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Error-preceding brain activity links neural markers of task preparation to cognitive stability and flexibility

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A B S T R A C T

Balancing stability and flexibility is required to facilitate successful task selection in situations with competing stimuli. Research suggests a set of counteracting control processes that maintains this balance. In the present study, we investigate how two neural correlates of task preparation in event-related potentials (ERPs), the mixing positivity and the switch positivity, can be linked to stability and flexibility in task selection. In a cued task switching paradigm, we analyzed deviations of these ERPs when task confusions occurred, that is, when participants erroneously executed the currently irrelevant task. We found a reduced mixing positivity to be a main source of task confusions in a task environment that required ongoing switches between competing tasks, whereas the switch positivity was uninvolved here. However, an overabundance of this latter component was a source of task confusions in a task environment that required the repetitive execution of the same task, although task switches were not required at all in this condition. These results not only highlight the distinct functional significance of the two preparatory ERPs and show that control processes can be maladaptive in certain contexts. They can also be utilized to locate the mixing positivity and the switch positivity on the stability-flexibility spectrum. Our results are in line with accounts that suggest that a balance between stability and flexibility is facilitated by the concurrent involvement of two control processes. One that manages the top-down bias of the relevant task set and one that increases or decreases competition between alternatively available stimuli.

1. Introduction

Flexibly adapting to changing task requirements is of paramount importance in a world of countless concurrent goals and situations. The human brain has developed a complex system of cognitive control processes that allows for rapidly modulating behavior in a way that fits best to the requirements of a specific situation while at the same time maintaining longer-lasting goals. Research has shown that this is achieved by the anticipatory allocation of cognitive resources necessary for optimally selecting and executing a relevant task (Kiesel et al., 2010). On the neural level, this is implemented as an interplay of structures in the prefrontal cortex and more parietal parts of the brain (Brass et al., 2005). Occasional lapses in the performance of simple tasks offer insight into these mechanisms of cognitive control because these errors can be linked to specific mental processes. In the present study, we investigate to which extent two event-related potentials (ERPs) from the task switching literature, the mixing positivity and the switch positivity, can be linked to the concepts of flexibility and stability. To this aim, we examine neural precursors of task confusions in two different task environments that have different requirements with regard to flexible and stable task execution.

The question of how the brain balances demands for stability versus flexibility in human behavior has attracted research from different lines within the neuroscience community, such as functional imaging (Armbruster et al., 2012; Ekman et al., 2012; Leber et al., 2008), genetics (e.g., Nolan et al., 2004; Rosa et al., 2010), and electroencephalography (EEG; Jamadar et al., 2010; Mansfield et al., 2012). It is argued that this balance between stability and flexibility is determined by levels of dopamine (DA) in the prefrontal cortex, as the formation of internal task representations – task sets – requires optimal levels of DA in order to be stable (Fallon et al., 2013). This receives support from neurogenetic studies that found a gene variant linked to the DA metabolism to predict individual differences in cognitive stability and flexibility (Nolan et al., 2004; Rosa et al., 2010).

Situations in which environmental cues dictate which task to execute at a particular point of time make special demands on a neural system that balances stability and flexibility. Here, task selection is not an endogenous process, but is based on correctly encoding the cue and successfully activating the task set that is prompted by it (Goschke, 2000; Herd et al., 2014; Miyake and Friedman, 2012). As a result, balancing stability and flexibility in this situation does not reflect the actual choice of staying with the same task or switching to a new task (as it is the case in voluntary task switching; for a review, see Arrington et al., 2014). Rather, this balance addresses the process of selecting and activating the cued task itself. In his Metacontrol State Model (MSM), Hommel (2015) suggested that stability and flexibility could be balanced in such a context

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through the interaction of two concurrently running control processes (see also Hommel, 2012; Hommel and Colzato, 2010). On the one hand, the impact of the currently relevant goal can be increased or decreased to move a bias towards more stability or more flexibility. That is, top-down control of information processing can be modulated based on the task features that are elicited by the cue. On the other hand, a bias towards stability or flexibility can also be established by regulating the competitiveness between the task alternatives, that is, the degree of attenuation of the processing of distracting stimuli. In the following, we will refer to the first process suggested by Hommel (2015) as the *goal-biasing process* and to the second one as the *competitor-receptivity process*. Ekman et al. (2012) recently provided neural evidence for such a two-component system in a fMRI study. A central core, situated primarily in the frontal cortex, was found to manage the stable representation of task goals by integrating information from different brain regions. More peripheral, parietally-located processes, however, were shown to be task-specific and address stimulus variability from trial to trial. Successful task selection and activation are therefore established by a dynamic interplay of these two network components.

EEG research has extensively investigated neural correlates of task preparation in situations with competing tasks (for a review, see Karayanidis et al., 2010). Predominant in this regard is the cued task-switching paradigm. Here, participants have to switch between two tasks in random order with a cue indicating the task on each trial, which leads to task repetitions as well as task switches. EEG studies have identified neural correlates of two distinct processes of task preparation (Karayanidis et al., 2011; Mansfield et al., 2012). The so-called *switch positivity* is an increased P3b-like posterior positivity in task switches compared to task repetitions during the cue-stimulus interval (Karayanidis et al., 2010; Karayanidis and Jamadar, 2014; Kieffaber and Hetrick, 2005; Rushworth et al., 2002). This component is seen as reflecting aspects of task-set activation that are more pronounced when the currently relevant task is switched. It is found in switches of stimulus sets as well as stimulus-response mappings (Astle et al., 2008; Karayanidis et al., 2010). In contrast, the *mixing positivity* is observed by contrasting task repetitions in regular mixed-task blocks with trials in single-task blocks, in which participants work on the same task throughout the whole block (mixed-repetition vs. all-repetition). The mixing positivity occurs somewhat earlier and is more centrally distributed than the switch positivity. It appears to represent more general task preparation that occurs in both task-switch and task-repetition trials and is reported to be associated with task readiness (Goffaux et al., 2008; Karayanidis et al., 2011; Kray et al., 2005; West and Travers, 2008; see also Rubin and Meiran, 2005).

Nonetheless, EEG research so far has not yet attempted to link these two ERPs to the concepts of stability and flexibility, although a tentative allocation of the two ERPs on such a stability-flexibility-spectrum seems plausible. The mixing positivity represents a *general preparation* that occurs both on repetition and switch trials. According to Rubin and Meiran (2005), this form of preparation puts a bias on the currently relevant task (see also Desimone and Duncan, 1995; Hommel, 2015; Miller and Cohen, 2001) and can be seen as facilitating stability in task selection and activation, thus reflecting the goal-biasing process in the MSM. The switch positivity, on the other hand, comes into effect only on switch trials, which is why it is also labeled *switch-specific preparation*. This process is reported to deal with continued priming of the previously relevant task, so-called task-set inertia, and when a switch is intended, suppressing this link to the previous task set in order to increase receptivity for new stimuli and tasks (Allport et al., 1994; Allport and Wylie, 1999; Friedman et al., 2007; Herd et al., 2014). Hence, this form of preparation appears to support flexibility in task selection in a similar way as the competitor-receptivity process as suggested in the MSM.

