

Attentional set mixing: Effects on target selection and selective response activation

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Abstract

Performance is impaired under set mixing conditions that require frequent readjustments of attentional focus over an extended time period. We compared set repetitions within pure blocks (constant focus of attention) to physically identical repetitions within mixed blocks (changing focus of attention). The aim was to investigate how set mixing affects target selection, indexed by the N2pc component, and selective response activation, indexed by the lateralized readiness potential (LRP). We found that set mixing prolonged the evolution of the N2pc while leaving its onset unaffected. Impaired target selection indicated by the N2pc mixing effect also delayed the start of response planning indexed by an onset delay of the stimulus-locked LRP, explaining one part of the behavioral mixing cost. A larger part of mixing cost could be attributed to a prolonged response planning phase, indexed by an earlier onset of the response-locked LRP.

Descriptors: Switching, Switch cost, Mixing cost, Event-related potentials, Event-related lateralization, Selective attention, Cognitive control, Mental chronometry

Virtually at any given moment in time, we can choose among multiple options of how to interact with our environment. For coherent, goal-directed behavior, mechanisms need to be in place that allow for selecting one single relevant target for action while other potential targets (i.e., distractors) are being discarded. When behavioral goals are rapidly changing over time, flexible readjustments of the focus of attention are required accordingly. Two types of performance costs have been identified under such conditions. On the one hand, “switching costs” reflect the consequences of transient, moment-by-moment adjustments that are more demanding in set switching trials than in set repetition trials (Meiran, 1996; Rogers & Monsell, 1995). On the other hand, constantly switching back and forth between different attentional sets over an extended period of time causes “mixing costs” for set repetitions within “mixed blocks” compared to physically identical set repetitions within “pure blocks” in which the focus of attention stays constant (Meiran, Chorev, & Sapir, 2000).

Historically, researchers interested in cognitive flexibility did not distinguish between mixing and switching, instead, comparing performance in pure blocks with the overall level of performance in mixed blocks (Jersild, 1927). With the revival of this topic (Sudevan & Taylor, 1987), the traditional procedure was criticized for confounding “unspecific” processing differences between pure blocks and mixed blocks (Meiran, 1996; Rogers & Monsell, 1995), most often citing unequal working memory de-

mands (i.e., one set vs. two sets to be kept in mind throughout the different experimental blocks). Consequently, research has since been focusing on the comparison of set switch trials and set repeat trials *within* mixed blocks (for reviews, see Monsell, 2003; Wager, Jonides, & Reading, 2004).

However, recent studies have started to view set mixing not as a to-be-eliminated experimental confound but rather as an interesting topic for explicit investigation (Los, 1996; Meiran et al., 2000; Rubin & Meiran, 2005). This trend has also been reflected by an increasing number of neuro-cognitive studies on set mixing (Braver, Reynolds, & Donaldson, 2003; Goffaux, Phillips, Sinai, & Pushkar, 2006; Slagter, Kok, Mol, Talsma, & Kenemans, 2005).

As just mentioned, the typical explanation for mixing cost usually refers to increased working memory demands in mixed blocks compared to pure blocks. However, a recent study *explicitly testing* this assumption failed to find supporting evidence (Rubin & Meiran, 2005). Moreover, a deeper conceptual analysis shows that mixing cost can potentially be traced back to a variety of contributing factors (e.g., Los, 1996). With this in mind, and going beyond the “classical” working memory hypothesis, the specific goal of the present study was to determine the contribution of two fundamentally different, though not mutually exclusive, potential causes of mixing cost. The “intra-selection” account suggests that set mixing directly affects target selection because currently irrelevant stimuli have served as targets in preceding trials, which makes them more difficult to ignore than in pure blocks, and, vice versa, targets have served as distractors in preceding trials, which makes them less salient than

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in pure blocks. The “extraselection” account suggests that response planning processes are prolonged under set mixing conditions because subjects put a strategic emphasis on accuracy at the cost of slower response speed in order to deal with a situation perceived as more difficult and error prone than in pure blocks (cf. Brown & Braver, 2005).

The present article describes the results of a chronometric analysis of event-related brain electrical potentials specifically associated with neural activity that is hemispherically lateralized depending on the location of target and distractor stimuli within the two visual hemi-fields or depending on the response hand used. In the following text, such electrical potentials are referred to as “event-related lateralization” (ERL). Of particular relevance are two well-known ERL components. One component is the N2pc (“pc” stands for posterior and contralateral to target position), which is assumed to reflect ongoing target selection specifically in the presence of irrelevant distractors (Hopf, Boelmans, Schoenfeld, Luck, & Heinze, 2004; Luck & Hillyard, 1994). The term *target selection* is used to refer to those attentional mechanisms that separate relevant from irrelevant perceptual information. The N2pc has been suggested to emerge through a biased competition process between target and distractor features, involving the enhancement of target locations and the suppression of distractor locations (Desimone, 1998; Luck, Girelli, McDermott, & Ford, 1997). The other component of interest is the lateralized readiness potential (LRP), which indicates selective response activation at a motoric stage of action planning (Coles, Gratton, & Donchin, 1988). An important distinction can be made between stimulus-locked LRP activation and response-locked LRP activation, hereafter referred to as LRP-s and LRP-r (Jentzsch, Leuthold, & Ridderinkhof, 2004; Leuthold, Sommer, & Ulrich, 1996; Osman & Moore, 1993). The onset of the LRP-s marks the start of motor planning, initiated after obligatorily preceding premotoric processing stages have been finished. The assumption is that such processes are directly triggered by external stimulation and, therefore, are most reliably mapped by using stimulus-locked signal averaging. In contrast, motor planning processes are tightly coupled with the observable behavioral response and, under many circumstances, decoupled from external stimulation. In this case, response-locked signal averaging is obviously the more appropriate approach. The rising time of the LRP-r—as indexed by its onset latency—can be used for estimating the duration of response planning processes (the earlier the onset, the longer the motor planning phase).

