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To switch or to repeat? Commonalities and differences in the electrophysiological correlates of preparation for voluntary and forced task choices

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Abstract

When switching tasks in the laboratory, either the experimenter or the participant can decide which task comes next. So far, this kind of forced and voluntary task switching is usually investigated in isolation. However, in our everyday life, switching between different tasks and goals often depends both on current situational demands and on our intentions. While research has mainly focused on differences between forced and voluntary switching, it is still unclear whether, and if so, which neural processes are shared between both switch types. To identify these, we compared electrophysiological preparatory activity in blocks of randomly intermixed voluntary and forced task-switching trials. We further manipulated the forced switch rate (20% vs. 80%) between blocks to de-confound voluntariness with switch frequency and to investigate how switch frequency effects influence preparatory potentials. ERP analysis revealed an enhanced early parietal activity pattern in the P3b time window on voluntary trials, possibly reflecting early traces of a decision process. A later pre-target negativity was enhanced on forced as compared to voluntary trials. Multivariate pattern analyses revealed that a common preparatory activity on both forced and voluntary switch trials can be found in the switch positivity time window, which we interpreted as an index of a common endogenous task preparation process.

KEYWORDS
classifier analysis, ERPs, preparatory activity, task switching, voluntary task switching

1 | INTRODUCTION

Task switching is extensively used to investigate cognitive control, as it allows to examine how goal-directed behavior is implemented (for reviews see Kiesel et al., 2010; Monsell, 2003; Vandierendonck et al., 2010). In this paradigm, participants are required to perform two tasks in an instructed order (forced task switching, Meiran, 1996), or in a self-chosen order (voluntary task switching, Arrington & Logan, 2004). In either case, the task-switching paradigm allows to investigate the flexible shift between goals (when the task is switched between two successive trials), but also the stable maintenance of goals (on task repetition trials; Dreisbach & Wenke, 2011). However, whether

the same preparation processes underlie forced and voluntary task switching is a matter of ongoing debate. In the present study, we used event-related potentials (ERPs) to isolate preparatory brain activity that underlies both forms of preparation and thus reflects an endogenous, generic task preparation process.

The classic and robust finding in task-switching performance is that task switch trials – in comparison to task repetitions – are associated with performance decrements in reaction times (RTs) and error rates (ERRs), which are usually referred to as switch costs. One prominent class of theories assumes that switch costs reflect time needed for control processes that are additionally engaged on task switches versus task repetitions (Meiran et al., 2008; Rogers & Monsell, 1995; Rubinstein et al., 2001). While switch costs are observed in both forced and voluntary task switching, these variants differ with respect to whether the upcoming task is selected based on processing a cue or on an active task choice. Regarding forced task switching, it has been argued that cue-based preparation is predominantly a stimulus-driven process in which a cue automatically activates a task set (Jost et al., 2013; Logan & Bundesen, 2003; Schmidt & Liefooghe, 2016). Voluntary task switching on the other hand requires a choice process and might involve more endogenous top-down preparation (Arrington et al., 2014; Arrington & Logan, 2004). Here, a consistent finding is that participants display a strong bias toward repeating tasks over successive trials (for a review see Arrington et al., 2014) even though participants are typically instructed to perform both tasks equally often and in random order (Arrington & Logan, 2004, 2005).

Several ERPs reflecting preparatory activity have been identified and their occurrence may be revealing with respect to shared versus unique processes in forced and voluntary task switching. One is a posterior positivity (sometimes also called switch positivity) that is maximal from 400–600 ms at centroparietal sites. It is larger for task switches than for task repetitions and has been found in both paradigms. In forced task switching it has been interpreted as an index of task-set reconfiguration, given that its size covaries with switch RT but not with repetition RT (Elchlepp et al., 2012; Karayanidis et al., 2011; Lavric et al., 2008). This idea implies that the task set (that is, suitable adjustments in attention, working memory, and stimulus–response mapping; Monsell, 2003) has to be reconfigured according to current task demands whenever the task switches. This reconfiguration process can – if the CTI is long enough – happen even before the stimulus is shown and the appropriate response is selected. Other authors proposed that interference resolution with respect to the previously active task set may equally account for the switch costs and their reduction with preparation (Allport

et al., 1994; Meiran et al., 2008; Rubinstein et al., 2001; Ruthruff et al., 2001). A computational model by Masson and Carruthers (2014) suggests that reconfiguration processes play a role in the emergence of switch costs in both forced and voluntary task switching. And indeed, Poljac and Yeung (2014) found evidence for a typical switch positivity also in a voluntary design (see also Forstmann et al., 2007; Orr et al., 2010). Hence, the switch positivity and the associated process of an endogenous task preparation process is a plausible candidate for a shared process in forced and voluntary task switching.

It should be noted, however, that the switch positivity is a conglomerate of more than one underlying component that may not necessarily reflect the same process(es) in both paradigms. Nessler et al. (2012) differentiated between an early (200–400 ms after cue onset) and late (400–900 ms after cue onset) posterior positivity (see also Karayanidis & Jamadar, 2014) and interpreted the former as an index of task-set updating and only the latter portion as an index of task-set reconfiguration (see also Elchlepp et al., 2012). Indeed, it has been suggested that some sort of task-set updating in working memory is crucial to successful task performance in both switch and repetition trials (Dreisbach et al., 2002; Dreisbach & Wenke, 2011; Nessler et al., 2012; Steinhauser et al., 2017; Steinhauser & Steinhauser, 2019) and necessarily precedes task-set reconfiguration (for a computational model, see Oberauer et al., 2013). One can also differentiate between an early and late portion of the posterior positivity in voluntary task switching – though the early portion may reflect partially different processes than in forced task switching. Forstmann et al. (2007) found a difference in an early (350–400 ms after cue onset) parieto-occipital activity pattern between choice and no-choice conditions and interpreted this difference as reflecting the need to categorize choice options. Hence, this early effect may reflect a first portion of a unique decision process that is necessary on voluntary, but not on forced trials. Vandamme et al. (2010) argued that voluntary switches are preceded by a first reactivation of the old task set which is then intervened by top-down control. Hence, reactivation processes – reflected in the early posterior positivity – may be more prominently present and hence a unique process in voluntary task switching, whereas reconfiguration processes may prevail in forced task switching – reflected in modulations of the late posterior positivity, that is, the typical switch positivity. Hence, we refer to the early posterior positivity as an index of task-set updating and the late portion as an index of task-set reconfiguration. Finally, it should be noted that some voluntary task switching studies also provided evidence for more *negative* amplitudes in centroparietal midline electrodes on switches as compared to repetitions (Chen & Hsieh, 2015; Kang et al., 2014).

Another important index of preparation is the pre-target negativity,[1] a frontocentrally maximal component peaking at target onset or shortly after. It is thought to reflect a "general" process of response-set preparation and stimulus anticipation, given that it covaries both with repetition and switch RTs in forced task switching, and also with the informational content of the cue (Jamadar et al., 2010; Karayanidis et al., 2009). As Karayanidis and Jamadar (2014) rightly point out, more than one underlying process drives the emergence of the pre-target negativity; these processes are often subsumed as creating a state of general task preparedness and anticipatory attention. Most voluntary task switching ERP studies yielded a larger pre-target negativity before a voluntary task switch as compared to a voluntary task repetition (Chen & Hsieh, 2015; Forstmann et al., 2007; Kang et al., 2014; Poljac & Yeung, 2014; Vandamme et al., 2010) – a difference that seems not to be present on forced trials (Chen & Hsieh, 2015; Kang et al., 2014). It is suggested to reflect the intervention of top-down control necessary on a voluntary task switch in order to overcome the repetition bias (Poljac & Yeung, 2014; Vandamme et al., 2010). In addition, it has been proposed that the enhanced pre-target negativity on voluntary switch trials as compared to repetition trials indexes a strategy of effector-specific preparation ensuring proper task control if different effectors are linked with different tasks (e.g. in hand-to-task mappings such as the present case; Chen & Hsieh, 2015). Current evidence thus points to an enhanced pre-target negativity on voluntary switch trials as compared to voluntary repetition trials, whereas this difference should be absent (or even reversed; Karayanidis & Jamadar, 2014) on forced trials, thus reflecting a unique process in voluntary task switching.