Our approach was to investigate the possible link of these two ERPs to stability and flexibility by looking at cases of maladaptation of these preparatory processes in different task environments. Recent studies have shown that control processes that are adaptive in one task environment can be maladaptive in another (Danielmeier et al., 2011; Eichele et al., 2010; R. Steinhauser, Maier and Steinhauser, 2017). As a result, also the control processes that balance stability and flexibility in the task switching paradigm may be subject to such maladaptation and individual control processes could be a source of errors in themselves. Specifically, a control process that facilitates stable task execution may be a source of errors in a variable task environment that requires frequent switches to other tasks. In contrast, a control process that supports flexibility may be a source of errors in a task environment that demands a constant focus on the same task while resisting distracting influences from other tasks. In the present study, we implemented these two task environments as mixed-task blocks and single-task blocks. Mixed-task blocks feature randomized task sequences and have consequently a demand for fast and flexible switches between the tasks. In contrast, single-task blocks require the steady execution of only one of the tasks.

As markers for adaptive or maladaptive balancing of stability and flexibility, we considered so-called *task confusions*, in which participants respond to the stimulus of the currently irrelevant task, presumably reflecting that the wrong task set became activated. When these task confusions result from maladaptations in the balancing of the two preparatory processes that favor stability and flexibility, we can investigate if the respective process is the one responsible for successful task selection in that task environment. If indeed the mixing positivity facilitates stable task activation by managing competition between simultaneously activated task sets (Rubin and Meiran, 2005), it should be the more eminent control process in mixed-task blocks, where we find strong competition from the distracting task. Hence, deviations in the mixing positivity should be linked to the occurrence of task confusions in this task environment. Likewise, the switch positivity, which is supposed to represent the suppression of the previously relevant task set and creates susceptibility towards new tasks (Herd et al., 2014), may be a more impactful origin of task confusions in single-task blocks, which require the steady repetition of the same task.

Conventionally, the two ERP components in question are quantified as the difference between two contrasting conditions. For the switch positivity, this is switch vs. mixed-repetition trials and for the mixing positivity, it is mixed-repetition vs. all-repetition trials (see Karayanidis and Jamadar, 2014). This way of measuring the components has a fundamental drawback: it is impossible to estimate the magnitude of the switch positivity in single-task blocks (as there are no switch trials in this environment) and impossible to estimate the mixing positivity in mixed-task blocks (as there are no all-repetition trials in this environment). For this reason, our methodological approach was to use multivariate pattern analysis (MVPA) as a decoder for the two distinct preparatory processes that underlie the switch positivity and the mixing positivity (Mansfield et al., 2012; Parra et al., 2002; Parra et al., 2005; M. Steinhauser and Yeung, 2010; R. Steinhauser et al., 2017). To not confuse the original ERP components with the respective decoded entities, we refer to the latter ones as switch-specific preparatory activity (based on the switch positivity) and general preparatory activity (based on the mixing positivity). Similar to Mansfield et al. (2012), we trained classifiers to distinguish, on the one hand, switch trials from mixed-repetition trials, and on the other hand, mixed-repetition from all-repetition trials, thus extracting switch-specific and general preparatory activity, respectively. This activity could then be analyzed on task confusions in all task environments to determine whether the respective preparatory process is responsible for the emergence of task confusions in each environment.

2. Method

2.1. Participants

32 participants (25 female) with mean age of 22.4 years (range: 19–33) participated in the study. They were recruited at the Catholic University of Eichstätt-Ingolstadt, had normal or corrected to normal vision and had no history of neurological or psychiatric diseases. They

received payment or course credit for participation. The study was approved by the ethics committee of the Catholic University of Eichstätt-Ingolstadt and informed consent was acquired from all participants. One subject had to be excluded from further analysis due to technical problems during data acquisition.

2.2. Tasks and procedure

We used a task-switching paradigm in which participants had to classify either a character or a picture (Steinhauser and Gade, 2015; Steinhauser et al., 2017). Each stimulus contained both a character and a picture in horizontal arrangement, whereas the positions of character and symbol switched randomly between left and right and the whole stimulus covered a visual angle of 5.6° width and 2.8° height (Fig. 1A). The set of characters contained four letters (A, B, C, D), four numerals (1, 2, 3, 4) and four symbols ($, %, &, ?), displayed as contours based on the font type Arial Bold. The set of pictures contained four animals (bird, cat, dog, mouse), four fruits (apple, banana, cherry, pear), and four vehicles (aircraft, bike, car, sailboat) from the Snodgrass-Vanderwart Set of Standardized Pictures (Snodgrass and Vanderwart, 1980). The tasks required either to classify the character as 'letter'', 'digit' or 'symbol' (character task) or to classify the picture as 'animal', 'fruit' or 'vehicle' (picture task). Responses from both tasks were mapped on the same three keys of a PC keyboard and were given with the index, middle, and ring fingers of the right hand by pressing 'arrow left' for categories 'letter' and animal, 'arrow down' for categories 'digit' and 'fruit' and 'arrow right' for categories 'symbol' and 'vehicle'. Only stimuli were used in which the two tasks led to different responses (i.e., incongruent stimuli), resulting in 384 possible stimuli, but participants were not informed about the exclusion of congruent stimuli. Preceding each stimulus, a cue in the form of a circle or a square (both 2.8° in diameter) indicated which task to perform. The cue-task mapping was counterbalanced across participants. All visual elements were presented in white color on a black background.

Each trial consisted of an initial 300 ms presentation of the cue that was followed by 900 ms of black screen (adding up to a cue-stimulus interval, CSI, of 1200 ms) and finally the presentation of the stimulus for another 150 ms. This long CSI was chosen in line with previous studies (e.g., Goffaux et al., 2008; Karayanidis et al., 2009; Mansfield et al., 2012; Rushworth et al., 2002), because shorter CSIs partially shift preparatory ERPs to the post-stimulus phase (see also Karayanidis et al., 2011; Nicholson et al., 2006). As no feedback on task performance was given to the participant, a response-cue interval of 1200 ms started after the participant's response, followed by the next trial (in case of self-corrections, the response-cue interval restarted after the last response). The study was conducted in two sessions, a practice session and a test session, which took place on two consecutive days. Each session consisted of 12 blocks – 6 blocks à 64 trials in which the same task (and cue) was repeated during the whole block (single-task blocks), and 6 blocks à 128 trials with randomized tasks (mixed-task blocks). Mixed-task blocks alternated with single-task blocks (e.g., mixed – single-character – mixed – single-picture) and the order of block succession was varied systematically over participants, with 50% of the participants starting with a mixed-task block, 25% starting with a single-character-task block and 25% starting with a single-picture-task block.