These temporal ERL markers can now be used to test the assumptions made by the intra- and extraselection accounts of mixing cost. First, impaired target selection, implicating a slower target extraction rate, should be reflected by a prolonged evolution of the N2pc component indexed by delayed peak activation. As a consequence, the start of response planning processes should be postponed, indexed by an onset delay of the LRP-s. Second, if set mixing caused subjects to engage in more thorough and therefore more time-consuming response planning, the LRP-r rising time should be prolonged, indexed by an earlier LRP-r onset.

Finally, mixing cost could simply reflect additional cue-decoding time in mixed blocks (in the present experiment each target–distractor display was preceded by a precue, which indicated the currently relevant target stimulus): Although in mixed blocks the cue must be considered for correct performance, it does not convey relevant information beyond predicting the

onset time of the upcoming target–distractor pair in pure blocks. Although a cue–target interval of 500 ms was thought to be sufficiently long for complete cue decoding in mixed blocks, subjects might not use this time in the optimal way on every trial (De Jong, 2000). As a consequence the start of target selection would be postponed until the currently relevant selection criterion has been determined. In this case, the N2pc onset should be delayed.

Methods

Participants

Twenty-eight healthy adults (aged 19–34 years, 13 women) participated in this study after written informed consent was obtained. All participants were right-handed and had normal or corrected-to-normal vision.

Apparatus, Stimuli, and Procedure

In each trial subjects were presented with one distractor letter and one target letter at two out of four possible locations (see Figure 1). The four locations were marked by underlines separated by a 4° visual angle being visible continuously across trials and throughout each block. A centrally presented instruction cue (“x” or “o”) indicated the relevant target letter (“X” or “O”). The distractor letter was always the letter that was not the target.

There was a pure block condition and a mixed block condition with block sequence balanced across subjects. In pure blocks the target was the letter “O” and the distractor was the letter “X” fixed for all trials. In mixed blocks the letters “X” and “O” were randomly exchanged between target and distractor from trial to trial. Thus, a mixed block trial could either be a set repetition trial or a set switching trial. To investigate set mixing, we compared pure block trials with physically identical set repetition trials within mixed blocks, thus being able to cleanly isolate effects of block context. We did not additionally compare the mixed-block set repetition condition to the set switching condition, not least because of a known confound with feature-to-location binding processes in the specific experimental setup used here, which usually results in reverse switching effects (i.e., faster response times for switch trials as compared to repeat trials; Milliken, Tipper, & Weaver, 1994).

In both blocks the centrally presented instruction cue preceded the target–distractor pair by 500 ms. The precue, the target, and the distractor were displayed until the response was

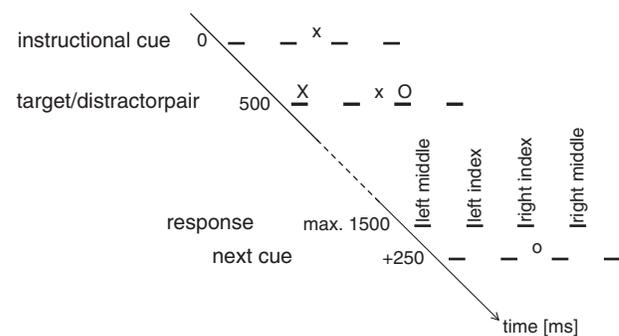


Figure 1. The structural and temporal features of an exemplary trial, starting with an instructional cue specifying the current target, followed by a target/distractor pair, which requires a manual response to indicate the position of the target.

made or until a 1000 = ms timeout limit was reached. The interval between the response and the next cue was 250 ms.

Stimulus presentation was controlled by a PC and displayed on a CRT monitor. Subjects responded by pressing the “S”, “D”, “J”, and “K” keys of a standard PC keyboard with their left and right hand index and middle fingers in a spatially compatible way to the four display positions.

A second objective behind this experiment, not dealt with in the present article, was to investigate so called negative location priming effects (Tipper & McLaren, 1990). For that purpose one half of all trials were designed according to the “DT” condition (prime distractor location becomes probe target location) and the other trials were designed as a control condition. In DT trials, the target was presented at the previous distractor location and the distractor was presented at one of the two previously empty locations. In control trials both the target and the distractor were presented at previously empty locations. The analyses reported in the present article were always collapsed across DT and control trials. The relevant results for the comparison of DT and control trials are reported in another paper (Ruge & Naumann, in press).

For each block and each subject a quasi-random sequence of conditions was computed off-line with the following constraints: equal number of DT and control trials, equal number of transitions between the conditions, and equal number of the 12 possible different arrangements of target and distractor locations for both conditions. In the mixed block all possible transitions between DT, control, set switching, and set repetition were additionally balanced.

In the pure block a total of 288 trials were presented. For a subset of 192 trials, target and distractor appeared at different visual half-field sides. In the mixed block a total of 384 trials were presented, of which 192 were set switching trials (not considered for analysis) and 192 were set repetition trials (including consecutive set repetition trials). Each of these two conditions contained 128 trials where target and distractor were presented at different visual half-field sides. All analyses were performed with the reduced bilateral stimulus sets to obtain interpretable event-related lateralizations. Error trials were excluded.

EEG Recording and Data Analysis

The EEG was recorded from 29 Ag/AgCl electrodes positioned according to the international 10–20 standard and referenced to Cz. The electrode positions included Fp1, Fpz, Fp2, F7, F3, Fz, F4, F8, FC3, FCz, FC4, T3, T4, C3, Cz, C4, CP3, CPz, CP4, P3, Pz, P4, T5, T6, O1, Oz, O2, and bilateral mastoids. Electrode impedance was kept below 5 k Ω . Bipolar horizontal EOG was recorded from electrodes located at the outer canthi of both eyes. Bipolar vertical EOG was recorded from above and below the left eye. The amplifier (SYNAMP, model 5083, Neuroscan) bandpass was 0.05–30 Hz, and a notch filter was set to 50 Hz. EEG and EOG were sampled at 200 Hz and stored on disk.