1.1 | The present study

To sum up, the above reviewed studies found evidence for diverging as well as common preparatory signals in forced and voluntary task switching, but differ with respect to where and when these differences versus commonalities were found. Moreover, even if an ERP component can be found in both forced and voluntary task switching, it may

not reflect a shared process, but two different and unique underlying processes. Standard ERP analyses do not allow to quantify the "sameness" of components. Hence, one of our study's aims was to investigate commonalities between forced and voluntary task switching in the same components by means of a multivariate pattern analysis (MVPA; Steinhauser & Steinhauser, 2019; Steinhauser & Yeung, 2010, 2012). With this method, a spatiotemporally defined set of classifiers is trained to maximally discriminate between repetitions and switches for both forced and voluntary trials. If the same discriminating activity can be found on forced and voluntary switches (in comparison to repetitions), this activity pattern may be telling with respect to a common preparation process on switches. Given that earlier ERP studies on voluntary task switching found switch-specific preparation effects in the switch positivity and the pre-target negativity, both are possible candidates for such a shared process. Note that we use the term „switch-specific "to denote any preparatory process that is more or only engaged on switches, that is, any process, that quantitatively or qualitatively differs between switches and repetitions.

To quantify unique preparation processes in the preparation for a forced and voluntary switch, we investigated ERPs. We examined an early posterior positivity (that is, the early switch positivity mentioned in earlier studies) in the P3b time window as an index for a decision process (on voluntary trials) and/or task-set updating (on both forced and voluntary trials). We want to stress here that the early posterior positivity that we assess likely reflects more than just an underlying P3b component – which is why we consistently refer to it as early posterior positivity. Second, the distinction between an early and late component was made based on several criteria: The most important one being the distinction made and confirmed in the EEG switch-frequency study done by Nessler et al. (2012). As we were interested in extending their findings to a voluntary context, we necessarily had to analyze the same time windows. Finally, the theoretical distinction between task-set updating and task-set reconfiguration processes that we made in our hypotheses has been linked to an early and late portion of the posterior positivity in previous ERP task-switching studies (e.g., Elchlepp et al., 2012). Further, we quantified activity within the switch-positivity (or late posterior positivity) time window as an index of task-set reconfiguration on both forced and voluntary trials. Finally, a later more frontal pre-target negativity was investigated as a representation for response-set or effector preparation and stimulus anticipation.

We used a modified task-switching design that allows to compare forced and voluntary task switching more directly as compared to previous studies. In the hybrid task-switching design introduced by Fröber and

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[1]Electrophysiological studies on voluntary task switching usually use the term contingent negative variation (CNV) to denote the late frontal negativity. However, for sake of consistency with the forced task-switching literature (where the term pre-target negativity is more common), and because the CNV usually refers to a very long-going, rather central component, we use the term pre-target negativity. Note that a similar effect is also sometimes referred to as stimulus-preceding negativity (cf. Karayanidis & Jamadar, 2014).

Dreisbach (2016, 2017), 50% forced and 50% voluntary trials are combined within each block. A task cue (announcing one of two tasks, in the case of a forced-choice trial) or a voluntary cue (announcing a free choice, in the case of a voluntary trial) is shown prior to each target – serving as onset point for investigating preparatory potentials in both forced and voluntary trials. This paradigm circumvents shortcomings of previous studies that compared voluntary and forced task switching: First, while some studies used a warning signal as onset for the cue-locked ERPs in voluntary task switching (e.g., Chen & Hsieh, 2015; Kang et al., 2014), others used the response of the previous trial as onset point (e.g., Poljac & Yeung, 2014). It has to be noted that neither is optimal, as in a completely voluntary design, task selection and preparation can in principle happen at any random time point before task execution (Arrington & Logan, 2005), sometimes even before response execution on the preceding trial (if so-called chunking occurs, Brüning, & Manzey, 2018; Verbruggen et al., 2014). Second, combining forced and voluntary choices renders the typically used instruction (to choose tasks randomly, "as if the flip of a coin" decided about task choice (Arrington & Logan, 2004, 2005) superfluous. The mere presence of a sufficiently high number of forced-switch trials increases the number of voluntary switches *even though* participants are not explicitly told to switch to a certain amount (Fröber et al., 2018; Fröber & Dreisbach, 2017). Third, diverging from previous voluntary task-switching experiments (except Forstmann et al., 2007), the cue has informative value and does not merely serve as a warning cue. Also, participants should not be inclined to start preparing a specific task right after the previous response (cf. Poljac & Yeung, 2014), because a forced task choice is equally likely. Consequently on the majority of trials, participants should start preparation with cue onset, making the cue a valid onset point for investigating preparatory potentials for both forced and voluntary trials.

Participants alternated between blocks with a high forced switch rate (FSR) of 80% (FSR 80 blocks) or a low FSR of 20% (FSR 20 blocks). This gave us the opportunity to look at how (and when during the preparation interval) the forced-choice context impacts voluntary task switching. Fröber and Dreisbach (2017) could show that a high FSR increases the voluntary switch rate, and later (Dreisbach & Fröber, 2019) speculated that the flexibility-enhancing effect of a high FSR may arise because the increased task uncertainty leads to both tasks being held active in working memory. As a consequence, the likelihood of a voluntary switch is increased and the repetition benefit in RTs is reduced (see also Dreisbach & Haider, 2006). On the downside, however, rare repetitions require a higher amount of task-set updating because of the stronger competition of both tasks in working memory. Nessler et al. (2012) found evidence in a pure forced design for an elevated early posterior positivity on rare repetition trials. As this early posterior positivity is taken as a sign of task-set updating, this finding corroborates the idea that a context of frequent switches is accompanied by a stronger activation level of both tasks. Exploring whether this effect extends to voluntary trials of a high-switch block was a secondary aim of the current study. On a more methodological note, the FSR 20 blocks allowed to examine possible confounding factors of switch probability. Usually, the voluntary switch rate – with intermixed forced trials – lies between 10% and 40% making a voluntary switch a somewhat rare event (Fröber et al., 2018; Fröber & Dreisbach, 2016, 2017). To not confound voluntary switch effects with frequency effects, it is necessary to compare voluntary task switching to a forced switching condition with comparable transition ratios. The interspersed FSR 80 blocks on the other hand are meant to increase the voluntary switch rate to a sufficient amount as to make any ERP analyses feasible.

2 | METHOD

2.1 | Participants

Thirty five students of the Catholic University of Eichstätt-Ingolstadt participated in this study (24 female; 28 right-handed; aged between 18 and 35; $M = 21.7$ years; $SD = 3.3$). All participants were naïve with respect to the purpose of the experiment, and had normal or corrected-to-normal vision. Psychology students ($N = 20$) earned course credits, all others were financially compensated for their participation (8 €/h). The study was approved by the ethics committee of the Catholic University of Eichstätt-Ingolstadt and all participants signed informed consent prior to the experiment.

2.2 | Stimuli and procedure

The experiment was run using E-Prime 2.0 (Psychology Software Tools, Sharpsburg, PA) on a 21-inch CRT display (display resolution at 1280×1024, refresh rate 75 Hz). Responses were collected with a German QWERTZ-keyboard, using the adjacent "y" and "x" keys as left and right response keys for one task (left hand), and "n" and "m" as keys for the other task (right hand). Participants were seated at approximately 70 cm from the screen (unconstrained).