Extensive practice was necessary to ensure stable task performance in the test session and to adjust the error rate. Two procedures were applied to ensure sufficiently high error rates of about 15–20% and low correction rates. First, during the practice session, a notification "SCHNELLER ANTWORTEN" (engl., respond more quickly) was displayed between the response and the response-cue interval for 1000 ms whenever the error rate within the last 30 trials fell below 15%. This procedure was not applied during the test session to not confound task preparation ERPs with brain activity linked to the processing of the feedback stimulus. Second, in both the practice session and the test session on completion of blocks with error rates below 15% and correction rates over 5%, the experimenter reminded the participant verbally to speed on (as the study aimed to investigate task performance under time pressure) and to avoid correcting their errors. No other feedback was given and neither error rates nor the subject of error processing was mentioned by the experimenters until the post-experiment debriefing.

2.3. Data acquisition

During the test session, EEG was recorded using a BIOSEMI Active-Two system (BioSemi, Amsterdam, The Netherlands) according to the

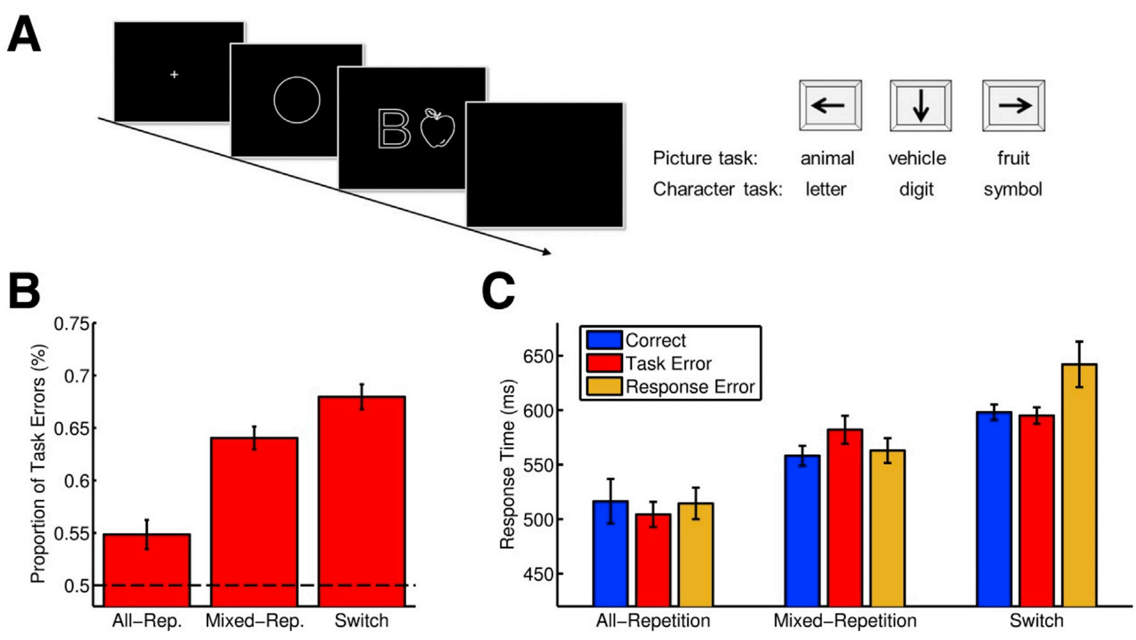

Fig. 1. A, cued task-switching paradigm used in this study (left) with bivalent response mapping (right). B, proportion of task errors among all error trials in the all-repetition trials of single-task blocks, and the mixed-repetition and switch trials of mixed-task blocks. The dotted line indicates chance level. C, mean response times for corrects, task errors and response errors in the three conditions. Error bars indicate within-subjects standard errors (Cousineau, 2005; Morey, 2008).

extended International 10–20 system with 64 Ag–AgCl electrodes from channels Fp1, AF7, AF3, F1, F3, F5, F7, FT7, FC5, FC3, FC1, C1, C3, C5, T7, TP7, CP5, CP3, CP1, P1, P3, P5, P7, P9, PO7, PO3, O1, Iz, Oz, POz, Pz, CPz, Fpz, Fp2, AF8, AF4, AFz, Fz, F2, F4, F6, F8, FT8, FC6, FC4, FC2, FCz, Cz, C2, C4, C6, T8, TP8, CP6, CP4, CP2, P2, P4, P6, P8, P10, PO8, PO4, O2 as well as the left and right mastoid. The CMS (Common Mode Sense) and DRL (Driven Right Leg) electrodes were used as reference and ground electrodes. Vertical and horizontal electrooculogram (EOG) was recorded from electrodes above and below the right eye and on the outer canthi of both eyes. All electrodes were off-line re-referenced to linked mastoids. EEG and EOG data were continuously recorded at a sampling rate of 512 Hz.

2.4. Data analysis

Behavioral data. Behavioral data analysis was conducted to demonstrate that our paradigm is able to elicit two separable types of errors, task errors and response errors and that typical task switching effects can be replicated. For this aim, trials were classified on two dimensions: (1) Regarding the response type, as *correct trials* when the response corresponded to the target, as *task errors* when the response corresponded to the distractor stimulus element, or as *response errors* when the response corresponded to none of the stimulus elements. (2) Regarding the task transition type, as *all-repeat* trials (in single-task blocks), as *mixed-repeat* trials, or as *switch* trials (the latter two in mixed-task blocks).

Response time analysis was conducted on trials deviating less than three standard deviations from the mean computed for each condition and participant. Furthermore, trials after errors were excluded because it is unclear whether such trials should be considered as task repetitions or switches (M. Steinhauser and Hübner, 2006). Because frequency data is per se not normally but binomially distributed, error rates were arcsine-transformed prior to statistical testing (Winer et al., 1991).

As the link between labeled error types (task errors, response errors) and actual error sources (task confusions, response confusions) in our paradigm is not deterministic (e.g., a task error can also occur if a response confusion leads to a response that incidentally matches the distractor), we fit a multinomial model that is able to estimate the probability of latent events from the frequencies of observable ones (for an overview, see Batchelder and Riefer, 1990; for examples, see Maier et al., 2012; Meiran and Daichman, 2005; M. Steinhauser and Hübner, 2006). The formal details of this multinomial model are reported in M. Steinhauser, Maier and Ernst (2017). In brief, the model assumes that each response type results from possible combinations of applied tasks and executed responses. The observable frequencies of each response type can thus be computed as a function of two free model parameters: the probability of executing the correct task, p(T), and the probability of executing the correct response, p(R). After estimating these parameters separately for each participant, one can derive and analyze the conditional probabilities of task confusions given each response type. Based on previous studies (M. Steinhauser and Gade, 2015; M. Steinhauser, Maier and Ernst, 2017), we hypothesized that actual task confusions should be far more prevalent among (labeled) task errors than among correct trials and (labeled) response errors. Such a result would imply that correlates of task confusions (and thus of reconfiguration failure) can be extracted by comparing task errors with response errors (M. Steinhauser et al., 2017).