Off-line preprocessing was performed with the Brain Vision Analyzer software (version 1.05, Brain Products GmbH). Visualization and parametrization were performed with the free statistical software package R (R-Development-Core-Team, 2005). The EEG was re-referenced to algebraically linked mastoids; artifacts due to eye movements were corrected via the Gratton, Coles, and Donchin (1983) algorithm. Epochs with nonphysiological artifacts (absolute amplitudes exceeding $\pm 200 \mu\text{V}$, difference between successive time points $> 100 \mu\text{V}$) were removed ($< 2\%$ of all epochs). For the extraction of stimulus-locked ERLs, the EEG time courses were segmented into

900-ms intervals, starting 200 ms before target presentation (defined as time point 0), and ERLs were subsequently baseline corrected for the interval [–200 ms to 0 ms]. Response-locked ERLs were based on 800-ms EEG segments, starting 600 ms before response execution (defined as time point 0), and were subsequently baseline corrected for the interval [–600 ms to –500 ms]. Regular ERPs were extracted for 1600-ms epochs starting 200 ms before cue presentation (defined as time point –500 ms), and were subsequently baseline corrected for the interval [–700 ms to –500 ms].

ERLs were computed with the Brain Vision Analyzer software according to Coles, Gratton, and Donchin (1995) based on the following algorithm:

$$\text{ERL} = [\text{Average}(\text{right electrode} - \text{left electrode})_{\text{target left}} + \text{Average}(\text{left electrode} - \text{right electrode})_{\text{target right}}] / 2 \quad (1)$$

The statistical analysis of onsets and peaks of ERL components was based on jackknife resamples (Efron, 1981; Miller, Patterson, & Ulrich, 1998). The advantage of jackknifing is that the parameters of interest (onsets and peaks) are identified in time courses averaged across subjects (grand averages). Thus, noise is reduced to an extent that allows for identifying the relevant features reliably. Jackknife resampling provides a simple tool to create a statistical distribution from grand-averaged values. Each of N subjects is excluded from grand averaging once. The resulting distribution of N grand averages (each omitting a different subject) can then be used to calculate estimates of standard errors or other statistics. Peaks were determined in jackknife time courses after being smoothed with a 12-Hz low-pass filter. For the identification of onsets, we implemented a nonlinear regression method fitting two straight lines to the unsmoothed jackknife time courses, one capturing the baseline before the curve starts to rise and another one capturing the rising flank (Mordkoff & Gianaros, 2000). Onsets were defined as the intersection of both lines. We used the Nelder–Mead fitting algorithm implemented in the R software (R-Development-Core-Team, 2005). Three degrees of freedom were allowed: the intersection point, the intercept of the baseline estimate, and the slope of the estimate for the rising flank. The slope of the baseline was set to zero and the intercept of the rising flank estimate was coupled with the intercept of the baseline estimate. The precise ramp function to be fitted was given by

$$\begin{aligned} \text{if } (x < \text{ONSET}), \text{ then } y &= \text{INTERCEPT}_{\text{baseline}} \\ \text{else } y &= (\text{INTERCEPT}_{\text{baseline}} + (x - \text{ONSET})) * \text{SLOPE}_{\text{rising_flank}} \end{aligned} \quad (2)$$

Results

Behavioral Results

The analysis aimed at revealing mixing costs defined as the performance difference between set repetition trials within mixed blocks and set repetition trials within pure blocks. For each subject, we averaged response times in each experimental condition and analyzed effects within subjects, using paired t tests—one for response times and another one for error rates. The t test for response times, $t(27) = 8.7$, $p < .001$, revealed significantly slower responses for the mixed block condition (mean = 563.7 ms, 95% c.i. = 27.8 ms) than for the pure block condition