Participants alternated between categorizing a number stimulus (125, 132, 139, 146, 160, 167, 174, or 181;

number task) as being smaller or larger than 153 and categorizing a letter stimulus (B, D, F, H, S, U, W, Y; letter task) as being closer to A or closer to Z in the alphabet (cf. Fröber & Dreisbach, 2017). Responses were given by pressing a left (smaller than 153/closer to A) or right (larger than 153/closer to Z) response key. Stimuli of both tasks appeared directly above one another in the center of the screen. Responses to the upper stimulus were always given with the left hand and responses to the lower stimulus with the right hand, while the mapping of number or letter task to position on the screen was fixed but counterbalanced across participants. All stimuli were displayed in black (Calibri font, 28 pt., ~1° of visual angle, bold) on a dark gray background. Contingent on a Gabor patch cue presented centrally (1.75° of visual angle) prior to each stimulus, participants either had to do the number or letter task or were free in their task choice. The task associated with the upper stimulus was announced by a leftward (45°) tilted Gabor patch, the one associated with the lower stimulus was announced by rightward (45°) tilted Gabor patch. Finally, voluntary trials were preceded by an upright oriented Gabor patch. The Gabor patch cues had spatial frequencies of either 3 or 9 cpd which were alternated in a pseudorandom order so that even on task or trial type repetitions, the perceptual identity (i.e., the spatial frequency) of the cue changed (cf. Logan & Bundesen, 2003; Monsell & Mizon, 2006).

Trial procedure is depicted in Figure 1. Each trial started with the presentation of the cue for 200 ms, followed by a blank screen for 800 ms, making up for a cue-stimulus interval of 1000 ms. After that, the target display appeared for 200 ms, either consisting of just one stimulus (in the case of a forced-choice trial) or one stimulus for each task (in the case of a voluntary trial). A blank response display stayed on screen until participants had responded. Only in practice blocks, this was followed by a 1000 ms feedback display. If participants made an incorrect response, the German word for error ("Fehler!") appeared on the screen; if they responded accurately, "Richtig!" ("correct!") was displayed. The intertrial interval showing a blank display had a random jittered duration between 900 and 1100 ms to prevent rhythmic responding.

Participants practiced both tasks separately in two short practice blocks (16 trials each, task order counterbalanced across subjects) already employing the task cues. These were followed by one forced task-switching practice block of 16 trials, and a voluntary task-switching practice block of another 16 trials. Here, the voluntary cues were introduced. After that, participants went through 14 test blocks that consisted of 80 trials each. Each block comprised 50% forced and 50% voluntary

trials. Within subjects but between blocks, the FSR within the forced trials was varied between 20% and 80% (in an alternating order). FSR of the first block was counterbalanced across participants. Stimuli appeared pseudorandomly ensuring that all transitions between tasks and/or voluntary trials appeared equally often and about equally distributed. For exploratory purposes at the end of each block, we measured the resting eyeblink rate for 10 s by presenting a horizontally striped Gabor patch (spatial frequency also randomly varied between 3 and 9 cpd).[2] After that, participants received a blockwise feedback on their performance in terms of error rate and mean RT with a reminder to respond as quickly and accurately as possible. Finally, they were instructed to move as minimally as possible before starting the next block.

2.3 | EEG data acquisition

The BIOSEMI Active-Two system (BioSemi, Amsterdam, The Netherlands) was used for EEG recording. Ag-AgCl electrodes 64 were placed on the scalp according to the extended International 10–20 system in the positions 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 during recording, and all electrodes were offline rereferenced to linked mastoids. EEG and EOG data were continuously recorded at a sampling rate of 512 Hz.

2.4 | Data analysis

Regarding task choice, the voluntary switch rate (VSR, in %) in 20% FSR versus 80% FSR blocks was compared using dependent *t* tests. Transition was determined on the basis of the chosen hand (cf. Arrington & Logan, 2004; Scheffers & Coles, 2000). Regarding task performance, RTs in ms and ERRs in % were analyzed in repeated-measures ANOVAs with the variables choice (forced choice vs. voluntary), FSR (20% vs. 80%), and transition (repeat vs. switch).

For the statistical analyses, only data from the experimental blocks were considered. The first trial of each block

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[2]Given that this measurement was intended for explorative purposes only, we will not report results here.
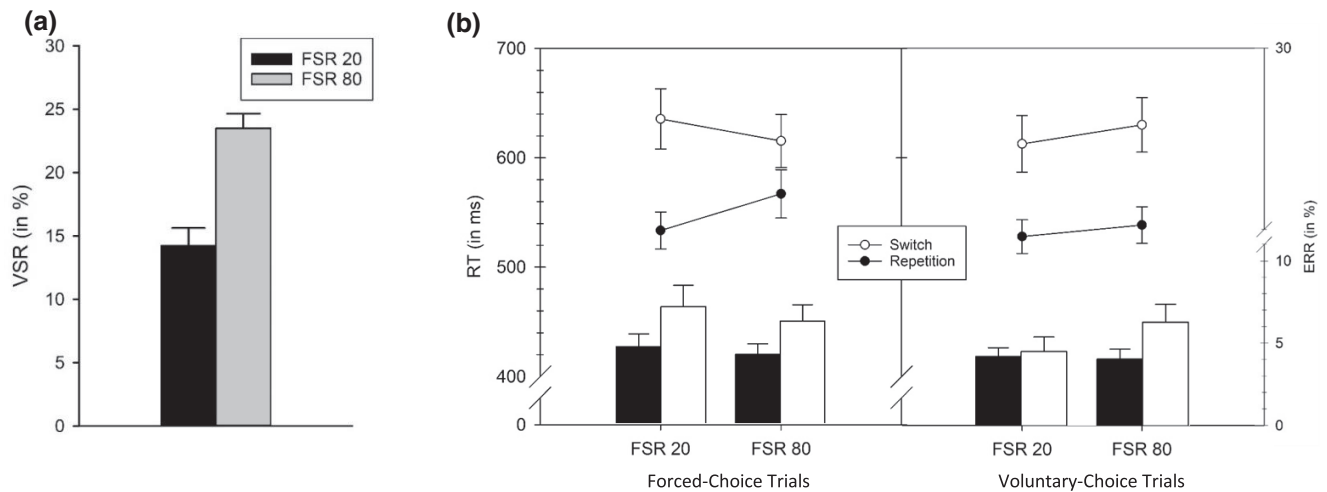
(a)

(b)
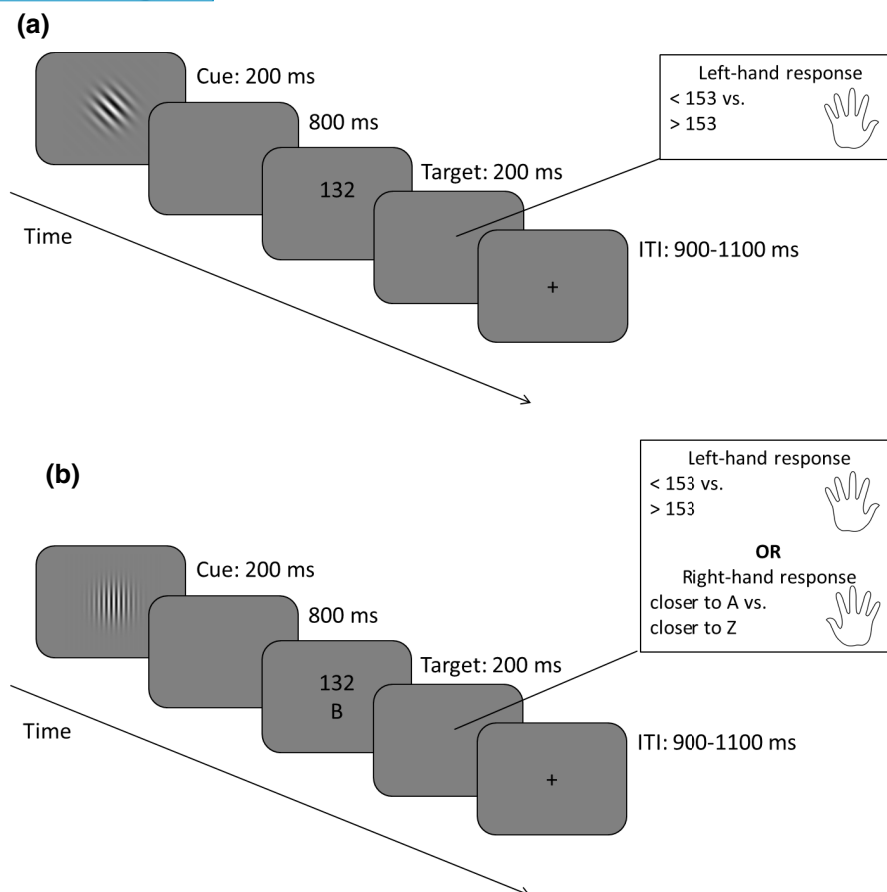
FIGURE 1 Course of a sample forced trial (a) and a voluntary trial (b). In both cases, the respective cue is presented for 200 ms, followed by an 800 ms blank. The target display is presented for 200 ms, followed by a blank screen until the participants responds. The length of the ITI was jittered between 900 and 1100 ms