Event-related potentials. All analyses were performed using MATLAB v8.2 (The Mathworks, Natick, MA) scripts in combination with EEGLAB v12.0 (Delorme and Makeig, 2004) functions. EEG data were band-pass filtered to exclude frequencies below 0.1 Hz and above 40 Hz, divided into epochs from 500 ms before to 1500 ms after cue onset and baseline-corrected to the interval of 200 ms before cue onset. Electrodes were interpolated using spherical spline interpolation if it met the joint probability criterion (threshold 5) as well as the kurtosis criterion (threshold 10) in EEGLAB's channel rejection routine (pop_rejchan.m). Epochs were removed that contained activity exceeding ±300 μV in any channel except AF1, Fp1, Fpz, Fp2, AF8 (to prevent exclusion of blink artifacts, which were corrected at a later stage) and whose joint probability deviated more than 5 standard deviations from the epoch mean. To correct for eye blinks and muscular artefacts, an infomax-based ICA (Bell and Sejnowski, 1995) was computed and components with time courses and topographies typical of these artefacts were removed after visual inspection. Based on the time windows described by Karayanidis et al. (2011a,b), mean amplitudes were computed at electrode Pz from 300 to 550 ms for the mixing positivity and from 450 to 850 ms for the switch positivity.

Decoder Analysis. To examine reconfiguration failure on *error* trials, we extracted specific forms of preparatory activity from the ERP data on *correct* trials by means of MVPA and used these as decoders of the respective task preparation processes. To this aim, we employed the linear integration method introduced by Parra et al. (2002) as it allows to extract spatial components from the ERP data that optimally discriminate between two conditions (M. Steinhauser and Yeung, 2010; R. Steinhauser et al., 2017). In a first step, we computed a set of classifiers, represented by weight vectors $v_{general}$, that discriminated maximally between all-repetition trials and mixed-repetition trials in partially overlapping time windows of 50 ms, separated by 10 ms during the cue-stimulus interval (0–1200 ms post cue). Each of these classifiers was trained on an equal, randomly drawn number of correct all-repetition and mixed-repetition trials per participant. This approach filters for a component that stands for general preparatory activity. Another set of classifiers, v_{switch}, was computed by discriminating between mixed-repetition trials and switch trials in the same time windows. This corresponds to a filter for switch-specific preparatory activity, as the classifier sensitivity of each weight vector expresses the amount to which a trial resembles a switch trial. To describe sensitivity of each resulting classifier, we report the area under the Receiver Operating Characteristic curve (Az score), of which Az = 0.5 would indicate classification at chance level. To prevent overfitting, leave-one-out (LOO) cross-validation was applied so that every weight vector used for further analysis was the mean of N weight vectors trained with T*(N-1) samples of N-1 trials to predict the T samples of the remaining trial. To visualize the spatial distribution of each classifier, we computed the coupling coefficient vector, which represents the activity at each electrode site that correlates with the respective discriminating component, and thus can be thought of as the "sensor projection" of that component (Parra et al., 2002, 2005).

For every time window t, this MVPA approach allows to assign an averaged prediction value $\overline{y}_e(t)$ to each trial, importantly also to those trials that were not part of the training set. The averaged prediction value stands for the probability of the trial to belong to the event e and ranges from 0 to 1, as it represents the predicted value of a logistic regression. Computed over $v_{general}$, (i.e., an $\overline{y}_e(t)$ is assigned to each trial based on the classifier set $v_{general}$), this classifier output represents how well the respective trial resembles a prototypical mixed-repetition trial in contrast to an all-repetition trial and thus is a single-trial measure for general preparatory activity. Likewise, computed over v_{switch}, this output mirrors switch-specific preparatory activity. For our analyses, we calculated such averaged prediction values for all task errors and response errors, separately based on $v_{general}$ and v_{switch}. Statistical testing of differences between the two error types was conducted at time windows at peak of the respective underlying ERP component, i.e. at 370 ms for general preparatory activity and at 600 ms for switch-specific preparatory activity.

In a final step, we tried to conceptually replicate the findings of M. Steinhauser et al. (2017) regarding different time courses of task preparation in repetitions and switches. To this aim, we followed this study's approach and computed participant-wise latencies of the peak difference between task errors and response errors, based on the prediction values of our MVPA. For switch-specific preparatory activity, we adopted that study's time window of interest from 300 ms to 1200 ms. For general preparatory activity, we specified a time window around the peak of the mixing positivity, from 100 ms to 600 ms.

3. Results

3.1. Behavioral data

Task-switching effects. We started by analyzing standard indices of task preparation in task switching. First, switch costs were obtained in mixed-task blocks, that is, switch trials were linked to higher error rates (22.8% vs. 16.4%), t (30) = 8.33, $p < .001$, $d = 0.79$, and RTs (598 ms vs. 558 ms), t (30) = 4.52, $p < .001$, $d = 0.27$, than repetition trials. Second, mixing costs were observed, that is, both error rates (16.4% vs. 14.1%), t (30) = 3.76, $p < .001$, $d = 0.30$, and RTs (558 ms vs. 516 ms), t (30) = 3.12, $p = .003$, $d = 0.40$, of mixed-repetition trials were significantly higher than the all-repetitions in single-task blocks.

Error types. The present paradigm was chosen as a way to distinguish two types of errors (task errors, response errors) caused by different error sources (task confusions, response confusions). However, the link between error types and error sources is not deterministic because some task errors could also be due to response confusions that incidentally corresponded to the distractor, and some response errors can be due to simultaneously occurring task confusions and response confusions. For our reasoning to be valid, we therefore had to validate our central assumption that task confusions are more prevalent in task errors than in response errors. We did this in two ways: First, we analyzed the proportion of task errors among all errors. If all task errors were actually response confusions, this proportion should be 50% as there are two possible error responses on each trial (Steinhauser and Gade, 2015). Second, we estimated the proportion of task confusions and response confusions in the two error types using a multinomial model (M. Steinhauser et al., 2017).

Fig. 1B depicts the proportion of task errors among all errors in the three conditions. It significantly exceeds 50% in all conditions, not only in mixed-task blocks, but even in single-task blocks, *ts* (30) > 3.24, *ps* < .003, *ds* > 0.81. A one-way repeated measures ANOVA on the variable Task Transition (all-repeat, mixed-repeat, switch) yields significant differences, F (2, 60) = 28.5, $p < .001$, $\eta^2_{part} = .49$, indicating that the proportion of task errors is higher in mixed-repetition trials than in all-repetition trials, t (30) = 5.00, $p <$. 001, $d = 1.10$, and again higher in switch trials than in mixed-repetition trials, t (30) = 2.66, $p = .013$, $d = 0.46$.