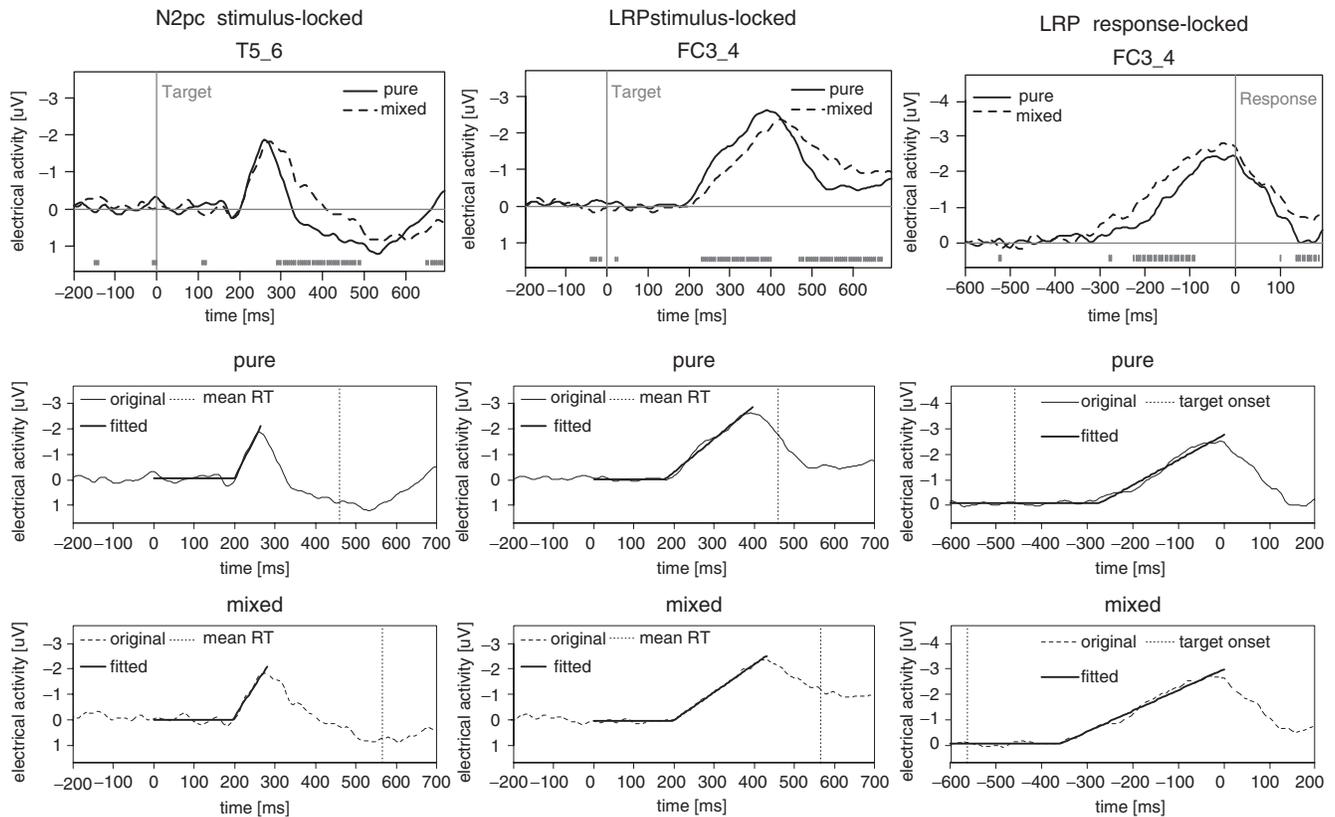


Figure 2. Event-related lateralizations for the N2pc, the stimulus-locked lateralized readiness potential (LRP), and the response-locked LRP. The top row panels depict pure block time courses together with mixed block time courses (solely based on set repetition trials). The gray marks at the bottom of each panel indicate where the two curves are significantly different from each other according to a running t test. The middle and bottom row panels depict the fitted ramp functions for onset extraction.

(mean = 458.3 ms, 95% c.i. = 29.0 ms). Analogously, the t test for error rates, $t(27) = 5.0$, $p < .001$, revealed significantly more errors for the mixed block condition (mean = 6.6%, 95% c.i. = 1.6%) than for the pure block condition (mean = 2.6%, 95% c.i. = 0.6%).

EEG Results

As mentioned in the introduction, we are mainly focusing on the results of a chronometric analysis of ERLs. To complete the picture, we also include a brief excursion dealing with mixing-related effects on regular, nonlateralized ERPs.

Analysis of event-related lateralizations. This analysis was focused specifically on two ERL components, the N2pc component at posterior temporal cortex electrodes (T5_6) as an indicator of target selection, and the LRP component at fronto-central electrodes (FC3_4) indicating selective motor activation. We separately assessed lateralized motor activation time-locked to stimulus onset (LRP-s) and time-locked to the execution of the motor response (LRP-r). The underlying ERL time courses, together with the fitted ramp function for onset estimation, are depicted in Figure 2.

Additionally, we wanted to make sure that the ERL time courses were not distorted by influences of lateralized electrical activation induced by horizontal saccadic eye movements that might have been insufficiently corrected by the Gratton–Coles algorithm we applied. To this end, we compared ERLs for two groups of subjects, either with ($N = 18$) or without ($N = 10$) sac-

cadic eye movements (Figure 3).¹ Whereas ERLs for the saccade group were, as would be expected (e.g., Croft, Chandler, Barry, Cooper, & Clarke, 2005), generally attenuated by the eye-movement correction, the relative timing characteristics of onset latencies and peak latencies remained largely unaffected by group membership (see Tables 1, 2, and 3). We therefore based our conclusions on the parameterization of time courses including all 28 subjects.

Table 1 summarizes the analysis of onset and peak latencies of the N2pc. Whereas onsets did not differ between pure blocks and mixed blocks, $t(27) = 0.02$, n.s., the peak latency was slightly (15.0 ms) but significantly, $t(27) = 3.6$, $p < .001$, delayed in mixed blocks compared to pure blocks. As can be seen in Figure 2, top left panel, the N2pc in mixed blocks was also receding more slowly after reaching its peak activation as indicated by a running t test.

Lateralized motor activation, indexed by the LRP component, was observed for both LRP-s and LRP-r time courses. The analysis of LRP onset latencies is summarized in Table 2 and Table 3. The LRP-s exhibited a slightly (25.5 ms), but significantly, $t(27) = 2.4$, $p < .03$, delayed onset in mixed blocks compared to pure blocks. The rising time of lateralized motor activation, as indexed by the onset latency of the LRP-r, was

¹Saccade onsets were delayed for mixed blocks compared to pure blocks, namely by 39.6 ± 22.8 ms for saccades to the right and 37.8 ± 15.9 ms for saccades to the left.

