in advance task preparation for the upcoming task. Performance also differed between ABA and CBA task sequences, replicating standard N-2 task repetition costs that indicate persisting task inhibition in ABA relative to CBA. Moreover, the N-3 effect reported by Schuch and Grange (2015) was replicated, with better performance after ABA than after CBA trials.

Further investigating the nature of the N-3 effect, it was hypothesized in the present study that the N-3 effect might reflect increased task preparation, triggered by a task conflict experienced in ABA trials. If this was the case, the N-3 effect should become more pronounced with long task preparation time. The results clearly show that the N-3 effect does *not* become larger with longer CSI. To the contrary, in both mean RTs and error rates, the N-3 effect was significantly *smaller* with long than with short CSI. Hence, the N-3 effect does not seem to involve improved task-specific preparation. Before further discussing this finding, we turn to Experiment 2, where we addressed a potential confound of Experiment 1.

Experiment 2

Experiment 2 served to disentangle the effects of CSI in the current trial from that in the previous trials. In Experiment 1, all trials within a block had short or long CSI, hence the effect of CSI in the current trial N could not be distinguished from potential effects of CSI in

the previous trials N-1, N-2, and N-3 (cf. Scheil & Kleinsorge, 2014). In Experiment 2, only every fourth trial had a short (100ms) or long (900ms) CSI (manipulated blockwise), while the three preceding trials always had an intermediate CSI of 500ms. Thus, when analyzing the trials with short versus long CSI, potential differences between the CSI conditions can now be unambiguously attributed to CSI on the current trial, and could not be due to CSI on the three preceding trials.

Method

Participants. 32 new participants were tested (28 women, 4 men; mean age: 23.0 years, SD= 4.1; range 19 to 35 years).

Tasks, Stimuli, and Responses. These were the same as in Experiment 1.

Procedure. Participants performed two short blocks of practice with 12 trials each, followed by 16 experimental blocks of 120 trials each, separated by self-paced breaks. Task cues and stimuli were presented in pseudorandom order with the same constraints as in Experiment 1. The experiment took about 2 hours in total.

In all blocks, the CSI was 500ms for three consecutive trials, followed by one trial with short (100ms) or long (900ms) CSI. Whether the CSI in every fourth trial was short or long was varied blockwise, with half of the participants starting with short CSI, the other half with long CSI.

The trial procedure for the trials with short and long CSI was as in Experiment 1; that is, the colored frame was presented for either 100ms or 900ms (depending on CSI condition), followed by presentation of the target picture, both of which remained visible until the left or right response key was pressed. After a correct response the screen turned black for 1,400ms or 600ms (depending on CSI condition). After a wrong response, an error feedback occurred after 500ms of blank screen and lasted for 1,000ms, after which the screen turned black again for another 900ms or 100ms (depending on CSI condition). In the trials with intermediate CSI, the colored frame was presented for 500ms, followed by the presentation of the target

picture; after correct responding the screen turned black for 1,000ms. After wrong responses, an error feedback occurred after 500ms of blank screen and lasted for 1,000ms, after which the screen turned black again for another 500ms. That is, the RSI was constant across all CSI conditions (1,500ms after correct responses; 2,500ms after incorrect responses).

Design

As in Experiment 1, a 2x2x2 within-subjects design was applied with the independent variables CSI (100ms vs 900ms), Task Sequence (ABA vs CBA), and Previous Task Sequence (Previous ABA, Previous CBA). In contrast to Experiment 1, only every fourth trial was analyzed, because only these had a CSI of either 100ms or 900ms. For the sake of completeness, the remaining trials with a CSI of 500ms were analyzed in an additional analysis, as a function of Task Sequence and Previous Task Sequence. The dependent variables were RT and Error Rates.

Results

Data filtering. The data were filtered in the same way as in Experiment 1. RTs above 10,000ms and premature responses (that occurred before stimulus onset) were excluded from further analysis (0.06% of the data). Outliers were identified as RTs above or below 2.5 *SDs* of each participant's mean per condition, separately for short, intermediate, and long CSI (2.7% of the data in total). The mean number of trials per condition and particpant for analysis of error rates was 49 (SD 8, min 27, max 67); for analysis of RT it was 46 (SD 9, min 23, max 66). We also checked for slow participants in Experiment 2; applying the same criterion as in Experiment 1 (i.e., participants showing an overall mean RT more than 2.5 SDs above the mean RT of all other participants) did not reveal any slow participants in Experiment 2.

Mean RTs. See Figure 3. The ANOVA on mean RTs revealed a large main effect of CSI, $F(1,31)=243.05$, $p<.01$, $\eta^2_p=.89$, indicating faster RT in trials with long CSI than with short CSI. A main effect of Task Sequence was obtained, $F(1,31)=52.40$, $p<.01$, $\eta^2_p=.63$, indicating N-2 task repetition costs, as well as a main effect of Previous Task Sequence, $F(1,31)=22.83$,

p<.01, η^2_p=.42, indicating faster RT after ABA than after CBA task sequences (i.e., the N-3 effect). Furthermore, an interaction of CSI and Task Sequence was obtained, F(1,31)=6.43, p=.02, η^2_p=.17, indicating larger N-2 task repetition costs with short than long CSI. There was no interaction of CSI and Previous Task Sequence, F<1, indicating that the N-3 effect did not differ between short and long CSI condition, and no other effects reached significance (F(1,31)=2.60, p=.12, η^2_p=.08, for the interaction of Task Sequence and Previous Task Sequence; F<1 for the three-way interaction).

Mean Error Rates. See Figure 3. The ANOVA on mean error rates revealed a main effect of CSI, F(1,31)=14.85, p<.01, η^2_p=.32, indicating lower error rates in trials with long CSI than short CSI. A main effect of Task Sequence was obtained, F(1,31)=5.64, p=.02, η^2_p=.15, indicating higer error rates in ABA relative to CBA sequences. No main effect of Previous Task Sequence was obtained, F<1. There was a marginally significant interaction of Task Sequence and Previous Task Sequence, F(1,31)=4.11, p=.05, η^2_p=.12, which was modulated by a trend for a three-way interaction of Task Sequence, Previous Task Sequence, and CSI, F(1,31)=3.05, p=.09, η^2_p=.09. As can be seen from Figure 3, the N-3 effect was stronger for ABA than CBA, and this data pattern tended to be more pronounced with long than with short CSI. No other effects reached significance, Fs<1.2.

Additional analysis of CSI 500 trials

In the main analysis above, only every fourth trial (that had either short or long CSI) was analyzed. For the sake of completeness, an additional analysis was conducted on the intermediate trials (i.e., trials with CSI of 500ms). These trials were analyzed in two-way ANOVAs with the independent variables Task Sequence and Previous Task Sequence (see Figure 4), in order to establish whether N-2 task repetition costs and the N-3 effect could be observed in these trials as well.

Data filtering. The same criteria as for the main analyses were applied, resulting in an average of 266 trials per condition and participant (SD 42, min 151, max 335) for analysis of mean RT; 282 trials (SD 34, min 185, max 341) for analysis of mean error rates.

Mean RTs. The ANOVA yielded a main effect of Task Sequence, $F(1,31)=56.06$, $p<.01$, $\eta^2_p=.64$, indicating N-2 task repetition costs, and a main effect of Previous Task Sequence, $F(1,31)=50.00$, $p<.01$, $\eta^2_p=.62$, indicating the N-3 effect. There was also an interaction of Task Sequence and Previous Task Sequence, $F(1,31)=16.59$, $p<.01$, $\eta^2_p=.35$, indicating a larger N-3 effect in CBA than ABA trials.

Mean error rates. The ANOVA revealed a main effect of Task Sequence, $F(1,31)=10.90$, $p<.01$, $\eta^2_p=.26$, indicating N-2 task repetition costs. The main effect of Previous Task Sequence did not reach significance, $F(1,31)=2.41$, $p=.13$, $\eta^2_p=.07$. There was an interaction of Task Sequence and Previous Task Sequence, $F(1,31)=6.12$, $p=.02$, $\eta^2_p=.17$, indicating a larger N-3 effect in ABA than CBA trials, that is, opposite to the interaction pattern observed in RT data.