Table 1 provides the model parameters (probability of executing the correct task, p(T); probability of executing the correct response, p(R)) and the conditional probabilities of task confusions that were estimated from these parameters. Crucially, the conditional probability of task confusions differed across response types and conditions. A two-way ANOVA on the variables Response Type (correct, task error, response error) and Task Transition (all-repeat, mixed-repeat, switch) revealed main effects of Response Type, F (2, 60) = 207.4, $p < .001$, and Task Transition, F (2, 60) = 38.7, $p < .001$, and a significant interaction, F (4,120) = 38.7, $p < .001$. The result pattern suggests that task confusions were most prevalent on task errors relative to response errors and correct responses. While this difference increases from all-repeat trials over mixed-repeat trials to switch trials, it is substantial in each condition, *ts* (30) > 3.17, *ps* < .004, *ds* > 0.80.

Table 1
Multinomial modelling: Estimated model parameters (probabilities of applying the correct task, p(T), and probabilities of selecting the correct response associated with the applied task, p(R)) and probabilities of task confusions among correct responses, task errors and response errors, separately for all-repetitions, mixed-repetitions and task switches.

	Estimated model parameters		
	p(T)	p(R)	
All-repetition	.982 (±.013)	.874 (±.044)	
Mixed-repetition	.949 (±.018)	.878 (±.041)	
Switch	.902 (±.031)	.847 (±.051)	
	Estimated probability of task confusions among …		
	Correct trials	Task errors	Response errors
All-repetition	.001 (±.001)	.194 (±.069)	.018 (±.008)
Mixed-repetition	.004 (±.001)	.449 (±.062)	.051 (±.010)
Switch	.011 (±.018)	.547 (±.067)	.098 (±.018)

Note. Values in brackets are standard errors of the mean.

Taken together, these results confirm our central assumption that task errors and response errors differ with regard to the proportion of true task confusions. It should particularly be noted that even all-repeat trials exhibit an estimated 19.4% of task confusions among task errors although participants had to perform the same task throughout the whole block.

With regard to RTs (Fig. 1C), a two-way repeated measures ANOVA was conducted on the variables Response Type (correct, task error, response error) and Task Transition (all-repeat, mixed-repeat, switch). In addition to a main effect of Task Transition, F (2,60) = 28.5, $p < .001$, $\eta^2_{part} = .49$, the interaction reached significance, F (4,120) = 3.17, $p = .017$, $\eta^2_{part} = .10$. Contrasts reveal that while there is no RT difference between task errors, response errors and corrects in all-repeat trials, *ts* (30) < 0.66, *ps* > .52, *ds* < 0.055, in switch trials response errors are responded to slower than task errors and correct trials, *ts* (30) > 2.11, *ps* < .043, *ds* > 0.21. Though not reaching the significance threshold, slower responses in task errors than response errors in mixed-repetition trials can be observed on the numeric level, t (30) = 1.41, $p = .17$, $d = 0.09$. These findings suggest that task errors and response errors have different behavioral consequences depending on whether they occur in single-task blocks, in mixed-repetitions or in switch trials.

3.1.1. Event-related potentials

Preparatory activity in correct trials. Analysis of event-related potentials, too, was able to replicate common findings of task-switching literature that support the ability of this paradigm to investigate preparatory activities in task-set reconfiguration (Fig. 2). The commonly reported posterior positivity in switch trials compared to mixed-repetition trials (e.g., Karayanidis et al., 2010; Karayanidis and Jamadar, 2014; Rushworth et al., 2002) can also be found in our data, t (30) = 3.88, $p < .001$, $d = 0.62$. Inspection of the time course and scalp topography reveals that this effect peaks around 660 ms. Comparing mixed-repetition trials with all-repeat trials, the also frequently reported, slightly earlier mixing positivity (e.g., Jost et al., 2008; Karayanidis et al., 2011) becomes evident, t (30) = 6.47, $p < .001$, $d = 0.86$. This second positivity peaks around 370 ms.

Preparatory activity in erroneous trials. Starting with mixed-task blocks, we compared task errors and response errors in two two-way ANOVAs on the variables Response Type (task error, response error) and Task Transition (mixed-repeat, switch) for general and switch-specific preparatory activity. Neither in the time window of the mixing positivity, all *Fs* < 0.26, all *ps* > .61, all $\eta^2_{part} < .01$, nor in the time window of the switch positivity, all *Fs* < 0.29, all *ps* > .59, all $\eta^2_{part} < .01$, did any effect reach significance. Equally, all contrasts involving task errors vs. response errors were non-significant, *ts* (30) < 0.64, *ps* > .53. Likewise, in single-task blocks, task errors did not differ significantly from response errors – neither in the time window of the mixing positivity, t (30) = 0.91, p = .37, d = 0.19, nor in that of the switch positivity, t (30) = 1.24, p = .22, d = 0.26. Taken together, this shows that conventional analysis of raw ERP waves reaches its limits when it comes to comparing these two types of errors. Additionally, it has to be noted that a thorough differentiation of the temporarily and spatially overlapping mixing positivity and switch positivity would hardly appear feasible here.

3.2. Decoder Analysis

Extracting preparatory activity in correct trials. In a next stage, we applied the linear integration method by Parra et al. (2002) to extract preparatory activity from the larger dataset of correct trials. In contrast to

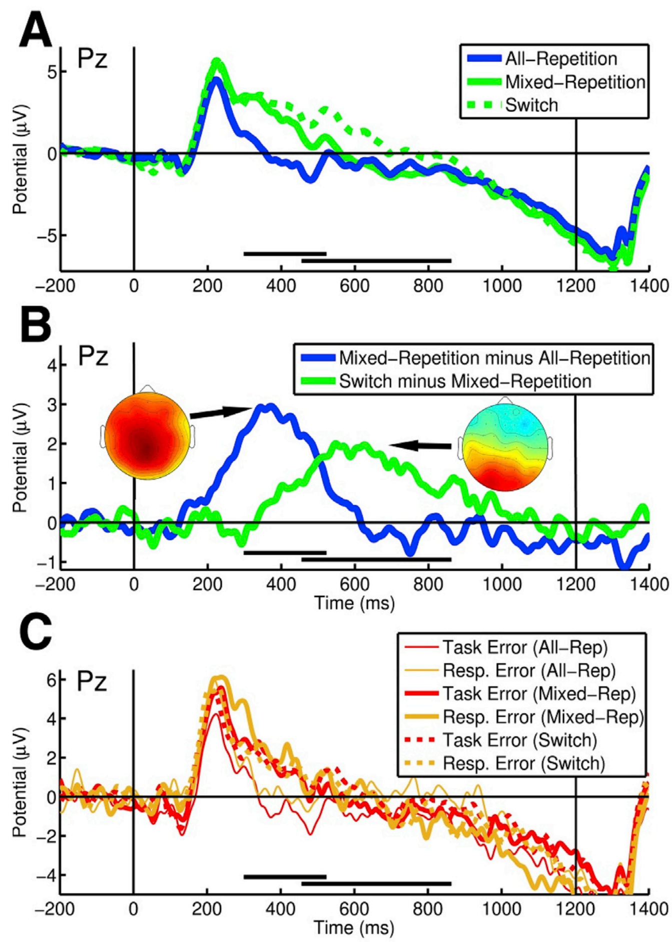

Fig. 2. Cue-locked activity at electrode Pz. A. Grand average ERP waves for correct trials in single-task blocks (blue) and in mixed-task blocks (green). B. Difference waves for the mixing effect (mixed-repetition minus all-repetition, blue) and switch effect (switch minus mixed-repetition). C. Significant differences between task errors and response errors can be found in raw ERP data neither in the mixing positivity nor in the switch positivity. Horizontal black bars represent the time windows used for quantification of the mixing positivity (300–550 ms) and the switch positivity (450–850 ms).