was omitted in all analyses (1.2% of all trials). Only prior to the behavioral RT analyses, we also excluded error trials (5.8%), trials following errors (5.3%), and trials in which the RT deviated more than three SDs from the individual mean of the condition (1.4%). In addition, two subjects were identified as RT outliers via boxplots, as their mean RT deviated more than three interquartile ranges from the overall mean in the baseline block. Consequently, they were not considered for any further analyses. Thus, the final sample used for the statistical analyses contained 29 subjects.

All EEG analyses were performed using MATLAB v9.0 (The Mathworks, Natick, MA) scripts in combination with EEGLAB v12.0 (Delorme & Makeig, 2004) functions. EEG data were band-pass filtered to exclude frequencies above 40 Hz and below 0.1 Hz, divided into epochs from 500 ms before to 1500 ms after cue onset and baseline-corrected to the interval 200 ms before cue onset.[3] If necessary,

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[3]An additional analysis based on a peri-stimulus baseline of −100 to +100 ms had no substantial effect on any of the findings in this study.

electrodes were interpolated using spherical spline interpolation if the joint probability criterion (threshold 5) or the kurtosis criterion (threshold 5) in EEGLAB's channel rejection routine (pop_rejchan.m) were met. Epochs were removed if they contained activity exceeding ±300 μV from the mean in any channel (except AF1, FP1, Fpz, Fp2, AF8 in order to prevent exclusion due to blink artifacts) or if their joint probability deviated more than five SDs from the epoch mean. To correct for eyeblinks and muscular artifacts, an infomax-based ICA (Bell & Sejnowski, 1995) was computed and components whose time courses and topographies were typical of these artifacts were removed after visual inspection. On average 274 trials ($SD = 15.3$) per participant were included in the averaging of the ERPs. The average trial number varied strongly for the different conditions (particularly for voluntary switches). The global minimum trial number was 25 for one condition and participant. Regarding the investigation of the differential preparatory activity on forced and voluntary trials, we will focus on the switch positivity, the P3, and the pre-target negativity (Karayanidis & Jamadar, 2014),

FIGURE 2 Behavioral results. (a) Voluntary switch rate (in %) in FSR 20 blocks as compared to FSR 80 blocks. (b) RTs (in ms) and ERR (in %) as a function of forced switch rate, trial type and transition. Black bars represent ERRs on repetition trials, white bars represent switch trials. Error bars represent ±1 *SEM*. FSR, forced switch rate; ms, milliseconds; RT, reaction time; *SEM*, standard error of the mean; VSR, voluntary switch rate
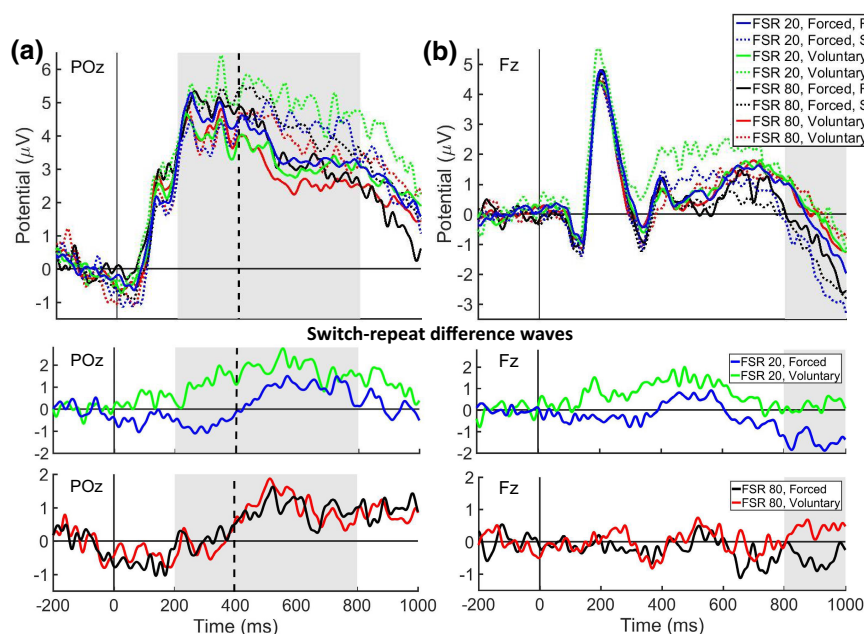
FIGURE 3 Waveforms in all conditions and difference waves (switch minus repetition) at channels POz (a) and Fz (b). The highlighted areas represent the time window used for testing the mean amplitudes of ERP components. Time point zero refers to cue onset. rep, repetition; sw, switch

each as a function of the within-subject variables forced switch rate, choice, and transition. Based on the time windows described by Karayanidis and Jamadar (2014; see also Karayanidis et al., 2011) and the grand average topography obtained here (see Figure 5), mean amplitudes for the switch positivity were computed at electrode POz in the time window from 400 to 800 ms, for the P3 at electrode POz from 200 to 400 ms, and for the pre-target negativity at electrode Fz from 800 to 1000 ms.