Discussion

Experiment 2 served to replicate Experiment 1, by comparing trials with short versus long CSI, while controlling for the potential confound of previous CSI length. To this end, in Experiment 2, the three trials preceding a short or long CSI always had an intermediate CSI. The results largely replicated the data pattern from Experiment 1. Performance was better with long than short preparation time, indicating that participants engaged in advance task preparation for the upcoming task. The CSI effect was more pronounced in Experiment 2 than in Experiment 1 (300ms versus 106ms in RT data; 1.8% versus 0.6% in error rates). N-2 task repetition costs were replicated, indicating worse performance in ABA than CBA, with similar effect sizes in Experiments 1 and 2. The N-3 effect was replicated as well, indicating better performance in trials *after* ABA than *after* CBA, again with comparable effect sizes in

Experiments 1 and 2. N-2 task repetition costs and the N-3 effect were observed in the intermediate trials with an CSI of 500ms as well, and again were of similar size.

As to the research question of whether the N-3 effect reflected increased task preparation, again no evidence was obtained to support this hypothesis. In Experiment 2, the N-3 effect did not differ between short and long CSI condition. Had the N-3 effect involved improved task-specific preparation, one would have expected the N-3 effect to become more pronounced with long task preparation time.

Diffusion model analysis of Experiments 1 and 2

In order to further investigate the nature of the N-3 effect, a diffusion model analysis was conducted on the data of Experiments 1 and 2. We aimed to determine whether the N-3 effect is reflected in decision time (i.e., processes related to response selection) or non-decision time (i.e., processes before or after response selection). As was outlined in the Introduction, previous studies applying diffusion modeling have found manipulations of the task preparation interval to be reflected in (a) non-decision time parameter and (b) drift rate parameter which is related to response selection (Schmitz & Voss, 2012, 2014). These findings are consistent with the idea that (a) cue-based task preparation takes place prior to response selection, leading to shorter non-decision time with long CSI, because more task preparation has occurred prior to stimulus onset with long CSI. These findings also indicate that (b) as a result of more task preparation, the task rules are implemented more strongly with long than short CSI, leading to a more efficient evidenc accumulation process (Schmitz & Voss, 2012, 2014). We reasoned that if the N-3 effect involves more intense task preparation, this should be reflected by an interaction of the factors CSI and Previous Task Sequence in the diffusion-model parameters non-decision time and/or drift rate.

Parameter Settings and Data Filtering

The software “fast-dm” (Voss & Voss, 2007) was used to estimate the three parameters response criterion (a), drift rate (v), and non-decision time parameter (t0). As recommended

by Voss, Voss, and Lerche (2015), the parameter for variability of non-decision time (st0) was allowed to vary as well in order to obtain robust estimations of parameters. The starting point bias was set to 0.5a (i.e., in the middle between the two thresholds). The lower and upper thresholds were set to reflect correct and wrong responses, respectively. All other parameters implemented in fast-dm were set to 0. The parameters v, a, t0, and st0 were estimated separately for each individual and each condition. Then, three-way ANOVAs with the independent variables CSI, Task Sequence, Previous Task Sequence were computed on each of the model parameters.

Data filtering for diffusion model analysis proceeded the same way as for analysis of mean performance, except that outliers were computed according to the procedure recommended by Schmiedek, Oberauer, Wilhelm, Süss and Wittmann (2007; see also Voss & Voss, 2007; Voss et al., 2015). That is, fast RTs below 300ms were excluded (based on visual inspection of the entire RT distribution), and outliers were defined as trials with RT above 4 SDs above the mean RT per condition and subject; this criterion was applied repeatedly until no further outliers were identified. The mean number of trials per condition and particpant for diffusion model analysis was 102 (SD 10, min 53, max 121) for Experiment 1 and 50 (SD 8, min 28, max 69) for Experiment 2.

Experiment 1

Model Fit. The Kolmogorov-Smirnov statistic provided by the fast-dm software did not reveal any significant deviations between empirical and estimated RT distributions, all *p*s > .19, suggesting that the model fitted the data reasonably well for all participants and all conditions (see online supplementary material, part 1, for graphical illustrations of model fit, showing empirical and predicted cumulative density functions of individual participants and conditions).

Model Parameters. The mean estimated model parameters for the different conditions are shown in Figure 5. For the threshold separation parameter, the three-way ANOVAs with the

independent variables CSI, Task Sequence, and Previous Task Sequence yielded a trend for a three-way interaction, $F(1,31)=3.87$, $p=.06$, $\eta^2_p=.11$; no other effects were significant, Fs<1.57. For the drift rate parameter, the respective ANOVA yielded a main effect of Task Sequence, $F(1,31)=6.27$, $p<.02$, $\eta^2_p=.17$; no other effects were significant, Fs<1.36. For the non-decision time parameter, the ANOVA revealed a main effect of CSI, $F(1,31)=7.94$, $p<.01$, $\eta^2_p=.20$, a main effect of Task Sequence, $F(1,31)=4.30$, $p<.05$, $\eta^2_p=.12$, and a trend for an interaction of CSI and Task Sequence, $F(1,31)=2.90$, $p=.10$, $\eta^2_p=.09$; no other effects were significant ($F(1,31)=2.44$, $p=.13$, $\eta^2_p=.07$, for the three-way interaction; all other Fs<1.21). The ANOVA on the variability of non-decision time did not reveal any significant effects ($F(1,31)=2.25$, $p=.14$, $\eta^2_p=.07$, for the main effect of CSI; all other Fs<1.0).

Experiment 2

Model Fit. The Kolmogorov-Smirnov statistic provided by the fast-dm software did not reveal any significant deviations between empirical and estimated RT distributions, all ps > .36 (see online supplementary material, part 2, for graphical illustrations of model fit).

Model Parameters. The mean estimated model parameters for Experiment 2 are shown in Figure 6. For the threshold separation parameter, the ANOVA with the independent variables CSI, Task Sequence, and Previous Task Sequence did not reveal any significant effects, all Fs<1.60. For the drift rate parameter, the respective ANOVA yielded a main effect of Task Sequence, $F(1,31)=6.62$, $p<.02$, $\eta^2_p=.18$; moreover, a main effect of CSI was obtained, $F(1,31)=4.87$, $p<.04$, $\eta^2_p=.14$, as well as a trend for an interaction of Task Sequence and CSI, $F(1,31)=3.66$, $p=.07$, $\eta^2_p=.11$; no other effects were significant, Fs<2.44. For the non-decision time parameter, the ANOVA revealed a large main effect of CSI, $F(1,31)=131.61$, $p<.01$, $\eta^2_p=.81$. Moreover, an interaction of CSI and Task Sequence was obtained, $F(1,31)=6.22$, $p<.02$, $\eta^2_p=.17$, as well as a trend for a main effect of Task Sequence, $F(1,31)=3.91$, $p=.06$, $\eta^2_p=.11$, and a trend for an interaction of CSI and Previous Task Sequence, $F(1,31)=3.23$, $p=.08$, $\eta^2_p=.09$ (for all other effects, Fs<1.49). Notably, the trend for an interaction of CSI and

Previous Task Sequence indicated a marginally smaller N-3 effect with long than with short CSI, which is opposite to the prediction outlined in the Introduction. The ANOVA on the variability of non-decision time revealed a large main effect of CSI, $F(1,31)=59.43$, $p<.01$, $\eta^2_p=.66$. There were also trends for main effects of Task Sequence, $F(1,31)=3.31$, $p=.08$, $\eta^2_p=.10$, and Previous Task Sequence, $F(1,31)=3.08$, $p=.09$, $\eta^2_p=.09$ (for all other effects, Fs<1.0).

Discussion of Diffusion Model Results

Effects of the CSI manipulation (short versus long CSI). In both Experiments 1 and 2, the CSI manipulation affected the non-decision time parameter, with larger non-decision time with short CSI than with long CSI. Regarding effect sizes, this effect was more pronounced in Experiment 2 (with intermediate CSI trials in between) than Experiment 1 (with blocked short and long CSI conditions). The finding of larger non-decision time with short than long CSI is in accordance with earlier research (Karayanidis et al., 2009; Madden et al., 2009; Schmitz & Voss, 2012, 2014), consistent with the idea that with long task-preparation interval, more task preparation can take place before stimulus onset, whereas with short task-preparation interval, more task preparation occurs after stimulus onset, prolonging RTs, and leading to longer non-decision time in diffusion-model analysis.

Apart from non-decision time, the CSI manipulation also had an effect on drift rate in Experiment 2 (but not in Experiment 1), with long CSI leading to higher drift rates than short CSI. A similar effect of CSI on the drift rate in task-switch trials was also observed in previous studies (Schmitz & Voss, 2012, Experiment 3c; Schmitz & Voss, 2014). Schmitz and Voss interpreted this finding in terms of an increased “task readiness” that is a consequence of better task preparation with long CSI than short CSI. Specifically, task preparation is assumed to involve retrieval of the relevant set of S-R rules from memory, and/or top-down biasing of the relevant set of S-R rules. The better the advance task

preparation, the less noisy the cognitive representation of the relevant set of S-R rules, and hence, the more efficient the response selection process once the stimulus is presented.