raw ERPs, this analysis also takes into account individual variability in scalp topographies and thus provides more statistical power to investigate differences between the two error types. One set of classifiers was trained to distinguish all-repetition trials from mixed-repetition trials, yielding an output that represents general preparatory activity. A second set of classifiers was trained to distinguish mixed-repetition trials from switch trials to produce a measure for switch-specific preparatory activity. For both classifiers, the time course of classification accuracy and the discriminating topography matched those of the switch positivity and mixing positivity in ERP analysis (Fig. 3).

Preparatory activity in error trials. We subsequently applied the classifiers that represent general and switch-specific preparatory activity to the much smaller dataset of error trials to investigate differences between task errors and response errors. Initially, we conducted omnibus ANOVAs on the variables Error Type (task error, response error) and Task Transition (all-repetition, mixed-repetition, switch) on the classifiers' prediction values. For general preparatory activity, this was done in the time window around the peak of the mixing positivity, and for switch-specific preparatory activity, this was done in the time window around the peak of the switch positivity.

For the 2 × 3 ANOVA on general preparatory activity, a main effect of Task Transition, F (1,30) = 21.54, $p < .001$, $\eta^2_{\text{part}} = .42$, which was

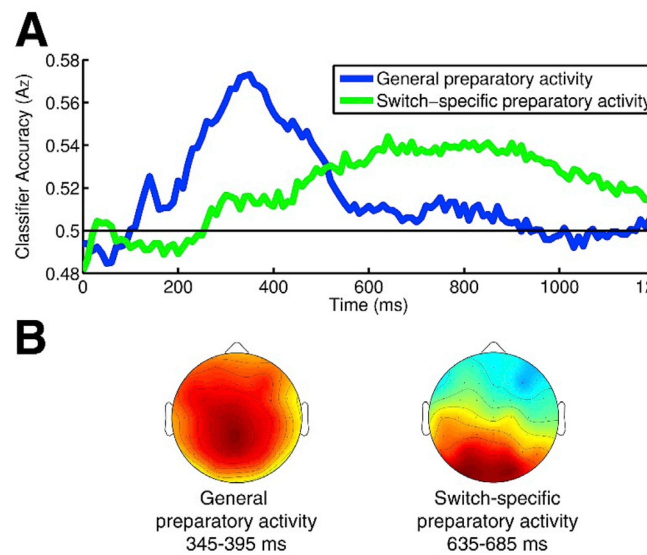

Fig. 3. Decoding preparatory activity by means of MVPA. Classifier accuracy (A) and discriminating topographies (B) for two sets of classifiers – all-repetition vs. mixed-repetition (general preparatory activity, blue) and mixed-repetition vs. switch (switch-specific preparatory activity, green) on time windows of 50 ms width, every 10 ms.

driven by a large difference between all-repetition trials on the one hand and switch-trials and mixed-repetition trials on the other hand, *ts* (30) > 2.53, *ps* < .017, *ds* > 0.71, substantiated this classifier's ability to distinguish trials in mixed-task blocks from those in single-task blocks also on error trials. Additionally, we observed an interaction between the variables, F (2,60) = 4.05, $p = .026$, $\eta^2_{\text{part}} = .12$. To reduce complexity, in subsequent analyses we treated the two task environments separately. In the 2 × 2 sub-analysis of mixed-task blocks (variable Task Transition as mixed-repetition vs. switch, see Fig. 4A), task errors were associated with significantly reduced general preparatory activity compared to response errors, F (1,30) = 7.73, $p = .009$, $\eta^2_{\text{part}} = .20$. Although noticeable on the numerical level, the interaction of Task Transition and Error Type did not become significant here, F (1,30) = 1.09, $p = .30$, $\eta^2_{\text{part}} = .03$. In the sub-analysis of single-task blocks (Fig. 5A), on the other hand, task errors were not different from response errors, t (30) = 1.09, $p = .29$, $d = 0.26$.

The omnibus 2 × 3 ANOVA on switch-specific preparatory activity showed a similar picture. A main effect of Task Transition, this time mainly driven by the difference between switch-trials on the one hand and mixed-repetitions and all-repetitions on the other hand, *ts* (30) > 2.53, *ps* < .017, *ds* > 0.58, again highlighted the classifier's ability to distinguish repetitions from switches also on error trials, F (1,30) = 6.83, $p = .003$, $\eta^2_{\text{part}} = .19$, and again, we observed an interaction of the two variables, F (2,60) = 4.98, $p = .016$, $\eta^2_{\text{part}} = .14$. In contrast to general preparatory activity, however, when analyzing the mixed-task blocks environment separately in a 2 × 2 ANOVA, we found switch-specific preparatory not suited to distinguish the two error types (Fig. 4B). Here, task errors did not show any significant differences from response errors, F (1,30) = 0.58, $p = .45$, $d = 0.019$, neither on mixed-repetition trials. This is notably different when analyzing the task environment of single-task blocks, in which task errors and response errors show a tremendous difference (Fig. 5B): task errors were associated with strongly increased switch-specific activity in all-repetition trials, t (30) = 3.10, $p = .004$, $d = 0.73$.