2.4.1 | Decoder analysis

To identify shared versus unique processes in forced and voluntary task switching, we extracted switch-specific preparatory activity from the EEG signal on forced and voluntary trials as training sets by means of MVPA (Steinhauser & Yeung, 2010), and used this as decoder of the switch-specific activity in this data set. That is, a decoder of forced switch-specific activity was trained on the forced
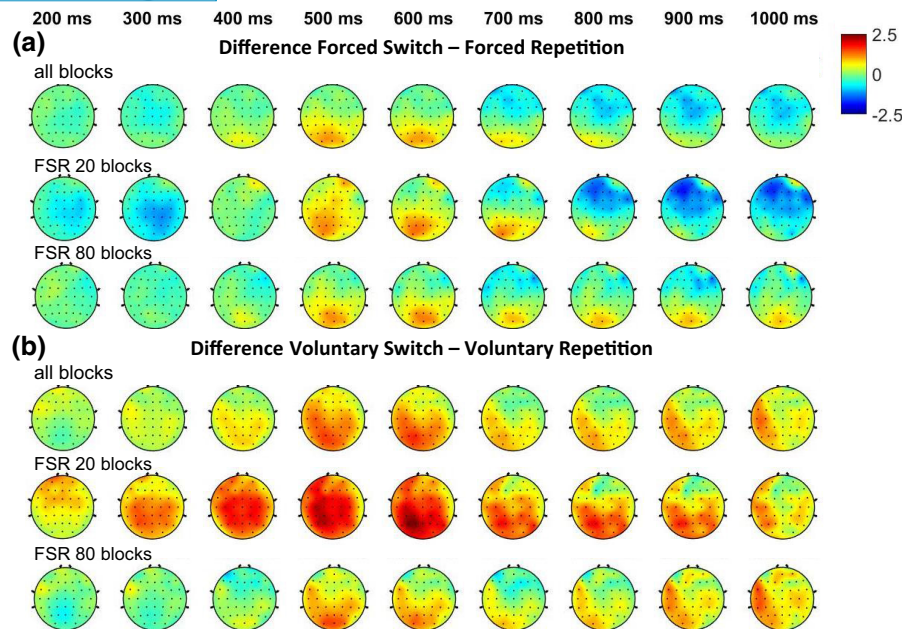
FIGURE 4 (a) Topography of the difference wave between forced switch and forced repetition trials in the cue-locked ERP over all blocks (upper), in FSR 20 blocks (middle), and in FSR 80 blocks (lower). (b) Topography of the difference wave between voluntary switch and voluntary repetition trials in the cue-locked ERP over all blocks (upper), in FSR 20 blocks (middle), and in FSR 80 blocks (lower). MVPA
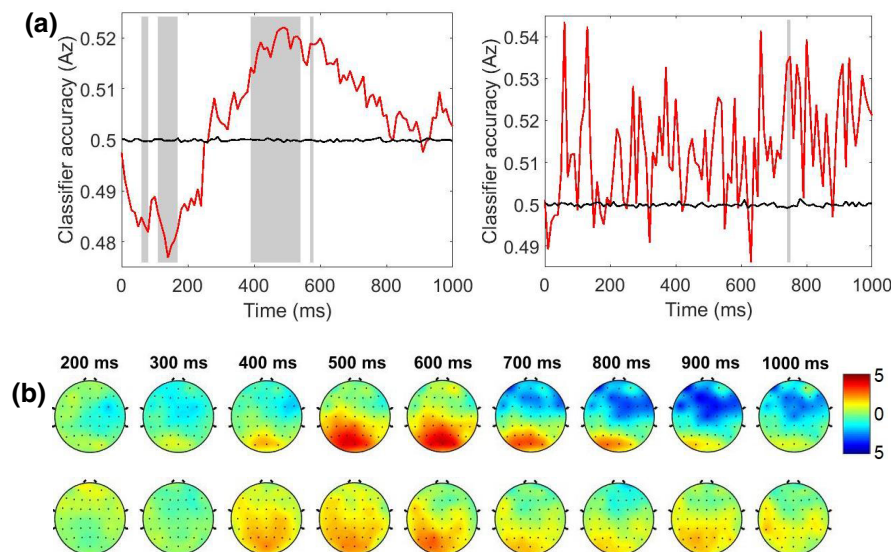
FIGURE 5 (a) Classifier accuracy (in red) for the switch-specific preparatory activity on time windows of 50 ms width, every 10 ms in forced (left) and voluntary (right) trials. Black line indicates the test distribution under a random permutation test. Gray areas mark time points with a significant accuracy against a random permutation test. (b) Discriminating topography of the classifier in contiguous time windows of 100 ms for forced (upper) and voluntary (lower) trials

(switch – repetition) difference, and another decoder of voluntary switch-specific activity was trained on the voluntary (switch – repetition) difference. For that, we used a linear integration method (Parra et al., 2002) that allows to extract specific spatial components from the ERP data that discriminate maximally between two conditions (Steinhauser

& Steinhauser, 2019; Steinhauser & Yeung, 2010, 2012). A set of classifiers was computed as spatiotemporal weighting coefficients in a logistic regression where the output distinguishes between two conditions as much as possible. For every time window, an averaged prediction value was assigned to each trial as the output of the logistic regression:

$$y(t) = \mathbf{v}^T x(t)$$

where $x(t)$ is the vector of electrode activity at time t and v^T describes the optimal spatial weighting coefficient for the particular condition difference. We first computed weight vectors v_{forced_switch} discriminating optimally between forced repetition trials and forced switch trials in partially overlapping time windows of 50 ms, separated by 10 ms during the cue-stimulus interval (0–1000 ms post cue). Each of these classifiers was trained on an equal, randomly drawn number of forced-repetition and forced-switch trials per participant. These weight vectors can be interpreted as filters for switch-specific preparatory activity on forced trials. We did the same for switch-specific preparatory activity on voluntary trials by training a classifier in the same way to maximally discriminate voluntary switches from voluntary repetitions. The resulting weight vectors $v_{voluntary\_switch}$ serve as filters for switch-specific preparatory activity on voluntary trials. Leave-one-out (LOO) cross-validation was applied in the training of each weight vector to prevent overfitting. That is, each weight vector used for further analysis equaled 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 (Steinhauser & Steinhauser, 2019), where N denotes the number of trials and T denotes the number of time samples.

To describe the sensitivity of the resulting classifiers, we report the area under the Receiver Operating Characteristic curve (Az score) where $Az = 0.5$ would indicate classification at chance level and $Az = 1$ signifies perfect identification. To test whether sensitivity significantly exceeded chance level, a permutation test was applied (Steinhauser & Yeung, 2012). For each participant, a test distribution under the Null hypothesis (i.e., no difference in preparatory activity for switch and repeat trials) was generated by recomputing Az scores 1000 times with random assignment of the switch/repeat categories. This test distribution was used to determine critical Az-values associated with significance levels of 0.05. Overall critical Az-values were computed by averaging across participants. This was done separately for both the forced and voluntary trials training set. For visualization of the spatial distribution of the weights of each discriminating component, we computed a coupling coefficient vector representing the activity at each electrode site that correlated with the discriminating component, and is interpreted as the "sensor projection" of that component (Parra et al., 2002, p. 225).

Finally, an averaged prediction value $\bar{y}_e$ as the output of a logistic regression can be calculated for every time window t of each trial, even for those trials that were not part of the training data set. In our case, $\bar{y}_e$ denominates the probability of a trial to be classified as being a switch trial (and thus can take on values between 0 and 1). Hence, computed for voluntary trials over v_{forced_switch}, this output mirrors the amount of forced switch-specific preparatory activity present on voluntary trials. Similarly, we computed such averaged prediction values for forced trials over $v_{voluntary\_switch}$. Statistical testing of differences was conducted at 50 ms time windows around the peaks of the three tested ERP components.

3 | RESULTS

3.1 | Behavioral data

We first investigated participants' voluntary choice pattern dependent on FSR. As expected, participants switched tasks significantly more often in the FSR 80 blocks than in the FSR 20 blocks, $t(28) = 11.20$, $p < .001$, $d = 1.35$ (see Figure 2a). The similarity in switch rate on forced and voluntary trials in the FSR 20 blocks makes those blocks especially suitable for later forced versus voluntary comparisons in the ERP and MVPA analyses.

In the RT analysis, the main effects of FSR, $F(1, 28) = 4.18$, $p = .050$, $\eta_p^2 = .13$, and transition, $F(1, 28) = 77.37$, $p < .001$, $\eta_p^2 = .73$, were significant. Furthermore, the two-way interaction of FSR and transition, $F(1, 28) = 4.21$, $p = .050$, $\eta_p^2 = .13$, as well as the three-way interaction with choice reached significance level, $F(1, 28) = 12.49$, $p = .001$, $\eta_p^2 = .31$ (see Figure 2b). Switch costs on forced-choice trials were reduced but not eliminated in the FSR 80 blocks (48 ms) as compared to the FSR 20 blocks (102 ms), which was both due to slower repetitions, $F(1, 28) = 22.05$, $p < .001$, $\eta_p^2 = .44$, and faster switches, $F(1, 28) = 4.59$, $p = .041$, $\eta_p^2 = .14$, in the FSR 80 blocks. Switch costs on voluntary choice trials were not significantly influenced by FSR, $F(1, 28) = 0.21$, $p = .653$. On a descriptive level, both voluntary switches and repetitions were performed faster in FSR 20 blocks, but only significantly so on repetitions, $F(1, 28) = 6.63$, $p < .016$, $\eta_p^2 = .19$. No other effect was significant (all Fs < 1.66, all ps > .20).