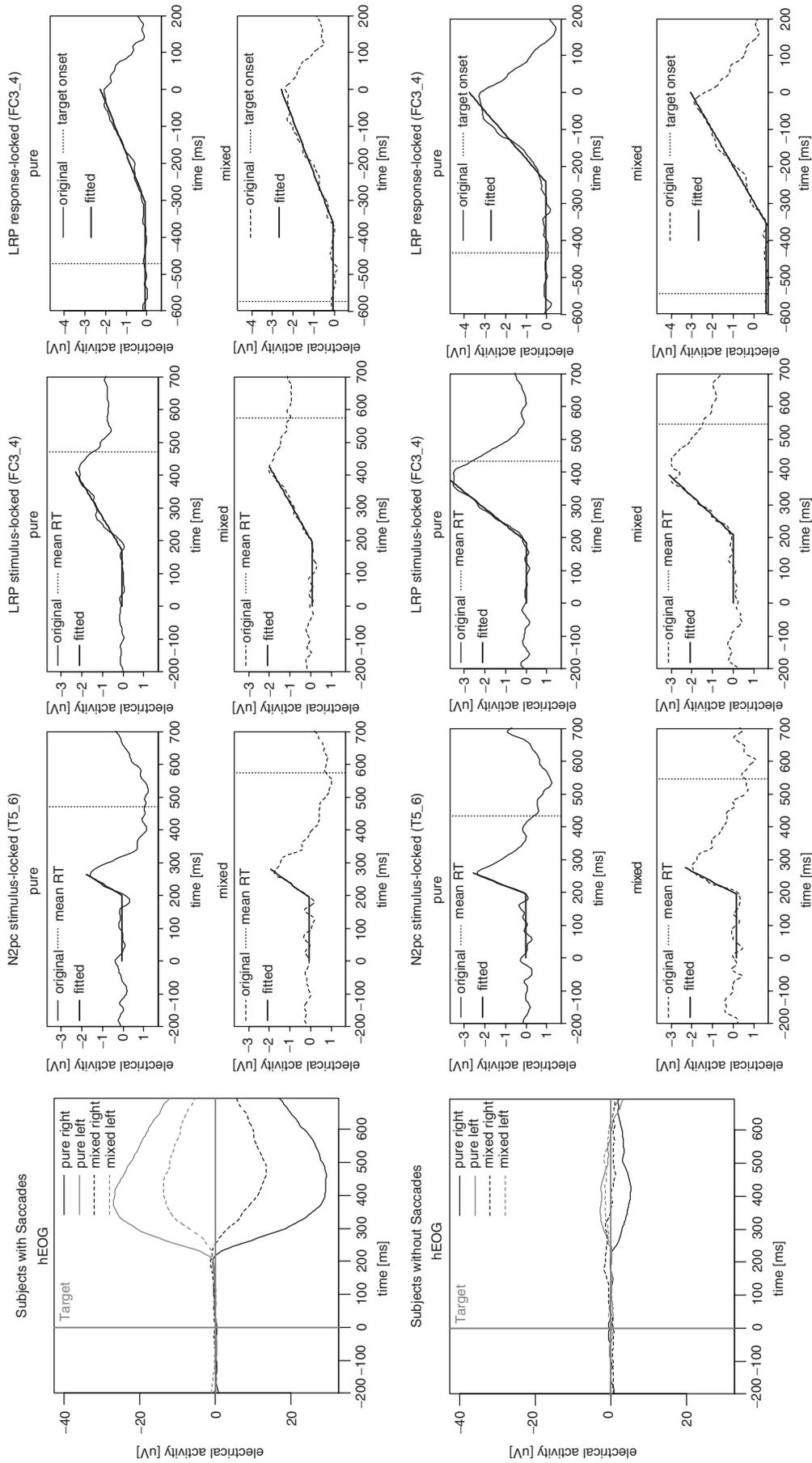


Figure 3. Event-related lateralizations separately averaged for two groups of subjects, either with or without saccadic eye movements present. This additional analysis was performed to check for potential distortions due to lateralized electrical activity induced by saccades.

Table 1. Estimates for Onset Latencies and Peak Latencies of the N2pc Component

	N2pc stimulus-locked			
	Onset latencies		Peak latencies	
	Pure block	Mixed block	Pure block	Mixed block
All subjects	197.0 ± 11.3 ms	196.8 ± 11.1 ms	267.3 ± 8.6 ms	282.3 ± 5.1 ms
No-saccade subjects	192.4 ± 24.2 ms	196.4 ± 20.4 ms	264.8 ± 13.6 ms	280.0 ± 8.6 ms
Saccade subjects	199.9 ± 9.8 ms	197.3 ± 13.3 ms	269.1 ± 11.5 ms	283.6 ± 5.7 ms

Note: mean latency ± 95% confidence interval.

Table 2. Estimates for Onset Latencies of the Stimulus-Locked Lateralized Readiness Potential (LRP)

	Stimulus-locked LRP onset	
	Pure block	Mixed block
All subjects	171.1 ± 16.5 ms	196.6 ± 19.0 ms
No-saccade subjects	187.3 ± 19.1 ms	208.4 ± 29.6 ms
Saccade subjects	167.9 ± 29.0 ms	194.8 ± 28.1 ms

Note: mean latency ± 95% confidence interval.

largely prolonged (85.5 ms) for mixed blocks compared to pure blocks, $t(27) = 4.6, p < .0001$.

Analysis of regular event-related potentials. The relevant ERP time courses for mixed blocks and pure blocks are depicted in Figure 4 at representative electrode sites. The time courses include the preparation interval between cue presentation and the onset of the target–distractor display, and the adjacent epoch covering brain electrical activation until response execution and beyond. *Cue-related* ERP profiles sharply differ between the mixed block condition and the pure block condition, strikingly evidenced by the emergence of mixed-block-specific components, including a frontal N1 arising as early as 100 ms after cue presentation followed by more posteriorly distributed P2–P3 effects.

The interpretation of *target-related* ERP mixing effects is hampered by the lack of an unbiased baseline due to the fact that cue-related effects have not yet fully vanished by the time of target presentation. However, about 200 ms after target the more positive-going activity for the mixed condition protracted from the cue–target interval starts developing into the opposite direction. Thus, it seems fair to conclude that target-related activity is more negative going in mixed blocks than in pure blocks during the N2–P3 time range, particularly pronounced at more posterior electrode positions.

Discussion

As far as behavioral performance is concerned, we obtained the typical result of slower response times and increased error rate for set repetitions within mixed blocks as compared to physically identical set repetitions within pure blocks. The aim of this article was to determine the extent to which two theoretical accounts can explain (different parts of) this behavioral mixing cost. According to the intraselection account, set mixing impairs performance, as target selection becomes harder in the face of distractors that are more difficult to ignore and targets that are less salient. According to the extraselection account, set mixing prolongs response planning processes, as subjects are supposed to put more emphasis on accuracy rather than speed to deal with

Table 3. Estimates for Onset Latencies of the Response-Locked Lateralized Readiness Potential (LRP)

	Response-locked LRP onset	
	Pure block	Mixed block
All subjects	–273.0 ± 42.3 ms	–358.5 ± 32.0 ms
No-saccade subjects	–241.4 ± 43.6 ms	–354.5 ± 66.1 ms
Saccade subjects	–303.1 ± 59.0 ms	–363.2 ± 26.6 ms

Note: mean latency ± 95% confidence interval.

a situation that is perceived as more difficult and error prone. A chronometric analysis of ERLs aimed at decomposing behavioral mixing cost according to the timing characteristics of two functionally well-defined ERL components, the N2pc and the LRP.