Regarding the research question on the nature of the N-3 effect, diffusion modeling results are less straightforward. We had reasoned that if the N-3 effect is related to task preparation, there should be an interaction of the factors CSI and Previous Task Sequence in non-decision time and/or drift rate, with larger effects of Previous Task Sequence with long than short CSI. There was no evidence for such an interaction in either Experiment 1 or 2; in Experiment 2, there was even a trend for a *reduced* N-3 effect with long relative to short CSI in non-decision time. That is, further corroborating the conclusions drawn from mean RT data, there is no evidence for the N-3 effect being linked to improved task preparation.

Effects of Previous Task Sequence (Previous ABA versus Previous CBA). The N-3 effect (i.e., better performance after ABA than after CBA) was not reflected as a main effect in any of the diffusion-model parameters. (The only effects of Previous Task Sequence were a trend for a three-way interaction in threshold separation in Experiment 1, but not in Experiment 2, and a trend for an interaction with CSI in non-decision time in Experiment 2 but not Experiment 1; it remains to be established whether these prove to be reliable effects.) Hence, diffusion-model analysis did not reveal any straightforward explanation of the N-3 effect.

Effects of Task-Sequence (ABA versus CBA). N-2 task repetition costs (ABA versus CBA) were reflected in drift rate in both Experiments 1 and 2, as was expected on the basis of previous research (Schuch, 2016; Schuch & Konrad, 2017). Drift rate is reduced in ABA relative to CBA trials, consistent with the idea that response selection is more difficult in ABA than in CBA trials due to persisting inhibition of task A in ABA relative to CBA.

In addition, N-2 task repetition costs were also reflected in non-decision time, with longer non-decision times in ABA than CBA (significant in Experiment 1, marginal in Experiment 2). This is different from previous studies (Schuch, 2016; Schuch & Konrad, 2017), where N-

2 task repetition costs in young adults were reflected in drift rate, but not in non-decision time. A closer look at the current data reveals that the effect in non-decision time occurred only in the short CSI condition (the interaction with CSI was marginally significant in Experiment 1, significant in Experiment 2). Hence, when preparation time is very short (100 ms), it seems that advance task preparation is less efficient in ABA than CBA.

Conclusions From Diffusion Modeling Results

In sum, diffusion model analyis confirmed the effect of CSI on non-decision time and drift rate, as well as the effect of Task Sequence on drift rate, both of which were reported in earlier research. Yet, diffusion modeling did not reveal any straightforward hints as to the cognitive mechanisms underlying the N-3 effect. All we can say at this point is that the N-3 effect does *not* seem to involve improved preparation for the upcoming task.

Analysis of congruency effects

An alternative hypothesis is that the N-3 effect is due to increased cognitive control in the form of increased task shielding. Several authors have proposed that there are varying degrees of how well the currently relevant task is established in a task-switching situation; if well established, there is very little interference from the competing tasks, and hence the relevant task is shielded very well (e.g., Goschke, 2013; Goschke & Bolte, 2014). In dual-task context, the degree of task shielding can be measured by assessing how much first-task performance is influenced by the stimulus feature that is relevant for the second task (backward crosstalk effect; e.g., Fischer, Gottschalk, & Dreisbach, 2014; Fischer & Hommel, 2012). Similarly, in the present task-switching experiments, task shielding may be measured by how much the currently irrelevant stimulus features influence performance of the relevant task, by assessing congruency effects (e.g., Bugg & Braver, 2016; Kiesel et al., 2010; Meiran, 2000; Rogers & Monsell, 1995).

When switching between two tasks that are mapped onto the same set of responses, a trial is either congruent or incongruent, depending on whether the currently irrelevant task requires

the same or a different response than the currently relevant task (Sudevan & Taylor, 1987). When switching between three tasks as in the current experiments, the definition of response congruency is more complex. Here, three levels of congruency can be distinguished: (a) Both irrelevant tasks require the same response as the relevant task; (b) one irrelevant task requires the same response, the other irrelevant task requires the alternative response; (c) both irrelevant tasks require the alternative response. Following Schneider (2014), these levels can be termed congruent, mixed, and incongruent, respectively. Schneider (2014) found that responses to incongruent trials were slower and less accurate than to mixed trials, which in turn were slower and less accurate than congruent trials (see also Longman et al., 2014).

In order to test the idea that the N-3 effect involves increased task shielding, in a post-hoc analysis, we analyzed congruency effects in the current data sets. If the N-3 effect involves increased task shielding, congruency effects should be smaller after ABA than after CBA task sequences. That is, there should be an interaction of the factors Congruency and Previous Task Sequence.

Experiment 1

Graded congruency effects were defined as in Schneider (2014): Trials could be either congruent (25%), mixed (50%), or incongruent (25%). For instance, consider a trial where the gender task was the relevant task, and the mapping condition where female, young, and happy were mapped onto the left response. In this case, a female-young-happy face would be a congruent trial; a female-young-angry face and a female-old-happy face would be mixed trials; a female-old-angry face would be an incongruent trial.

Mean RTs and mean error rates were analyzed as a function of Congruency (congruent, mixed, incongruent) and Previous Task Sequence (Previous ABA, Previous CBA). Descriptives are shown in Figure 7. Data filtering was the same as for the main analysis. For RT analysis, the mean number of trials per condition and participant was 129 (SD 49, min 61, max 231); for error analysis it was 135 (SD 49, min 71, max 233).

Mean RTs. The two-way ANOVA yielded main effects of Congruency, $F(2,62)=24.21$, $p<.01$, $\eta^2_p=.44$, and of Previous Task Sequence, $F(1,31)=8.31$, $p<.01$, $\eta^2_p=.21$; the interaction was not significant, $F(2,62)=1.26$, $p=.29$, $\eta^2_p=.04$. Pre-planned contrasts further investigating the main effect of Congruency revealed a significant difference between congruent and mixed trials, $F(1,31)=9.50$, $p<.01$, $\eta^2_p=.24$, as well as between mixed and incongruent trials, $F(1,31)=29.34$, $p<.01$, $\eta^2_p=.49$.

Mean Error Rates. See Figure 7. The corresponding two-way ANOVA on Error Rates yielded a main effect of Congruency, $F(2,62)=16.99$, $p<.01$, $\eta^2_p=.35$, and no other effects, Fs < 1. The pre-planned contrasts on the main effect revealed a significant difference between congruent and mixed trials, $F(1,31)=14.43$, $p<.01$, $\eta^2_p=.32$, as well as between mixed and incongruent trials, $F(1,31)=11.19$, $p<.01$, $\eta^2_p=.27$.

Full factorial analysis. For Experiment 1, we also performed the full factorial analysis with Congruency, Previous Task Sequence, Task Sequence, and CSI as factors (see Appendix 3 for details). Again, there was no two-way interaction of Congruency and Previous Task Sequence, neither in RT nor in error rate, Fs<1.32. There was no systematic pattern of higher-order interactions with Congruency, either. (In RT data, a three-way interaction with CSI was obtained, however, this was not reflected in error rates, where a trend for a four-way interaction was obtained; the data patterns in RTs and error rates did not go in the same direction, see Appendix 3). Hence, the full factorial analysis did not reveal any interaction of Congruency and Previous Task Sequence, or any systematic modulation thereof.

Experiment 2

Graded congruency effects were defined the same way as in Experiment 1. Mean RTs and mean error rates were analyzed as a function of Congruency and Previous Task, and are plotted in Figure 8. Data filtering was the same as for the main analysis of Experiment 2. The data from all CSI levels (100ms, 500ms, 900ms) were included. For RT analysis, the mean number of trials per condition and participant was 238 (SD 95, min 101, max 432); for error

analysis it was 253 (SD 96, min 120, max 441). (For Experiment 2, we did not perform the full factorial analysis including CSI and Task Sequence as factors, because there were not enough trials in some of the conditions with CSI of 100ms and 900ms.)

Mean RTs. The two-way ANOVA yielded main effects of Congruency, $F(2,62)=10.04$, $p<.01$, $\eta^2_p=.25$, and of Previous Task Sequence, $F(1,31)=43.55$, $p<.01$, $\eta^2_p=.58$; the interaction was not significant, $F(2,62)=1.03$. Pre-planned contrasts further investigating the main effect of Congruency revealed a significant difference between congruent and mixed trials, $F(1,31)=8.84$, $p<.01$, $\eta^2_p=.22$, as well as between mixed and incongruent trials, $F(1,31)=4.30$, $p<.05$, $\eta^2_p=.12$.