For the ERRs, a main effect of transition was significant, $F(1, 28) = 11.22$, $p = .002$, $\eta_p^2 = .29$, with switch costs of 2.4% (repetition: 4.7% vs. switches: 7.1%). In addition, only the interaction of FSR and choice was significant, $F(1, 28) = 4.41$, $p = .045$, $\eta_p^2 = .14$ (see Figure 2b). In FSR 20 blocks, participants made fewer errors in voluntary than in forced-choice trials, $F(1, 28) = 5.23$, $p = .030$, $\eta_p^2 = .16$, an effect that was not

present in FSR 80 blocks, $F(1, 28) = 0.20$, $p = .657$. No other effect reached significance (all Fs < 3.75, all ps > .06).[4]

3.2 | Event-related potentials

Guided by the task-switching literature (for a review see Karayanidis & Jamadar, 2014), we focused on three cue-locked ERP components: an early posterior positivity, a later extended posterior positivity with a similar scalp topography (often named "switch positivity"), and finally a pre-target negativity that peaks at or shortly after target onset. We checked for effects of FSR, choice, and transition on mean amplitudes (see Figure 3). Scalp topographies of the switch-repeat difference wave in all conditions can be found in Figure 4.

In the P3 time window (200 to 400 ms after cue onset), both a two-way interaction of choice and FSR, $F(1, 28) = 11.55$, $p = .002$, $\eta_p^2 = .29$, as well as a three-way interaction of transition, choice, and FSR, $F(1, 28) = 8.18$, $p = .008$, $\eta_p^2 = .23$, reached significance (see Figure 4). The switch-repeat difference was only significant on voluntary trials of FSR 20 blocks, $t(28) = 2.95$, $p = .006$, Cohen's $d = 0.27$ (all other differences: ts < 1.40, ps > .17). All other effects were nonsignificant (all Fs < 2.45, all ps > .12). Voluntary switch trials were markedly preceded by an enhanced early posterior positivity. The pronounced effect in rare voluntary switches of the FSR 20 blocks is likely due to the associated enhanced task-set updating demands in this condition.

For the amplitude of the switch positivity (400 to 800 ms post-cue), a significant main effect of transition, $F(1, 28) = 19.32$, $p < .001$, $\eta_p^2 = .41$, was observed. As expected, switch trials were accompanied by a more positive deflection in POz (difference: 1.15 μV, 95% CI [.62 μV; 1.69 μV]) in the tested time window. Furthermore, the interaction of choice and FSR became significant, $F(1, 28) = 5.01$, $p = .033$, $\eta_p^2 = .15$. A trend toward a more positive deflection in FSR 20 as compared to FSR 80 blocks was observed on voluntary trials (difference: 0.80 μV; 95% CI [−0.05 μV; 1.67 μV], but not on forced-choice trials (difference: 0.04 μV; 95% CI [−0.94 μV; 1.02 μV]. No other effect reached significance (all Fs < 1.05, all ps > .30). Thus, switches indeed showed a more positive going deflection than repetitions, which was neither significantly influenced by choice nor by FSR – possibly reflecting a common component for forced and voluntary task switching. In the time window and electrode used for analyzing the switch positivity, an interaction of choice and FSR was observed. Similar to the effect in the P3b time window, voluntary trials in the FSR 20 blocks were preceded by an enhanced positivity; thus, this interaction could reflect an overspill of the earlier posterior positivity effect.

By contrast, the same analysis on the pre-target negativity at electrode Fz revealed only a main effect of choice, $F(1, 28) = 7.82$, $p = .009$, $\eta_p^2 = .22$ with a more negative amplitude on forced choice trials (difference: −1.27 μV; 95% CI [−2.20 μV; −.34 μV]). Neither transition nor FSR significantly impacted the pre-target negativity (all Fs < 3.03, all ps > .09).

3.3 | MVPA

The ERP analyses suggest that forced and voluntary waveforms are comparable in the late posterior positivity time window as the main effect of transition was neither significantly influenced by choice nor by FSR – but of course, absence of evidence is not evidence of absence. A stronger test regarding the commonality between both choice types is provided by an MVPA because it allows to quantify common activation between different conditions. Moreover, since this methodological approach takes inter-individual variability in the scalp topographies into account, signal-to-noise ratio is increased with regard to differential comparisons between conditions (Steinhauser & Steinhauser, 2019; Steinhauser & Yeung, 2010, 2012). In a first step, we extracted switch-specific preparatory activity separately for both forced-choice and voluntary trials by applying the linear integration method by Parra et al. (2002, 2005). A set of classifiers was trained to maximally discriminate between forced switch and repetition trials, and another for the voluntary switch-repeat

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[4]The current design involves not only task transitions (task repetition vs. switch), but also transitions of the current choice type (choice type repetition vs. switch), which may require a different set of preparation that could differentially show up in ERPs (Astle et al., 2006; Jamadar et al., 2010). Even though our design was not made to address this question, we ran exploratory analyses including the factors FSR, Choice Type (free vs. forced), Choice Transition (choice type repetition vs. switch), and Task Transition to check whether performance was influenced by these choice type transitions. Note that we only have very limited trial numbers for these analyses (<5 trials for more than half of the participants in at least one condition), which is why only behavioral data were analyzed in this way. For RTs, no significant effect involving Choice Transition was found (all Fs < .88, all ps > .358). The ERR analysis yielded a significant main effect of Choice Transition, $F(1, 19) = 6.01$, $p = .024$, $\eta_p^2 = .24$, and an interaction of FSR × Choice Transition, $F(1, 19) = 5.12$, $p = .036$, $\eta_p^2 = .212$. Choice type switches were associated with higher costs than choice type repetitions, and this difference was reduced on FSR 80 blocks. Most importantly, no interaction with choice nor task transition was found. Hence, as none of these effects interacted with or contradicted any of our main hypotheses, we do not include the factor Choice Transition in any of the following analyses. We thank an anonymous reviewer for addressing the potential role of choice type transitions which may be an interesting question for future research."
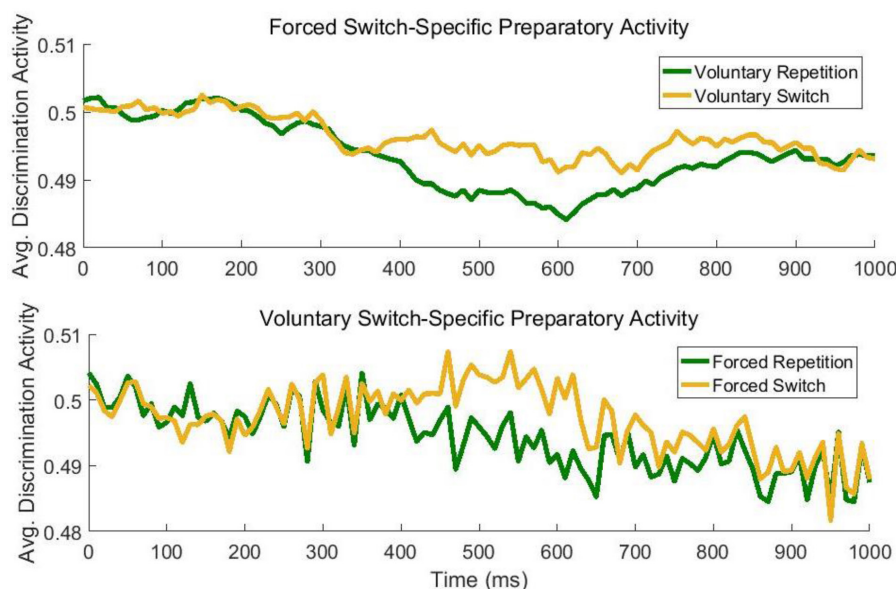
FIGURE 6 Average discrimination activity on voluntary trials based on the set of classifiers trained on the switch-specific preparatory activity on forced trials (upper); average discrimination activity on forced trials based on the voluntary switch-specific preparatory activity (lower)

difference. As shown in Figure 5, the resulting time course of classification and the discriminating topography matched those of the late posterior positivity (switch positivity) and, to a lesser degree, that of the pre-target negativity in the ERP analysis. Further, the sensitivity analysis against a random distribution generated via permutation tests showed robust, significant discrimination performance of the former classifier set (see Figure 5a). Notably, the classifier set of the voluntary switch-specific preparatory activity shows a lower signal-to-noise ratio and hence more variability in the ensuing Az scores. This may in large part be due to lower and interindividually more variable switch trial numbers used for training the classifiers.[5]

We then tested (1) whether the forced switch-specific preparatory activity was able to significantly distinguish voluntary switches from voluntary repetitions, and

(2) whether the voluntary switch-specific preparatory activity was able to discriminate forced switches from forced repetitions. If both sets of classifiers are analogously able to distinguish between switches and repetitions in the respective test data set, we can crossvalidate that the activity pattern we extracted reflects inherent switch-specific preparatory activity that precedes a prepared switch irrespective of voluntariness. Time windows for testing were defined as the 50 ms around the peak within the time windows of the three tested ERP components, that is: for the P3 at 350 ms, for the posterior positivity at 560 ms, and the pre-target negativity at 940 ms.