In a final step of analysis, we aimed to conceptually replicate the findings of M. Steinhauser et al. (2017), who found general preparatory activity in repetitions to peak significantly earlier than in switches. To this aim we compared the latencies of the maximum difference in average prediction values between task errors and response errors in mixed-repetition and switch trials. As for general preparatory activity, we

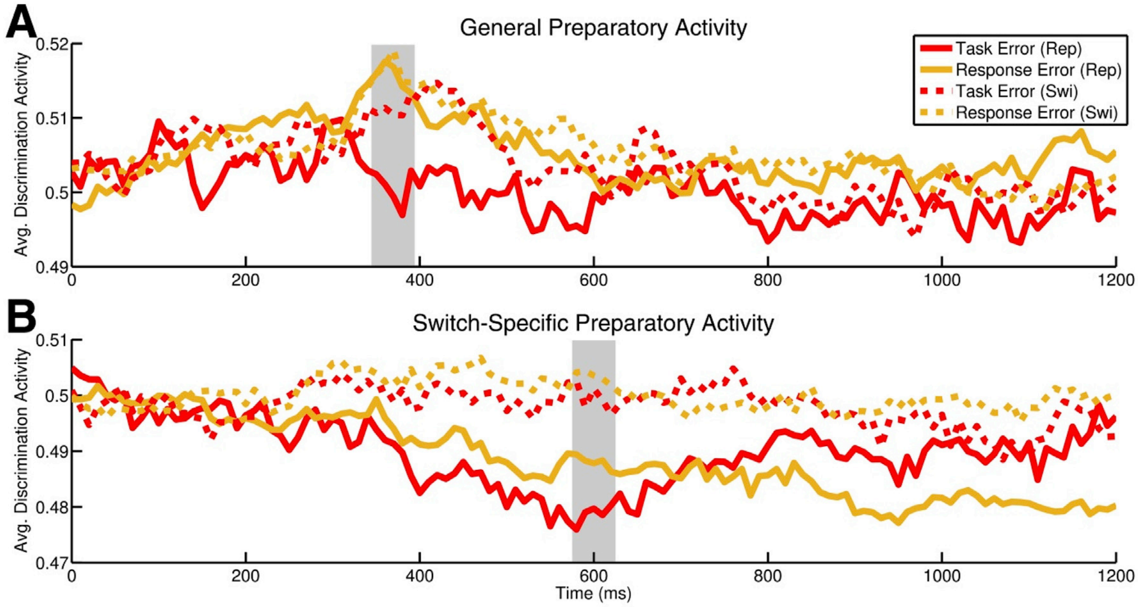

Fig. 4. Average discrimination activity of error trials in mixed-task blocks, based on classifiers representing general (A) and switch-specific preparatory activity (B). Grey areas indicate the classifier windows at the amplitude peak of the respective ERP component (A: mixing-positivity, B: switch-positivity).

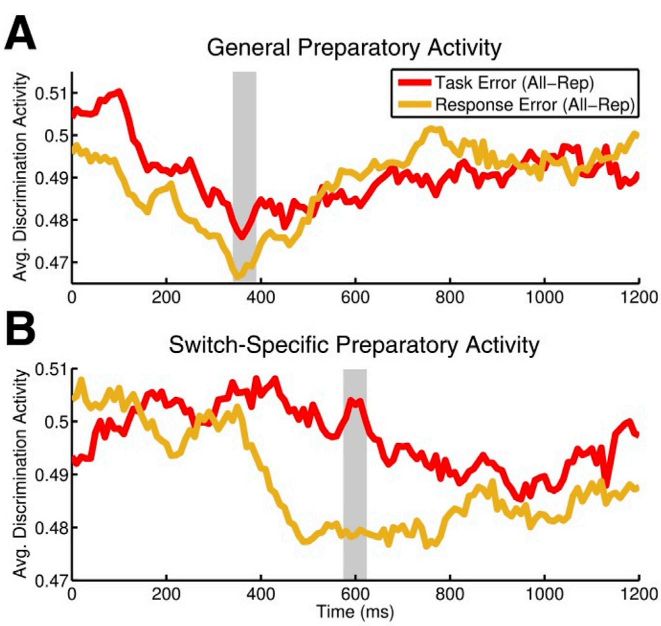

Fig. 5. Average discrimination activity of error trials in single-task blocks, based on classifiers representing general (A) and switch-specific preparatory activity (B). Grey areas indicate the classifier windows at the amplitude peak of the respective ERP component (A: mixing-positivity, B: switch-positivity).

too found the maximum difference significantly earlier in mixed-repetitions (322 ms) than in switches (400 ms), t (30) = 2.06, $p = .049$, $d = 0.54$. Latency analysis based on switch-specific activity, however, showed only a trend towards earlier preparation in mixed-repetitions (762 ms) than in switches (874 ms), t (30) = 1.73, $p = .093$, $d = 0.42$.

4. Discussion

Previous research suggests that balancing stability and flexibility in human behavior is achieved by a combination of control processes (Goschke, 2000; Hommel, 2015), which may be linked to fundamental neuromodulatory states within the DA system (Fallon et al., 2013; Nolan et al., 2004; Rosa et al., 2010). The aim of this study was to examine if also two commonly observed ERP components in the task switching literature, the mixing positvity and the switch positivity (for a review, see Karayanidis and Jamadar, 2014), can be linked to the concepts of stability and flexibility. In two task environments that required different levels of stability and flexibility in participants' behavior, the two preparatory processes were differentially involved in the emergence of task confusions. In mixed-task blocks, a task environment requiring frequent switches between alternative tasks, we found general preparatory activity, the MVPA-analog to the mixing positivity, to be reduced in task errors, whereas switch-specific preparatory activity, the MVPA-analog to the switch positivity, proved to be equal in task errors and response errors. Conversely, in single-task blocks, a task environment requiring the repetitive execution of the same task, general preparatory activity was similar in both error types. Instead, we observed switch-specific preparation to be increased in task errors. This finding contradicts more traditional accounts that suggest that both general and switch-specific preparation represent rather similar, consecutive steps of task readiness and subsequent activation (e.g., Karayanidis et al., 2010; Karayanidis et al., 2011; Mansfield et al., 2012). Rather, it provides first evidence to link these preparatory processes differently to the concepts of stability and flexibility and empirically supports Hommel's (2015) two-component Metacontrol State Model of task preparation.

Our data support the idea that a general form of preparation, represented by the mixing positivity, is mainly responsible for selecting and subsequently activating the relevant task set in repetitions as well as switches (Altmann, 2004a, 2004b; Dreisbach et al., 2002; Koch, 2003, 2005; Loose et al., 2017; Rubin and Meiran, 2005). By resolving the competition between competing tasks (cf. Desimone and Duncan, 1995; Hommel, 2015; Miller and Cohen, 2001), general preparation appears to facilitate the stable activation of the cued task set on each trial in task environments with distracting stimuli. This can be deduced from the finding that in mixed-task blocks, reduced general preparation led to an increased frequency of unfavorable switches to the distracting task (and thus causing task confusions) when participants were required to suppress this competing task set. It must be noted, however, that our results do not necessarily imply that general preparation is implemented entirely equally in task switches and repetitions, although it occurs in both conditions. Replicating M. Steinhauser et al. (2017), we found a different time course of general preparation in task switches and task repetitions with repetitions reaching a peak in general preparation about 80 ms earlier than task switches.