Regular Event-Related Potentials

Before we turn to the main discussion of the ERL results, a look at the regular, nonlateralized event-related potentials is useful to show how massively the set mixing manipulation altered the general processing characteristics. This was most impressively demonstrated by the emergence of mixing-specific components during the cue–target interval (Figure 4), including a frontal N1 component and a more posteriorly distributed P2–P3 component. The early N1 effect might reflect the extraction of cue information in mixed blocks, which is not necessary in pure blocks in which advance cues do not convey selection-relevant information. The subsequent P2–P3 effect, resembling the findings from another recent set mixing study (Slagter et al., 2005), might reflect the preparatory trial-by-trial formation of cue-appropriate attentional sets for subsequent control of target selection. Moreover, the anterior–posterior distribution of N1 and P2–P3 mixing effects can possibly be related to recent fMRI studies of cue-based task set preparation that typically report two brain areas exhibiting preparatory activation, one in the posterior lateral prefrontal cortex and another one in the posterior parietal cortex (Brass & von Cramon, 2002; Ruge et al., 2005).

Furthermore, event-related activation following target presentation was more negative going under mixing conditions within the N2–P3 time range. This effect is consistent with findings from earlier studies (Goffaux et al., 2006; Michie et al., 1999) and putatively falls into the category of ERP “selection negativities” reflecting (a) the more demanding control of initial target selection and (b) further extraction of information carried by the selected stimulus during subsequent response planning processes (Mangun & Hillyard, 1995; Wijers, Mulder, Gunter, & Smid, 1996).

Notably, a number of set *switching* studies comparing switch and repeat trials within mixed blocks have also reported more

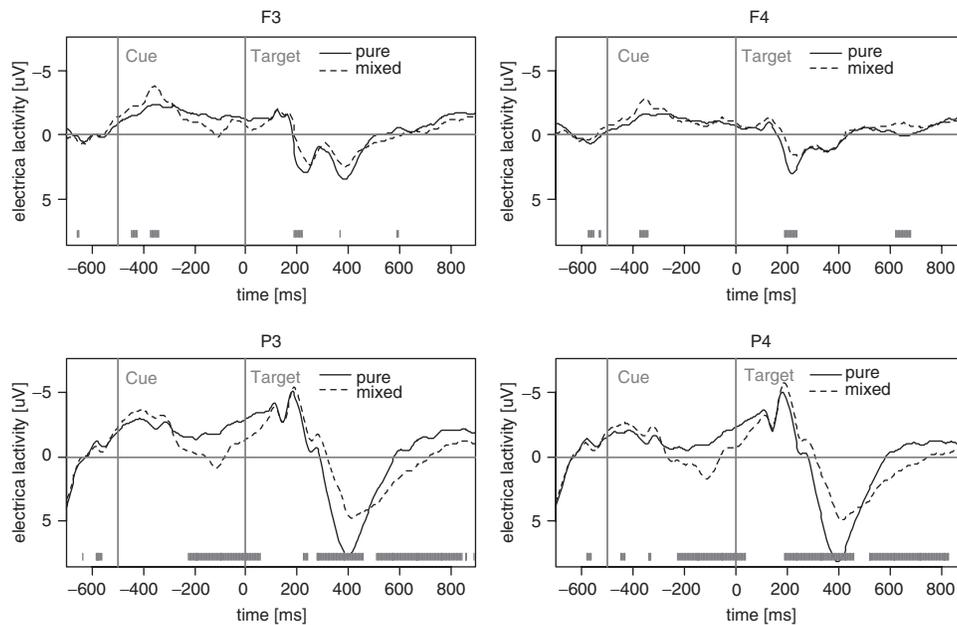


Figure 4. Regular event-related potentials at four representative electrode positions depicting pure block time courses together with mixed block time courses (solely based on set repetition trials). The gray marks at the bottom of each panel indicate where the two curves are significantly different from each other according to a running t test.

positive-going cue-related ERPs and more negative-going target-related ERPs for switch trials, resembling the ERP *mixing* effects found in the present study—except for the cue-related N1 effect (Kieffaber & Hetrick, 2005; Nicholson, Karayanidis, Poboka, Heathcote, & Michie, 2005; Rushworth, Passingham, & Nobre, 2002). This suggests that set switching and set mixing rely on similar neural processes (but note the refined conclusion derived from the analysis of ERLs below).

Event-Related Lateralizations

Extending the ERP results discussed above, the main goal of the present article was to use the precise chronometric information provided by ERL time courses to decompose behavioral mixing costs according to the functionally well-defined N2pc, LRP-s, and LRP-r components. This analysis revealed that, generally speaking, both target selection and selective response activation are prolonged by set mixing, yet also suggesting that behavioral response slowing is, for the larger part, explained by the latter.

First of all, ruling out a “trivial” explanation of mixing cost, N2pc onset latencies did *not* differ between pure blocks and mixed blocks: This observation discards the hypothesis that parts of mixing costs might be due to a delayed onset of target selection caused by occasional cue neglect during the preparation interval, in which case some additional time for cue decoding would be required after target presentation in mixed blocks (De Jong, 2000).