As visualized in Figure 6, the classifiers were able to distinguish between repetition and switch trials in the respective test data set, but apparently only in the time window of the switch positivity. To further test this, we examined local peaks of the three components under scrutiny. For the P3, both the effect of the forced switch-specific activity, $F(1, 28) < 0.01$, $p = .985$, $\eta_p^2 < .001$, as well as the effect of the voluntary switch-specific activity, $F(1, 28) = 0.22$, $p = .643$, $\eta_p^2 < .01$, were nonsignificant. That is, neither classifier was able to significantly distinguish switches from repetitions in the other data set. At the peak of the posterior positivity, however, both for the forced switch-specific activity, $F(1, 28) = 6.10$, $p = .020$, $\eta_p^2 = .18$, and the voluntary switch-specific activity, $F(1, 28) = 6.28$, $p = .018$, $\eta_p^2 = .18$, a significant difference in the discrimination activity between switches and repetitions was found in the respective other data set. That is, some portion of the differential preparatory activity preceding voluntary switches resembles the activity preceding forced switches, and analogously, the preparatory activity preceding forced switches as compared to forced repetitions bears similarities to forced switch-specific activity. Topography and

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[5]Please note that in contrast to other MVPA-based approaches, Az-Scores are not the actual measure of interest in the present decoding analysis but rather a by-product for a full assessment of the underlying methodology, as they represent a standard method to illustrate classifier accuracy. The actual analysis of relevance (the cross-validation on the respective other data set) is not directly dependent on the significance of the Az-Scores against a random distribution via permutation tests, as the permutation test of Az scores calculates the classifier accuracy on a single-subject level, which is then averaged. The Average Discrimination Activity, on the other hand, which is used in the present decoding approach, tests our hypothesis on the sample level. The resulting Averaged Discrimination Activity scores are remarkably robust and feature distinct time courses of discrimination for both sets of classifiers (Figure 6). The subject-level analysis of Az Scores is much more conservative than a sample-level test of Average Discrimination Activity and therefore, significant Az scores should not be viewed as a precondition for the present MVPA approach (see also Parra et al., 2002; Steinhauser & Yeung, 2010; Steinhauser et al., 2017).

time windows of significant discrimination activities are remarkably similar (see Figures 5b and 6). In accordance with the ERPs, the sensor projection of both classifiers shows a posterior and slightly left-lateralized activity pattern in the time window of the posterior positivity.

Finally, for the peak of the pre-target negativity, again, no significant effect was found, neither for forced switch-specific activity, $F(1, 28) = 0.04$, $p = .838$, $\eta_p^2 < .01$, nor for voluntary switch-specific activity, $F(1, 28) = 0.11$, $p = .740$, $\eta_p^2 < .01$.

In an exploratory Transition × FSR ANOVA, we checked whether the effect visible in the posterior positivity was influenced by FSR. No significant effects of FSR arose (all Fs < 1.23, all ps > .27). The finding that the common preparatory activity preceding forced and voluntary switch trials was not further qualified by the forced switch rate suggests that this commonality cannot be ascribed to a simple switch frequency effect: Commonality between forced and voluntary switch-specific preparatory activity can be found in FSR 20 blocks, where forced switch rate and voluntary switch rate are more similar, but also in FSR 80 blocks, where switch frequency in forced and voluntary trials differs more strongly.

4 | DISCUSSION

In the current experiment, we compared electrophysiological preparatory activity in forced and voluntary task switching. By combining both choice types within blocks, each trial preceded by a task or choice cue, this study is methodologically distinguished from previous studies and hence allows to compare forced and voluntary task switching more directly. The manipulation of forced switch rate between blocks ensured that switch frequency and choice type could be investigated independently. In a multivariate pattern analysis on the preparatory activity differentiating switches from repetitions, we examined commonalities between forced and voluntary task switching. This similarity can be pinpointed to a task-set reconfiguration process captured by the late posterior positivity. ERP analyses allowed us to quantify differences between forced and voluntary task switching: First, the decision process on voluntary trials showed up in an enhanced early posterior positivity. In contrast and against our initial hypothesis, forced-choice stimuli were preceded by an enhanced pre-target negativity, possibly reflecting enhanced response-set preparation and preparatory attentional processes. Finally, switch-frequency effects on voluntary trials were only accompanied by an enhanced posterior positivity, likely an index of the increased task-set updating demands.

4.1 | Commonalities and differences of forced and voluntary task switching

The extracted markers for switch-specific preparatory activity significantly distinguished switches from repetitions. Moreover, similarity between forced and voluntary switch-specific preparatory activity around the peak of the posterior positivity (at 560 ms) was confirmed: Repetition and switch trials showed significant differences in switch-specific preparatory activity when MVPA classifiers of forced or voluntary switch-specific preparatory activity were applied to the respective other data set. Moreover, we could exclude that these effects are due to less frequent voluntary than forced switches: The forced switch rate mainly affected an early posterior positivity but did not interact with transition in later phases. Hence, the current results offer another piece of evidence that switch-specific preparation on forced trials does not merely reflect the retrieval of a cue-stimulus compound (cf. Logan & Bundesen, 2003; Schneider & Logan, 2005) – instead, it reflects a generic process of endogenous task preparation. Studies using other designs offer support for this rather universal finding of the switch positivity in task switching, as it was similarly found in intermittently instructed cued task switching (Barceló et al., 2007), in both response-effector and stimulus-dimension shifts (Hsieh et al., 2014), and with transition instead of task cues (West et al., 2011). More importantly, against the background of methodologically diverse and hence partially contradicting ERP studies in voluntary task switching (Chen & Hsieh, 2015; Forstmann et al., 2007; Kang et al., 2014; Orr et al., 2010, November; Poljac & Yeung, 2014; Vandamme et al., 2010), the current results offer strong support that switch preparation under forced- and voluntary-choice conditions is very similar, after all.

Some authors suggested that in order to perform a successful task switch, the cognitive system has to reconfigure the currently active set of task representations in order to match the now relevant task (Monsell, 2003). This reconfiguration process seems to be necessary irrespective of whether the task switch is predetermined or self-chosen by the participant. Similarly, a modeling study has argued that task-set reconfiguration is equally involved in both forced and voluntary task switching, whereas cue-related task retrieval processes are confined to forced task switching (Masson & Carruthers, 2014). This reconfiguration process hence does not only reflect the retrieval of task codes from memory, but also the appropriate attentional and response-related adjustments (Demanet & Liefooghe, 2014; Meiran et al., 2000). However, it should be noted that the current results do not allow to infer that this switch-specific posterior positivity effect reflects

a qualitative difference between switch and repetition trials. It is equally possible that it merely reflects a task-preparatory process that is more engaged on switches than on repetitions.