Mean Error Rates. The corresponding two-way ANOVA on Error Rates yielded a main effect of Congruency, $F(2,62)=43.16$, $p<.01$, $\eta^2_p=.58$, and no other effects, $F(1,31)=1.80$ for the main effect of Previous Task Sequence, $F(2,62)=1.70$ for the interaction. The pre-planned contrasts on the main effect revealed a significant difference between congruent and mixed trials, $F(1,31)=43.68$, $p<.01$, $\eta^2_p=.59$, as well as between mixed and incongruent trials, $F(1,31)=33.55$, $p<.01$, $\eta^2_p=.52$.

Discussion of congruency effects

In both experiments, reliable congruency effects were found in both RTs and error rates. Confirming previous findings of graded congruency effects in a three-task switching situation (Longman et al., 2014; Schneider, 2014), performance was worst in incongruent trials and best in congruent trials, and performance on mixed trials (i.e., partly incongruent and partly congruent trials) was in between. The congruency effects did not interact with Previous Task Sequence, suggesting that differences in task shielding do not play a major role in the N-3 effect. Hence, we can rule out improved task shielding as mechanism behind the N-3 effect.

General Discussion

The present study set out to investigate the "N-3 effect" in task switching, which has been suggested to reflect increased cognitive control after task conflict. In task sequences of the

type ABA, persisting inhibition of task A needs to be overcome, leading to more task conflict than in sequences of the type CBA. Hence, in the trial following an ABA sequence, cognitive control is increased relative to a trial following a CBA sequence. Schuch and Grange (2015) provided evidence for such increased control after task conflict, with better performance after ABA than after CBA sequences, which they termed the "N-3 effect" in task switching. In the present study, we replicated this new effect across two experiments, and further investigated what cognitive processes might be underlying this effect.

N-3 effect and task preparation

In order to investigate whether the N-3 effect involves increased cognitive control in the form of improved preparation for the upcoming task, we manipulated task-preparation time in the present study. Using a cue-based task switching paradigm, the cue-stimulus interval (CSI) was varied blockwise, and was either short (100ms) or long (900ms). In Experiment 1, all trials within a block had an either short or long CSI; in Experiment 2, three consecutive trials had an intermediate CSI (500ms), followed by one trial with either short or long CSI. The prediction was the same for both experiments: If the N-3 effect involves improved task preparation, it should be more pronounced with long than with short preparation time. The reasoning was that if task preparation is more intense after ABA than after CBA, then the longer the task-preparation interval, the more pronounced the effect of more intense task preparation should become. The results clearly show that this was not the case. In both experiments, we replicated the N-3 effect, but this effect did *not* become larger with longer CSI. Rather, in Experiment 1, the N-3 effect was significantly *smaller* with long than with short CSI in both mean RTs and error rates. In Experiment 2, the N-3 effect was not systematically affected by CSI. Hence, the N-3 effect does not seem to involve improved task preparation, such as stronger activation of the relevant task rules in working memory.

Notably, our reasoning hinges on the assumption that task preparation (e.g., activation of the relevant task rules in working memory) builds up gradually over time, and tasks can be

performed with different levels of advance preparation. According to this reasoning, the upcoming task is better prepared with long than short CSI (e.g., the relevant task rules are activated more strongly with long than short CSI). If the N-3 effect leads to more intense cognitive control in the sense of stronger top-down biasing of the relevant task rules, then this top-down biasing should have larger effects when there is more time for such top-down biasing to take place (i.e., with long CSI).

An alternative view put forward in the task-switching literature (see Kiesel et al., 2010; Koch et al., 2018, for reviews) is that task preparation takes a fixed amount of time, and is completed to the same degree in both trials with short and long CSI. According to this view, the only difference between short and long CSI conditions is that with long CSI, more task preparation is completed prior to stimulus onset than with short CSI. From this viewpoint, the N-3 effect might be due to a shortening of the time needed for task preparation. When further assuming that task preparation takes 900ms at maximum, and is even shorter after ABA than after CBA sequences, one would expect that there is no N-3 effect with a CSI of 900ms (because task preparation has reached its optimum anyway). In contrast, with a CSI of 100ms, one would expect an N-3 effect. The data pattern in Experiment 1 (but not Experiment 2), where we observed a larger N-3 effect with short CSI than long CSI, is in line with this viewpoint.[1]

Results from diffusion modeling

Diffusion model analysis revealed that variation of task-preparation interval was reflected in the non-decision time parameter (in both Experiments 1 and 2) and in drift rate (in Experiment 2 only), in line with previous research applying diffusion modeling (Karayanidis et al., 2009; Madden et al., 2009; Schmitz & Voss, 2012, 2014). Non-decision time was smaller with long than short CSI, consistent with the notion that task-preparation processes

[1] We would like to thank an anonymous reviewer for pointing this out.

occur prior to response-selection processes; with short CSI, more task preparation occurs after stimulus onset than with long CSI, where more task preparation can occur prior to stimulus onset. (This result is in line with the alternative view of task preparation taking a fixed amount of time that was outlined above.) The finding that drift rate was larger with long than short CSI in Experiment 2 is consistent with the notion that the current task rules are implemented more strongly with long than short CSI; that is, the cognitive representation of the current task rules is less noisy due to more task preparation with long than short CSI. (This result is in line with the view endorsed here, that task preparation can occur to different degrees.)

Moreover, diffusion model analysis confirmed previous findings regarding N-2 task repetition costs (Schuch, 2016; Schuch & Konrad, 2017): N-2 task repetition costs, as measured by the performance decrement in ABA relative to CBA task sequences, were reflected in the drift rate parameter, with smaller drift rate in ABA than CBA. This finding is in line with the idea that N-2 task repetition costs reflect persisting inhibition of a previously abandoned task set (Mayr & Keele, 2000; see Koch et al., 2010, for review); in the diffusion model, persisting task inhibition is reflected in a noisier representation of the task rules, as evidenced by smaller drift rates in ABA than CBA. That the ABA-CBA contrast affects drift rate is in line with previous research suggesting that the task inhibition effect is mainly due to prolonged response selection in ABA relative to CBA trials (cf. Koch et al., 2010; Schuch & Koch, 2003). Apart from drift rate, N-2 task repetition costs were also reflected in non-decision time in the present data sets, with longer non-decision times in ABA than CBA (significant in Experiment 1, marginal in Experiment 2), particularly when preparation time was short (the interaction with CSI was marginally significant in Experiment 1, significant in Experiment 2). This is different from previous studies (Schuch, 2016; Schuch & Konrad, 2017), where N-2 task repetition costs in young adults were reflected in drift rate, but not in non-decision time.

Regarding the N-3 effect, results from diffusion model analysis did not reveal any straightforward interpretation of this empirical effect, as there were no main effects or interactions involving the factor Previous Task Sequence that occurred consistently across both experiments. (In Experiment 1, but not Experiment 2, there was a trend for a three-way interaction in threshold separation; in Experiment 2, but not Experiment 1, there was a trend for a two-way interaction with CSI in non-decision time.)

N-3 effect and task shielding

An alternative hypothesis is that the N-3 effect is due to increased cognitive control in the form of increased task shielding. The better a task is shielded against the competing, currently irrelevant, tasks in a task-switching situation, the less interference there is from the competing tasks (e.g., Goschke, 2013; Goschke & Bolte, 2014). One way to measure the degree of task shielding is by assessing congruency effects in a task switching situation. If a currently irrelevant stimulus feature (that is relevant for a competing task) triggers a response that is different from the response triggered by the relevant stimulus feature, performance is worse than when both trigger the same response (e.g., Bugg & Braver, 2016; Meiran, 2000; Rogers & Monsell, 1995; Sudevan & Taylor, 1987; see Kiesel et al., 2010, for review). In order to explore whether the N-3 effect involves improved task shielding, we analyzed congruency effects in the present task-switching experiments. Improved task shielding should be indicated by smaller congruency effects after ABA than after CBA.

We observed congruency effects in the present three-task experiments, replicating previous reports of congruency effects when switching between three tasks (Longman et al., 2014; Schneider, 2014). Performance was worst when both irrelevant tasks triggered a different response as was afforded by the relevant task; performance was intermediate when one irrelevant task triggered the same response as the relevant task and the other triggered a different response; performance was best when both irrelevant tasks triggered the same response as the relevant task. These congruency effects did not differ between trials after

ABA and trials after CBA sequences, suggesting that differences in task shielding are not a major cause for the observed N-3 effect.