The effect of set mixing on target selection was reflected by a prolonged evolution of the N2pc component in mixed blocks as compared to pure blocks, reaching its peak with a 15-ms delay and receding more slowly over a period of approximately 200 ms after peak activation was reached. Moreover, the N2pc mixing effect overlaps in time with the increased “selection negativity” observed within the N2–P3 epoch of regular ERPs. These results combined can be interpreted within the already mentioned two-

phase account of ERP selection negativities. Accordingly, more demanding initial target selection, supposed to be reflected by the early ERP negativation phase, is accompanied by a slower target extraction rate that is indicated by the delayed N2pc peak latency. The later ERP negativation phase, supposed to reflect the continued analysis of the selected stimulus by subsequent processes, is paralleled by the more slowly receding N2pc activity. Given that the subjects’ task was to indicate the current target position, the extended N2pc mixing effect probably indicates that more time is being spent on the extraction of information about the current target location for response planning purposes. This interpretation fits well to the mixing-related prolongation of response planning processes indicated by the shifted LRP-r onset latency discussed below.

The N2pc modulation in itself, though clearly demonstrating that selective target processing is affected by set mixing, is not conclusive as to whether this would eventually impact overt motor response times. In this respect more conclusive is a consideration of LRP-s and LRP-r onset times. First, we can consider the LRP-s onset that indicates the start of motor planning processes after premotoric processes have gathered sufficiently accurate information regarding the current target of action. If it is true that the delayed N2pc peak latency is indicative of a slower target extraction rate under mixing conditions, the threshold for the start of motor planning processes should be reached at a later point in time. This, in turn, should be reflected by a delayed LRP-s onset. Indeed, we found that set mixing delayed the LRP-s onset by 25 ms. Second, we can consider the LRP-r onset latency that provides information about the time being spent on motor planning before a motor response is finally emitted. We found that the motor planning phase was prolonged by 85 ms in mixed blocks as compared to pure blocks. In sum, the onset shifts of LRP-s and LRP-r (25+85 ms) are rather accurately matching the behavioral mixing effect of 105 ms.

Notably, studies comparing switch and repeat trials within mixed blocks have found consistent switching effects only for LRP-s onsets but not for LRP-r onsets (Hsieh, 2006; Hsieh & Liu, 2005; Hsieh & Yu, 2003). This suggests that set mixing and set switching are similar in that both affect target selection processes resulting in a delayed start of selective response activation (LRP-s). In contrast, only set mixing but not set switching appears to affect the duration of motor planning processes (LRP-r).

The prolongation of the response planning phase is consistent with our initial hypothesis that set mixing causes subjects to adopt a strategy favoring increased accuracy at the cost of slower responding in order to prevent rampant error rates. In this respect, the impact of set mixing is reminiscent of strategic response-slowness effects demonstrated for other situations that

are more error prone and/or imply higher response conflict (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Logan & Zbrodoff, 1979; Rabbit, 1966). An alternative interpretation could be that increased distractor interference under mixing conditions does not only affect the initial target selection phase (early ERP selection negativity, N2pc peak delay) but continues to directly impact subsequent response planning processes during their attempt to access information about the location of the currently selected target stimulus (late ERP selection negativity, postpeak N2pc effect). From this perspective, the prolongation of response planning processes is not the result of strategic speed-accuracy adjustments, but, instead, is genuinely driven by continued interference from the distractor stimulus. Future research will need to address this issue more conclusively.