The most pivotal finding of the present study is that task confusions in single-task blocks were caused by an increased amount of switch-specific preparation, i.e., of the switch positivity. It is per se interesting that task confusions were also observable in single-task blocks in which participants had to execute the same task throughout the block and distraction by the competing task was present only in a subtle way, most likely from preceding mixed-task blocks and previous single-task blocks focussing on the other task. Nonetheless, replicating previous studies (M. Steinhauser and Gade, 2016; M. Steinhauser et al., 2017), task confusions occurred also in this environment, as proved by labeled task errors occurring significantly above chance level in all-repetition trials (Fig. 1B) as well as by the multinomial model (Table 1). These task confusions were associated with increased switch-specific preparation whereas general preparation was in no way different from the baseline condition of response errors. The switch positivity was previously linked to suppressing the continued priming of the previously relevant task set to increase receptivity for competing task sets and response sets (Allport et al., 1994; Allport and Wylie, 1999; Friedman et al., 2007; Herd et al., 2014).[1] In single-task blocks, a task environment that requires stability of the task set across trials, this receptivity is disadvantageous. Possibly in conjunction with attentional lapses or mind wandering, such an occasional overabundance of this form of preparation can endogenously initiate the erroneous switch to the competing task. The idea that switch-specific preparation represents a process that suppresses ongoing activation of the previously relevant task set and as a result increases susceptibility towards new, possibly distracting stimuli is supported by studies that investigated individual differences in task preparation. Switch-specific preparation was increased in children with weaker self-control (Friedman et al., 2011) and in adolescents with attention problems (Friedman et al., 2007), whereas other executive functions in these studies (that are closer related to general preparation) were reduced in children with weaker self-control and in adolescents with attention problems.

The observation that the switch positivity is a precursor of task confusions only in the single-task environment is interesting for another reason. It was not at all linked to task confusions in the more conventional mixed-task blocks, in which the MVPA-analog of the switch positivity was more pronounced in switches compared to repetitions, equally on task errors and response errors. On the one hand, this supports accounts that call into question the importance of a switch-specific preparatory process but instead highlight the importance of a general preparation process that is common to switch and repetition trials in the conventional task switching paradigm with two task alternatives (Altmann and Gray, 2008; de Baene et al., 2012; Dreisbach et al., 2002; Koch, 2005; M. Steinhauser et al., 2017). In line with the reasoning of a previous study (Steinhauser et al., 2017), our results suggest that the general preparatory process is the actual prerequisite for effective task set reconfiguration, whereas the switch-specific component serves only a subordinate, possibly efficiency-optimizing purpose. In mixed-task blocks, the switch-specific process is unable to cause task confusions because the dominant general preparation process is active and determines task selection. Only in the special environment of single-task blocks, in which general preparation is less involved, the switch-specific optimization process, which increases the susceptility towards distractors, comes into (unfavorable) effect and is linked to the emergence of task confusions. In other words, too much flexibility (i.e., switch-specific preparation) causes task errors only if the balancing influence of stability (i.e., general preparation) is absent.

This differentiated functional involvement of the mixing positivity and the switch positivity provide neural evidence for Hommel's (2015) MSM, in which he argues that two processes run in parallel to enable successful task selection and activation. Hommel suggests that one of these processes manages the impact of the goal in a top-down way by biasing the currently relevant task set. The present results allow us to link this process to the mixing positivity, which we found to be primarily responsible for successful task selection in an environment in which updating the relevant task set is of key importance on each trial. The other process in the MSM manages the competitiveness between concurrently accessible tasks and thus can increase the receptivity towards new tasks in case of a task switch. Our data suggest that the switch positivity is closely related to this second process in the MSM. We found an overabundance of the switch positivity to elicit task confusions when an activation of the alternative task set should be precluded per se. Too much receptivity towards alternative options appears to create this type of error particularly in the repetitive and little challenging environment of single-task blocks.

Considering the switch positivity as being linked to a process that manages the receptivity for new tasks and stimuli leads to a number of implications for possible future research. First, this receptivity may not be limited to distracting task sets but instead could also increase the impact of unfavorable response tendencies. Previous studies found that congruency effects are increased on switch trials (Kalanthroff and Henik, 2014; Monsell et al., 2003; Schuch and Koch, 2003; Wendt and Kiesel, 2008). Whereas this effect has previously been attributed to reduced proactive task control in task switches (e.g., Kalanthroff and Henik, 2014), future studies should investigate whether this could also be explained by an actively increased receptivity for distractors in this condition. Second, similarly interesting appears the question whether and how the causal roles of general and switch-specific preparation in the emergence of task confusion are linked to the attentional selection of the respective task stimuli. If this were the case, the maladaptive effect of the switch positvity that we found in single-task blocks might be limited to task environments that explicitly feature a separate distracting stimulus as in our paradigm (see also Rogers and Monsell, 1995). Paradigms with only one stimulus element for both tasks (such as parity vs. magnitude judgments on a single digit) might hence offer additional insight into the interaction of general and switch-specific preparation. Third, incentivising participants' focus on stable vs. flexible task execution might modulate the balancing of the processes that underly the mixing positivity and the switch positivity. For example, additional effort for stable task execution in single-task blocks might reduce participants' receptivity towards distracting stimuli and hence the maladaptive influence of the switch positivity.

Taken together, our findings provide first neural evidence that the control processes underlying the switch positivity and the mixing positivity are involved in balancing stability and flexibility in the task switching paradigm (Goschke, 2000; Herd et al., 2014; Hommel, 2015; Miyake and Friedman, 2012; Scherbaum et al., 2010). By biasing the neural representation of the relevant task set, general preparation facilitates stability in task execution. In addition, and matching the two-component approach in Hommel's (2015) MSM, switch-specific

[1] As suggested by an anonymous reviewer, we investigated how task errors and response errors are linked to such a possible suppression also of the *response set* of the previous trial, thus maybe leading to response perseveration errors. To this end, we computed the ratio of response repetitions that occurred during the experiment and compared these response repetition rates in a two-way ANOVA on the variables Response Type (task error, response error) and Block Type (mixed-task, single task). In fact, response repetitions occurred more frequently in single-task blocks than in mixed-task blocks, $F(1,30) = 7.70$, $p = .009$, $\mu^2_{part} = .20$, and – marginally significant – more frequently among task errors than among response errors, $F(1,30) = 3.90$, $p = .057$, $\mu^2_{part} = .12$. Although the difference between task errors and response errors appears more pronounced in single-task blocks on the numerical level (response repetitions in mixed-task blocks: 28.1% of task errors, 27.4% of response errors; in single-task blocks: 35.7% of task errors, 30.3% of response errors), the interaction effect was non-significant, $F(1,30) = 2.24$, $p = .15$, $\mu^2_{part} = .07$. Empirical evidence for such perseveration errors is hence limited.

preparation appears as a counterpart that ensures adequate flexibility by regulating the competitiveness between the alternative stimuli. Our study thus extends previous fMRI and genetics findings on complementary subcomponents of cognitive control that maintain this balance (Armbruster et al., 2012; Ekman et al., 2012; Nolan et al., 2004; Rosa et al., 2010) to electrophysiology and helps to allocate the two ERPs mixing positivity and switch positivity on the stability-flexibility spectrum.

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