Outlook on further research

In order to elucidate the cognitive mechanisms underlying the N-3 effect, several further hypotheses could be tested in future experiments. Apart from congruency effects, other effects have been reported in the task-switching literature that might serve as an indicator of task shielding. For instance, Astle, Jackson, and Swainson (2012) reported evidence for a specific inhibitory mechanism in task switching, which they termed "dimension inhibition". Analyzing performance in a three-task switching paradigm, Astle and colleagues focused on trials that were preceded by an intermediate congruency level. They found worse performance when switching to the previously incongruent stimulus dimension than when switching to the previously congruent stimulus dimension. Astle and colleagues suggested that the irrelevant stimulus dimension that triggered an incongruent response in trial N-1 becomes inhibited more strongly than the irrelevant stimulus dimension that triggered a congruent response in trial N-1 (see also Goschke, 2000; Katzir, Ori & Meiran, 2018; Meiran, Hsieh & Dimov, 2010), which may be conceived as a specific form of task shielding. Hence, it is possible that the N-3 effect involves increased task shielding; in this case, one would expect a larger dimension inhibition effect after ABA than after CBA task sequences.

Another open question is whether the N-3 effect is specific to task switches, or could be observed in task repetitions as well. So far, the N-3 effect has only been investigated in paradigms involving task switches. In principle, however, the N-3 effect might be observed with task repetitions as well. Specifically, one might hypothesize that performance is better in task repetitions after ABA task sequences than in task repetitions after CBA task sequences (i.e., better performance in ABAA than in CBAA). If the N-3 effect generalizes to task repetitions, this would indicate that the underlying mechanism is not switch-specific.

Conclusion

In two experiments, we replicated the N-3 effect in task switching, with better performance after ABA than after CBA task sequences. The data provide further evidence that the N-3 effect is a reliable effect in sequential task switching. We explored two potential mechanisms possibly underlying the N-3 effect: Whether it involves improved task preparation, or improved task shielding. We did not find evidence in support of either mechanism: The N-3 effect was not systematically affected by task preparation time, nor did it modulate the size of congruency effects. We conclude that the N-3 effect does not seem to be due to improved task preparation or improved task shielding.

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Predictions

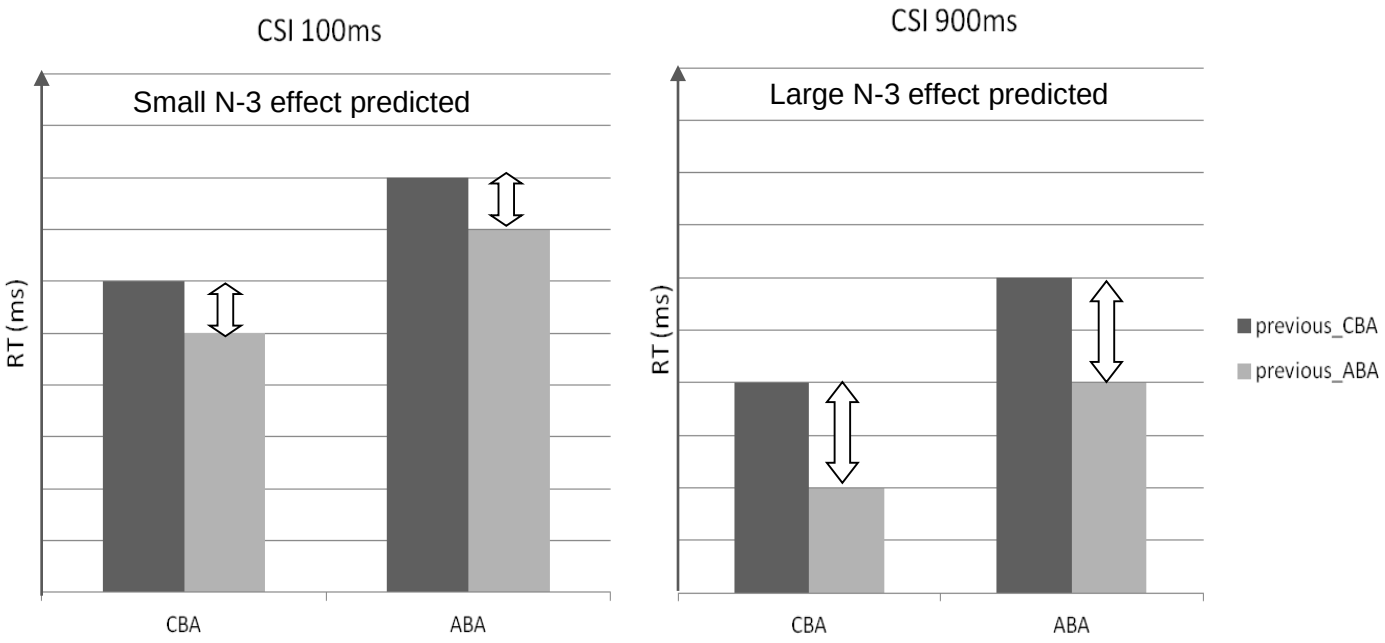

Figure 1. Schematic drawing of predictions. A three-factorial design is used with the factors Cue Stimulus Interval [CSI] (short, long), Task Sequence (ABA versus CBA, corresponding to standard N-2 task repetition costs), and Previous Task Sequence (trials after ABA versus trials after CBA, corresponding to the N-3 effect). Assuming that the N-3 effect (i.e., better performance after ABA than after CBA task sequences) is due to better advance preparation for the upcoming task, the N-3 effect should be larger with long CSI than with short CSI.