REFERENCES

- Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychological Review*, *108*, 624–652.
- Brass, M., & von Cramon, D. Y. (2002). The role of the frontal cortex in task preparation. *Cerebral Cortex*, *12*, 908–914.
- Braver, T. S., Reynolds, J. R., & Donaldson, D. I. (2003). Neural mechanisms of transient and sustained cognitive control during task switching. *Neuron*, *39*, 713–726.
- Brown, J. W., & Braver, T. S. (2005). Learned predictions of error likelihood in the anterior cingulate cortex. *Science*, *307*, 1118–1121.
- Coles, M. G., Gratton, G., & Donchin, E. (1988). Detecting early communication: Using measures of movement-related potentials to illuminate human information processing. *Biological Psychology*, *26*, 69–89.
- Coles, M. G., Gratton, G., & Donchin, E. (1995). Mental chronometry and the study of human information processing. In M. D. Rugg & M. G. Coles (Eds.), *Electrophysiology of mind: Event-related brain potentials and cognition* (pp. 86–131). New York: Oxford University Press.
- Croft, R. J., Chandler, J. S., Barry, R. J., Cooper, N. R., & Clarke, A. R. (2005). EOG correction: A comparison of four methods. *Psychophysiology*, *42*, 16–24.
- De Jong, R. (2000). An intention-activation account of residual switch costs. In S. Monsell & J. Driver (Eds.), *Control of cognitive processes: Attention and performance XVIII* (pp. 357–376). Cambridge, MA: MIT Press.
- Desimone, R. (1998). Visual attention mediated by biased competition in extrastriate visual cortex. *Philosophical Transactions of the Royal Society of London—Series B: Biological Sciences*, *353*, 1245–1255.
- Efron, B. (1981). Nonparametric estimates of standard error: The jackknife, the bootstrap, and other methods. *Biometrika*, *68*, 589–599.
- Goffaux, P., Phillips, N. A., Sinai, M., & Pushkar, D. (2006). Behavioural and electrophysiological measures of task switching during single and mixed-task conditions. *Biological Psychology*, *72*, 278–290.
- Gratton, G., Coles, M. G., & Donchin, E. (1983). A new method for off-line removal of ocular artifact. *Electroencephalography and Clinical Neurophysiology*, *55*, 468–484.
- Hopf, J. M., Boelmans, K., Schoenfeld, M. A., Luck, S. J., & Heinze, H. J. (2004). Attention to features precedes attention to locations in visual search: Evidence from electromagnetic brain responses in humans. *Journal of Neuroscience*, *24*, 1822–1832.
- Hsieh, S. (2006). The lateralized readiness potential and P300 of stimulus-set switching. *International Journal of Psychophysiology*, *60*, 284–291.
- Hsieh, S., & Liu, L. C. (2005). The nature of switch cost: Task set configuration or carry-over effect? *Brain Research. Cognitive Brain Research*, *22*, 165–175.
- Hsieh, S., & Yu, Y. T. (2003). Switching between simple response-sets: Inferences from the lateralized readiness potential. *Brain Research. Cognitive Brain Research*, *17*, 228–237.
- Jentsch, I., Leuthold, H., & Ridderinkhof, K. R. (2004). Beneficial effects of ambiguous precues: Parallel motor preparation or reduced premotoric processing time? *Psychophysiology*, *41*, 231–244.
- Jersild, A. T. (1927). Mental set and shift. *Archives of Psychology*, *89*, 1–82.
- Kieffaber, P. D., & Hetrick, W. P. (2005). Event-related potential correlates of task switching and switch costs. *Psychophysiology*, *42*, 56–71.
- Leuthold, H., Sommer, W., & Ulrich, R. (1996). Partial advance information and response preparation: Inferences from the lateralized readiness potential. *Journal of Experimental Psychology: General*, *125*, 307–323.
- Logan, G. D., & Zbrodoff, N. J. (1979). When it helps to be misled: Facilitative effects of increasing the frequency of conflicting stimuli in a Stroop-like task. *Memory and Cognition*, *7*, 166–174.
- Los, S. A. (1996). On the origin of mixing costs: Exploring information processing in pure and mixed blocks of trials. *Acta Psychologica*, *94*, 145–188.
- Luck, S. J., Girelli, M., McDermott, M. T., & Ford, M. A. (1997). Bridging the gap between monkey neurophysiology and human perception: An ambiguity resolution theory of visual selective attention. *Cognitive Psychology*, *33*, 64–87.
- Luck, S. J., & Hillyard, S. A. (1994). Spatial filtering during visual search: Evidence from human electrophysiology. *Journal of Experimental Psychology: Human Perception and Performance*, *20*, 1000–1014.
- Mangun, G. R., & Hillyard, S. A. (1995). Mechanisms and models of selective attention. In M. D. Rugg & M. G. Coles (Eds.), *Electrophysiology of mind: Event-related brain potentials and cognition* (pp. 40–85). New York: Oxford University Press.
- Meiran, N. (1996). Reconfiguration of processing mode prior to task performance. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *22*, 1423–1442.
- Meiran, N., Chorev, Z., & Sapir, A. (2000). Component processes in task switching. *Cognitive Psychology*, *41*, 211–253.
- Michie, P. T., Karayanidis, F., Smith, G. L., Barrett, N. A., Large, M. M., O'Sullivan, B. T., et al. (1999). An exploration of varieties of visual attention: ERP findings. *Brain Research. Cognitive Brain Research*, *7*, 419–450.
- Miller, J., Patterson, T., & Ulrich, R. (1998). Jackknife-based method for measuring LRP onset latency differences. *Psychophysiology*, *35*, 99–115.
- Milliken, B., Tipper, S. P., & Weaver, B. (1994). Negative priming in a spatial location task: Feature mismatch and distractor inhibition. *Journal of Experimental Psychology: Human Perception and Performance*, *20*, 624–646.
- Monsell, S. (2003). Task switching. *Trends in Cognitive Sciences*, *7*, 134–140.
- Mordkoff, J. T., & Gianaros, P. J. (2000). Detecting the onset of the lateralized readiness potential: A comparison of available methods and procedures. *Psychophysiology*, *37*, 347–360.
- Nicholson, R., Karayanidis, F., Poboka, D., Heathcote, A., & Michie, P. T. (2005). Electrophysiological correlates of anticipatory task-switching processes. *Psychophysiology*, *42*, 540–554.
- Osman, A., & Moore, C. M. (1993). The locus of dual-task interference: Psychological refractory effects on movement-related brain

- potentials. *Journal of Experimental Psychology: Human Perception and Performance*, *19*, 1292–1312.
- Rabbitt, P. (1966). Errors and error-correction in choice-response tasks. *Journal of Experimental Psychology*, *71*, 264–272.
- R-Development-Core-Team. (2005). *R: A language and environment for statistical computing*. Vienna, Austria: Author.
- Rogers, R. D., & Monsell, S. (1995). Costs of a predictable switch between simple cognitive tasks. *Journal of Experimental Psychology: General*, *124*, 207–231.
- Rubin, O., & Meiran, N. (2005). On the origins of the task mixing cost in the cuing task-switching paradigm. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *31*, 1477–1491.
- Ruge, H., Brass, M., Koch, I., Rubin, O., Meiran, N., & von Cramon, D. Y. (2005). Advance preparation and stimulus-induced interference in cued task switching: Further insights from BOLD fMRI. *Neuropsychologia*, *43*, 340–355.
- Ruge, H., & Naumann, E. (in press). Brain-electrical correlates of negative location priming under sustained and transient attentional context conditions. *Journal of Psychophysiology*.
- Rushworth, M. F., Passingham, R. E., & Nobre, A. C. (2002). Components of switching intentional set. *Journal of Cognitive Neuroscience*, *14*, 1139–1150.
- Slagter, H. A., Kok, A., Mol, N., Talsma, D., & Kenemans, J. L. (2005). Generating spatial and nonspatial attentional control: An ERP study. *Psychophysiology*, *42*, 428–439.
- Sudevan, P., & Taylor, D. A. (1987). The cuing and priming of cognitive operations. *Journal of Experimental Psychology: Human Perception and Performance*, *13*, 89–103.
- Tipper, S. P., & McLaren, J. (1990). Evidence for efficient selectivity in children. In J. T. Enns (Ed.), *The development of attention: Research and theory* (pp. 197–210). Amsterdam: North-Holland.
- Wager, T. D., Jonides, J., & Reading, S. (2004). Neuroimaging studies of shifting attention: A meta-analysis. *Neuroimage*, *22*, 1679–1693.
- Wijers, A. A., Mulder, G., Gunter, T. C., & Smid, H. G. O. M. (1996). Die Hirnelektrische Analyse der selektiven Aufmerksamkeit. In O. Neuman & F. Sanders (Eds.), *Aufmerksamkeit*. Göttingen: Hogrefe.

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