As reviewed in the introduction, it has been argued that the early portion of the posterior positivity provides an index of task-set updating, while the later typical switch positivity reflects task-set reconfiguration (Karayanidis & Jamadar, 2014; Nessler et al., 2012). Hence, the early portion may reflect a more general process of task-set updating in working memory, that is engaged on switches and repetitions (Altmann & Gray, 2008; Dreisbach, 2012; Dreisbach et al., 2002; Meiran, 2000). This task-set updating process ensures that stimulus–response links in working memory are sufficiently activated to ensure successful task performance. Indeed, Steinhauser and colleagues (Steinhauser et al., 2017; Steinhauser & Steinhauser, 2019) found evidence that task errors (that is, forced trials in which participants perform the wrong task) are characterized by the absence of an early posterior positivity. In voluntary task switching, it is suggested that proper task control is characterized by a first reactivation (that is, updating) of the previously performed task (Forstmann et al., 2007; Vandamme et al., 2010), that is later in the preparation interval intervened when participants decide to switch tasks. Therefore, the enhanced early posterior positivity that we found on voluntary trials, particularly on voluntary switches in FSR 20 blocks, may reflect a (frequency-dependent) decision process, and the associated demands for task-set updating.

In the pre-target negativity time window, the ERP analysis revealed a larger enhancement preceding forced than voluntary trials. In line with evidence from both voluntary task switching (Poljac & Yeung, 2014) and forced task switching (Karayanidis et al., 2011; but see Lavric et al., 2008), this effect seemed dissociable from the posterior positivity, as it was not significantly influenced by task transition and differed significantly between choice types. However, the effect is not in line with previous ERP studies on voluntary task switching (Chen & Hsieh, 2015; Kang et al., 2014; Poljac & Yeung, 2014; Vandamme et al., 2010) that found a (transition-dependent) enhancement on voluntary trials. A possibility for the diverging effects could be the different stimulus types. Chen and Hsieh (2015) and Kang et al. (2014) let participants either alternate between choice types between blocks or only once in the middle of the experiment. Hence, the information transmitted through the stimulus display did not differ within a block (cf. Koechlin & Summerfield, 2007). In our design, the target display on voluntary trials comprised two stimuli, whereas on forced trials, only one stimulus appeared. Therefore, target-level interference differed between forced-choice and voluntary-choice

trials and differences in the pre-target negativity could reflect differences in preparation for interference resolution. In addition, preparatory processes that are targeted at the stimulus anticipation should be enhanced on forced trials – and this should be the case irrespective of the decision to switch or repeat tasks, as may be reflected in the enhanced pre-target negativity on forced trials in the present study.

The current results also do not indicate that the switch-repeat difference in the late posterior positivity was larger preceding forced than voluntary trials, as found by several previous studies (Forstmann et al., 2007; Kang et al., 2014). Even though the MVPA classifier was able to distinguish switches from repetitions on forced trials in a larger time window (see Figure 5a), this is mainly due to the higher classifier accuracy that is achieved by larger trial numbers. Kang et al. (2014) found evidence for a switch negativity preceding voluntary task switching, and argued that memory processes prevail in forced task switching, whereas voluntary task switching is able to truly capture an endogenous task-set reconfiguration process. However, neither our results nor other studies (e.g., Chen & Hsieh, 2015; Poljac & Yeung, 2014) are in line with this hypothesis. Instead, we think the current study is a clear indication that switch-specific preparation is largely similar between forced and voluntary task switching.

4.2 | Switch-frequency effects on voluntary task switching

The behavioral evidence in this study corroborates and extends previous findings. We found an increased voluntary switch rate in FSR 80 blocks as compared to FSR 20 blocks. This effect was mirrored in RTs especially on forced trials: In FSR 80 blocks with a high number of forced switches, repetitions were performed slower and switches were performed faster than in FSR 20 blocks. The present results therefore line up with previous performance (Dreisbach & Haider, 2006) and choice (Fröber & Dreisbach, 2017) results. They extend previous choice results from a between-subjects to a within-subjects design, hence providing further evidence that cognitive control mode adapts to changing task contexts on the basis of a few trials (Abrahamse et al., 2016; Braem & Egner, 2018; Goschke & Bolte, 2014).

Dreisbach and Fröber (2019) suggest that the forced-choice context modulates the extent to which both tasks are held simultaneously in working memory: Even though this goes along with higher interference between concurrently active task representations, being frequently forced to switch means that this cost is offset by a higher switch efficiency needed in a majority of trials (Dreisbach & Haider, 2006). This interpretation is backed up by recent

evidence showing that a high forced switch rate does not generalize to a voluntary switching context with new tasks but only to new stimuli of the same tasks (Fröber et al., 2021). Those findings contradict the alternative assumptions that participants in a high switch context simply learn to switch or feel like they should mirror the switch rate from the forced choices. It follows that the probability of a voluntary switch (in a high forced switch context) is increased because of continued parallel activation of both tasks. On the other hand, if forced switches are rare (as in the current FSR 20 blocks), switch trials should be characterized by a particularly demanding updating process of task rules in working memory. Therefore, the current switch-frequency dependent effect of an enhanced early posterior positivity in voluntary switches in blocks with infrequent forced switches (FSR 20 blocks) make be taken as indirect support for this theoretical account. In any case, the observation that none of the considered components simply vary with the frequency of switches and repetitions (with generally higher amplitudes for the infrequent trial type) speaks against the idea that cue-locked activity is only sensitive to the informational content, and thus frequency, of the cues (Barceló & Cooper, 2018).

4.3 | Future outlook

The current results suggest that preparation in anticipation of a task switch is similar in both forced and voluntary task switching. Whether the same is true regarding a general preparation process – that is, a process that is similarly engaged in switches and repetitions – will remain to be investigated. As findings by Steinhauser and Steinhauser (2019) suggest, such a process can be captured by comparing single-task to mixed-task blocks and is reflected in an enhanced early posterior positivity. A similar cue-locked P3 activity in an intermittently instructed cued task-switching paradigm (Barceló et al., 2007) was taken to reflect a necessary re-activation of the already active task set, consistent with a task-set updating process. The authors argued that this re-activation reflects a sort of default operation (cf. O'Reilly, 2006), as they found strong correlations between the early and late part of the posterior positivity. In the present study, we found the strongest early parietal positivity preceding rare *voluntary* switches, providing first preliminary evidence that a general preparatory process is indeed involved in voluntary switching. However, devising a useful voluntary analog to a single-task condition to quantify general preparatory activity will be challenging. Future studies could be guided by voluntary Go/No go ERP studies (Karch et al., 2014, 2016). Though Karch and colleagues found significant effects during intentional actions only in time-frequency

analysis, this may be different when voluntary Go conditions are compared to voluntary task switching.

5 | CONCLUSION

The present study sought out to clarify the commonalities and differences between forced and voluntary task switching by comparing electrophysiological preparatory processes. Using an MVPA, we provided clear evidence that both choice types share a common endogenous task preparation process that is reflected in a late posterior positivity. Most task-switching evidence corroborates the notion that this effect reflects a common task-set reconfiguration process. In contrast, a decision process on voluntary trials – possibly linked with a task-set updating process (Forstmann et al., 2007; Nessler et al., 2012; Vandamme et al., 2010) – was mirrored in an enhanced early posterior positivity in the P3b time window particularly on voluntary switches in blocks of low switch frequency.

AUTHOR CONTRIBUTIONS
Vanessa Jurczyk: Formal analysis; investigation; methodology; software; visualization; writing – original draft. **Robert Steinhauser:** Formal analysis; methodology; software; visualization; writing – review and editing. **Gesine Dreisbach:** Conceptualization; funding acquisition; methodology; project administration; resources; supervision; writing – review and editing. **Marco Steinhauser:** Conceptualization; funding acquisition; methodology; project administration; resources; software; supervision; writing – review and editing.

CONFLICT OF INTEREST
All authors declare that they have no conflict of interest.

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