Experiment 1: Mean performance

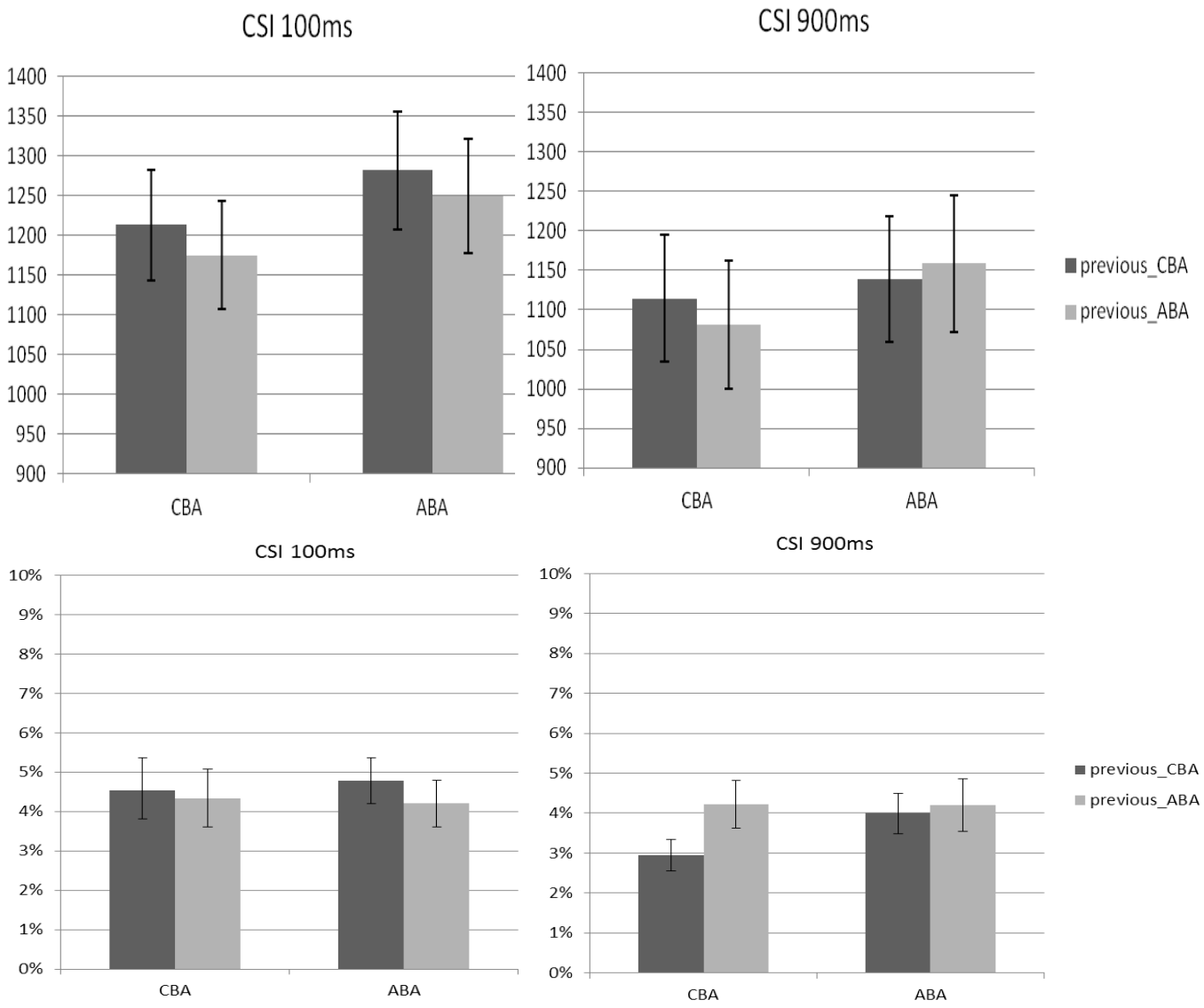

Figure 2. Experiment 1. Mean reaction time (in milliseconds; upper panel) and mean error rates (lower panel) plotted as a function of Cue-Stimulus Interval (CSI), Task Sequence, and Previous Task Sequence. Error bars describe one standard error of mean.

Experiment 2: Mean performance

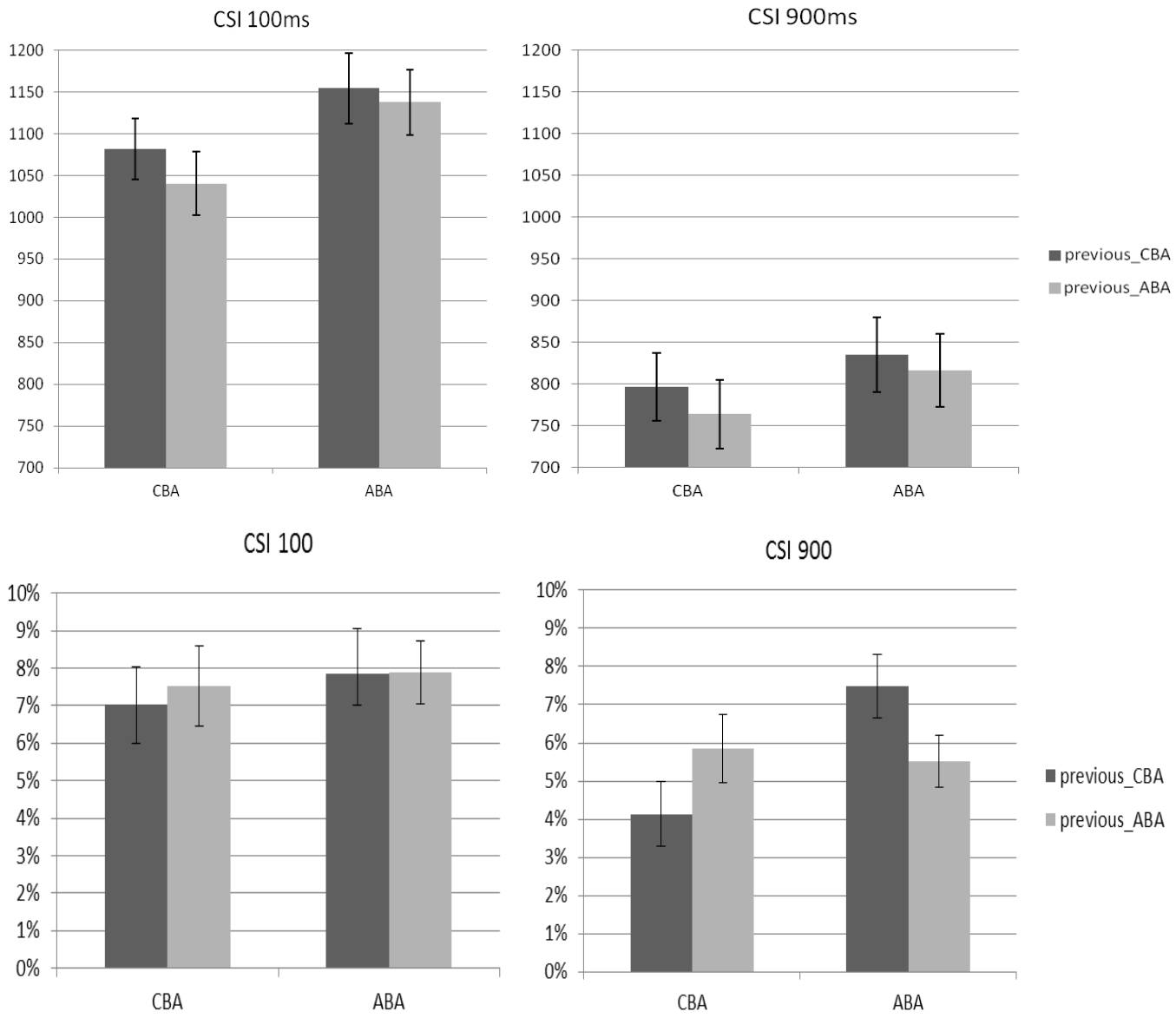

Figure 3. Experiment 2. Mean reaction time (in milliseconds; upper panel) and mean error rates (lower panel) plotted as a function of Cue-Stimulus Interval (CSI), Task Sequence, and Previous Task Sequence. Error bars describe one standard error of mean.

Experiment 2: Additional analysis of CSI 500 trials

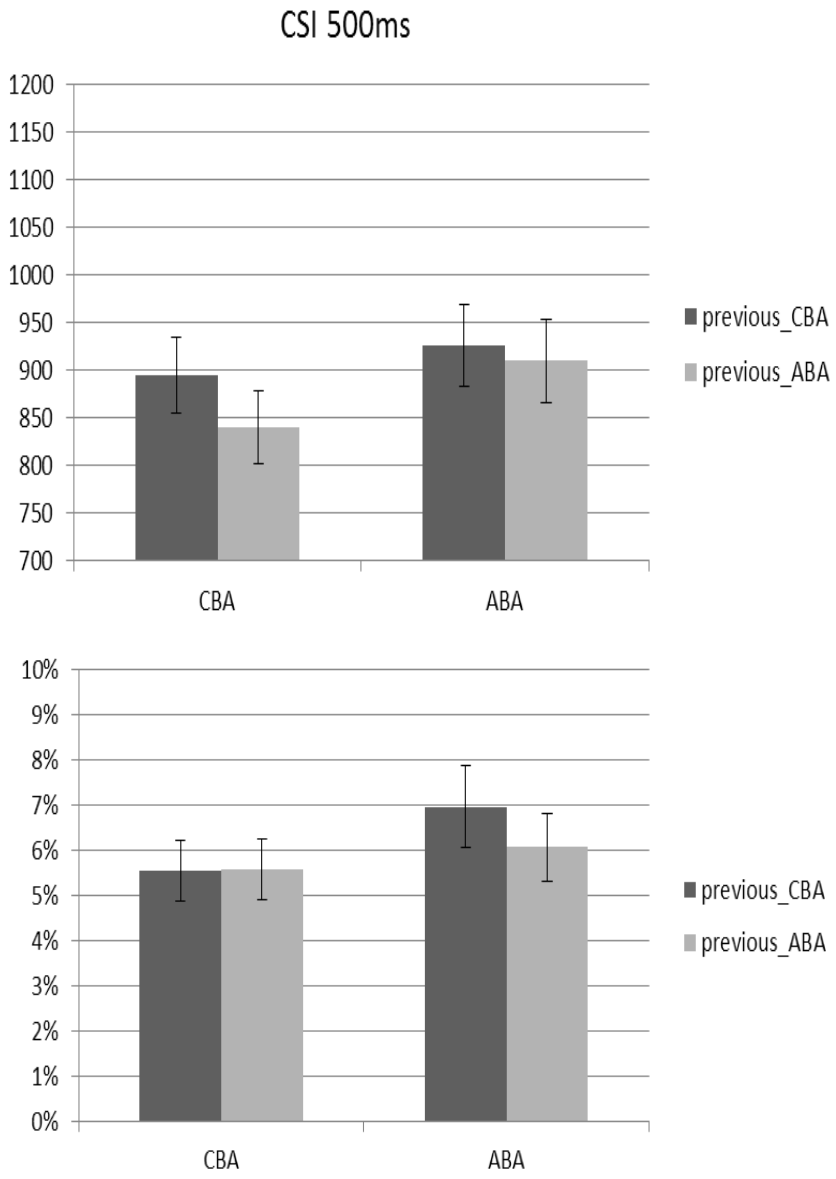

Figure 4. Experiment 2, trials with Cue-Stimulus Interval (CSI) of 500ms. Mean reaction time (in milliseconds; upper panel) and mean error rates (lower panel) are plotted as a function of Task Sequence and Previous Task Sequence. Error bars describe one standard error of mean.

Experiment 1: Diffusion model analysis

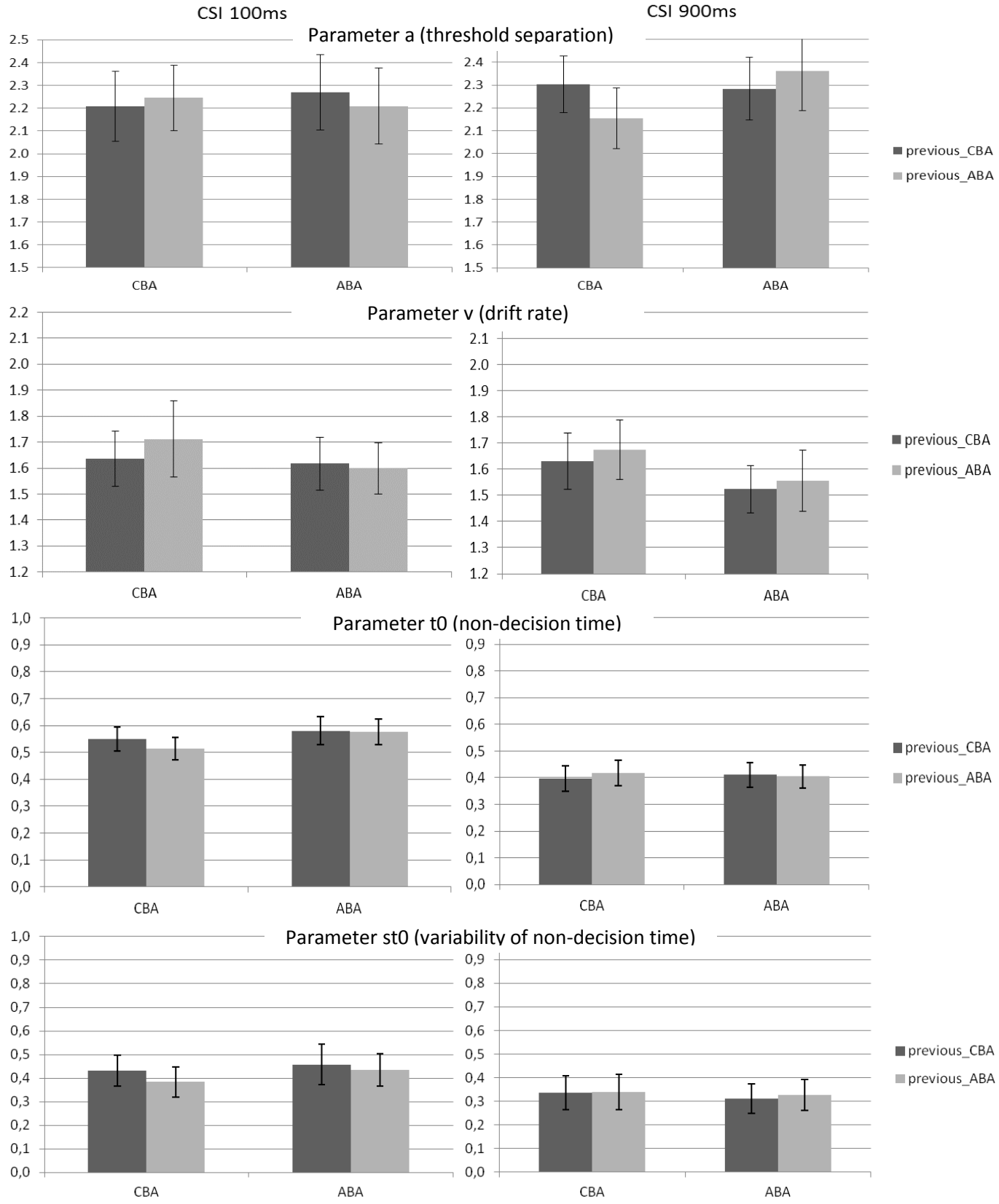

Figure 5. Experiment 1. Mean diffusion model parameters a (threshold separation), v (drift rate), t0 (non-decision time) and st0 (variability of non-decision time), plotted as a function of Cue-Stimulus Interval (CSI), Task Sequence, and Previous Task Sequence. Error bars describe one standard error of mean.

Experiment 2: Diffusion model analysis

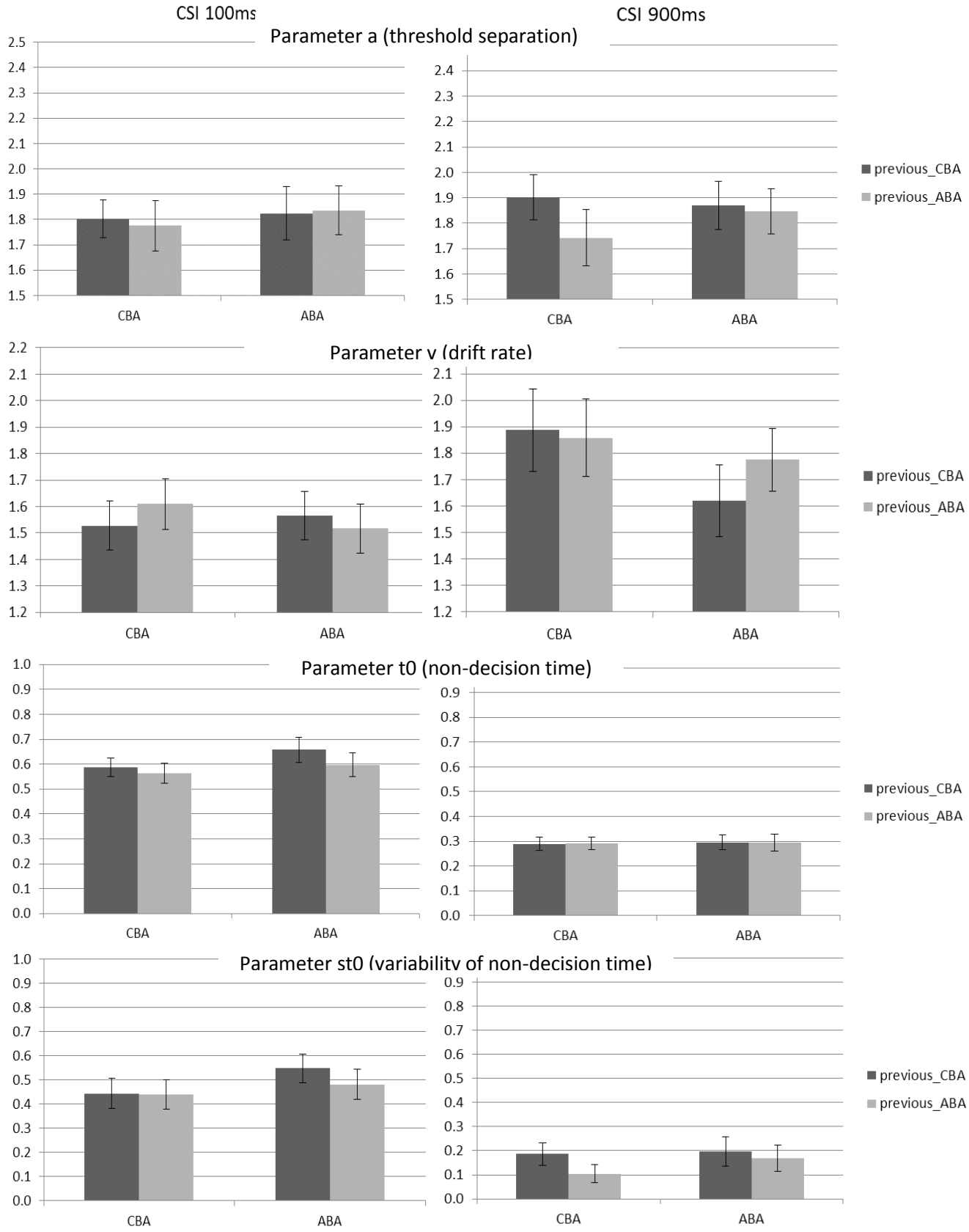

Figure 6. Experiment 2. Mean diffusion model parameters a (threshold separation), v (drift rate), t0 (non-decision time) and st0 (variability of non-decision time), plotted as a function of Cue-Stimulus Interval (CSI), Task Sequence, and Previous Task Sequence. Error bars describe one standard error of mean.

Experiment 1: Congruency effects

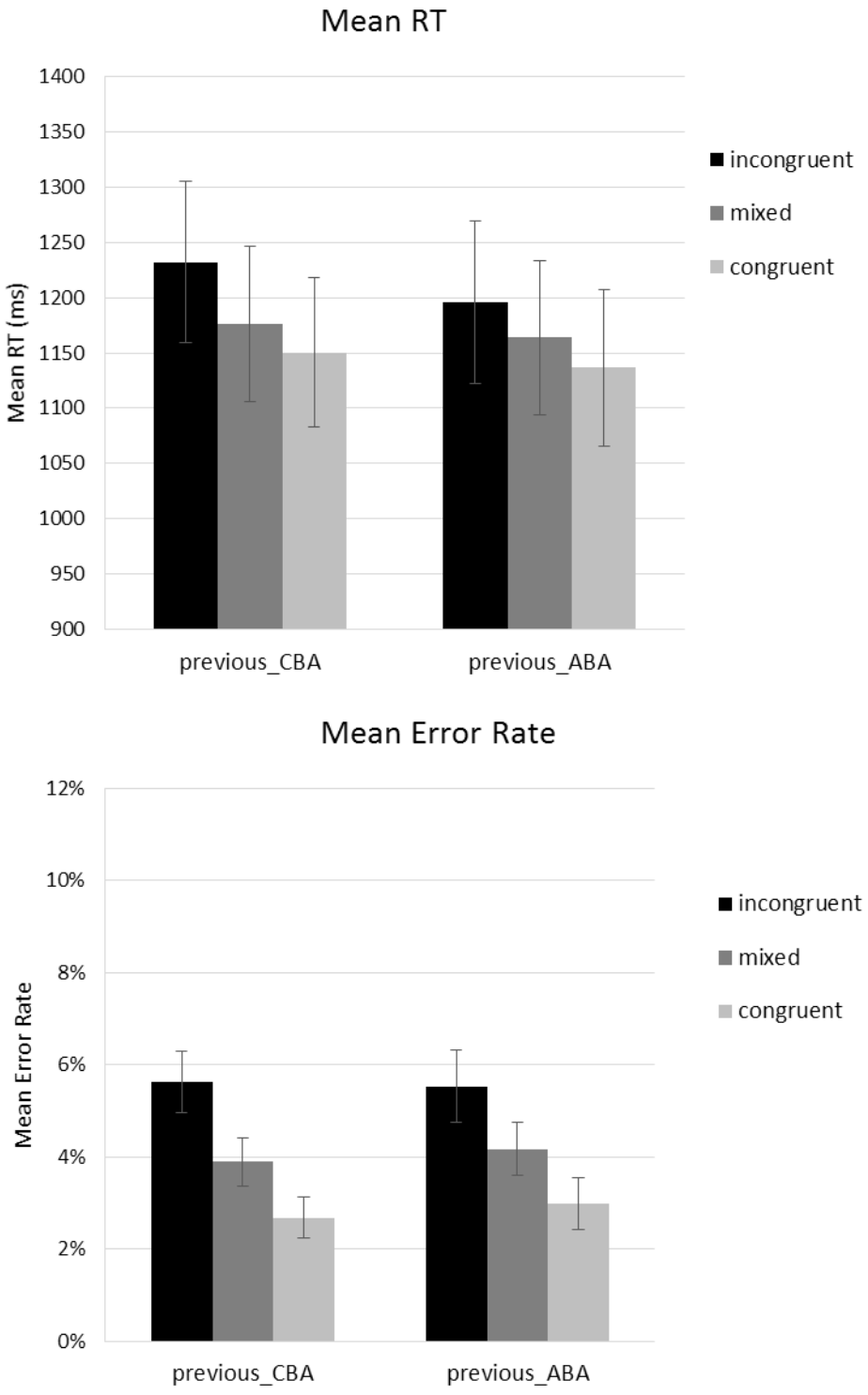

Figure 7. Experiment 1. Mean reaction time (in milliseconds; upper panel) and mean error rates (lower panel) plotted as a function of Congruency and Previous Task Sequence. Error bars describe one standard error of mean.

Experiment 2: Congruency effects

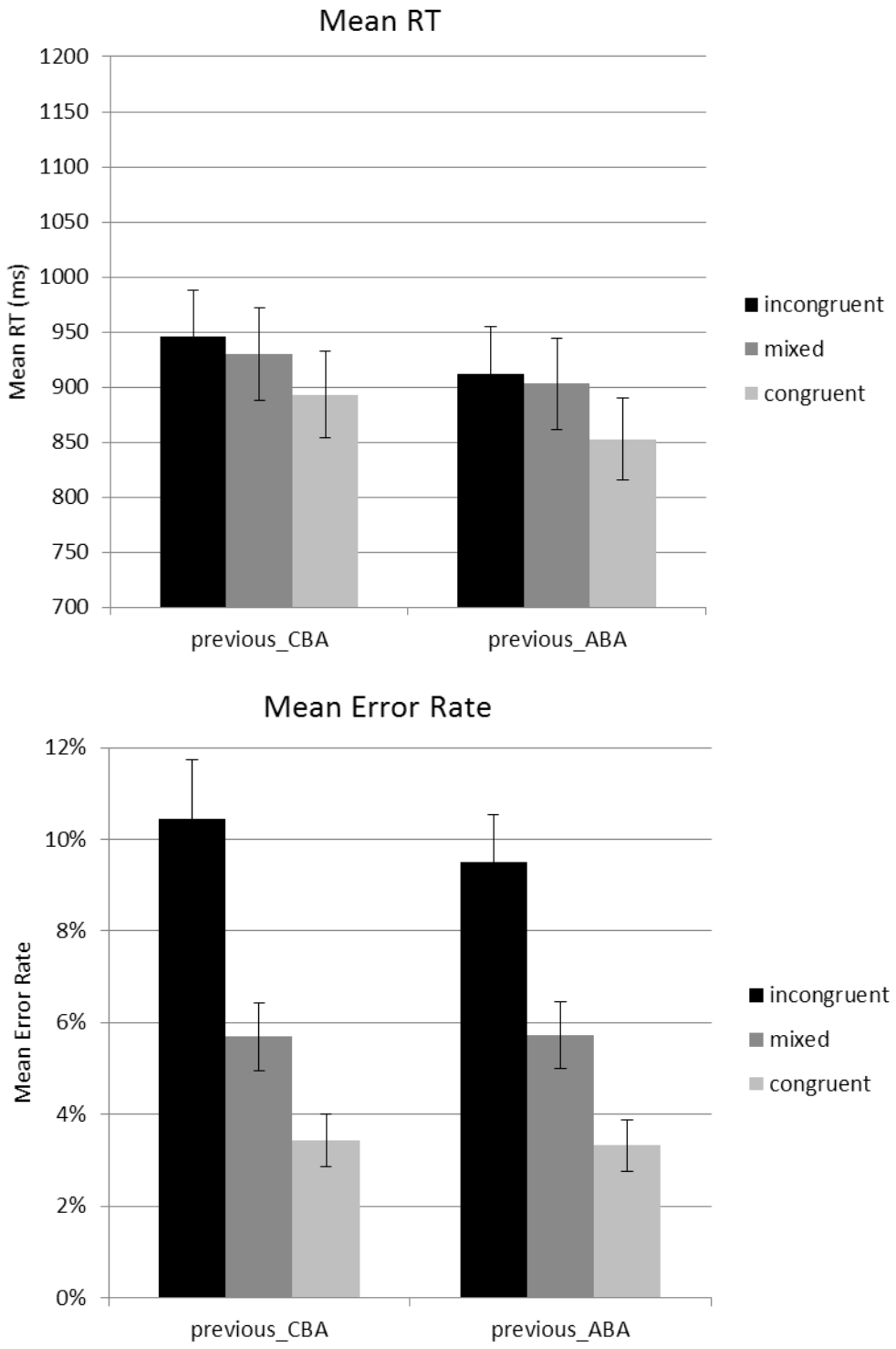

Figure 8. Experiment 2. Mean reaction time (in milliseconds; upper panel) and mean error rates (lower panel) plotted as a function of Congruency and Previous Task Sequence. Error bars describe one standard error of mean.