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The electrophysiology of sequential adjustments of dual-task order coordination

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Abstract

Performing two tasks simultaneously involves the coordination of their processing. This task coordination is particularly required in dual-task situations with varying task orders. When task order switches between subsequent trials, task order coordination leads to task order switch costs in comparison with order repetitions. However, it is open, whether task order coordination is exclusively controlled by the relation of the task orders of the current and the previous trials, or whether additional conditions such as task order before the previous trial leads to a behavioral and neural adjustment of task order coordination. To answer this question, we reanalyzed the data of two previously published experiments with order-cued dual-task paradigms. We did so with regard to whether task order switch costs and the EEG component order-switch positivity in the current dual-task trial would be modulated by order switches vs. repetitions in the previous trial (Trial N-1). In Experiment 1, we found a modulation of the task order switch costs in RTs and response reversals; these costs were reduced after an order switch compared with order repetitions in Trial N-1. In Experiment 2, there were no effects on the task order switch costs in the behavioral data. Nonetheless, we found the order-switch positivity to be strongly modulated by the order transition of the previous trial in both experiments. The order-switch positivity was substantially reduced if the previous trial was an order switch (compared to an order repetition) by itself. This implies that order coordination of dual tasks is adjusted in a gradual way depending on trial's history.

KEYWORDS

attention < content/topics, cognitive control < content/topics, EEG < methods, executive function < content/topics

1 | INTRODUCTION

From our real-world experience, we know that performing two tasks simultaneously or performing two tasks that overlap in time can be a challenging endeavor. Such so-called dual tasks are commonly associated with increased error rates, increased time to perform the tasks, or both, in comparison with single tasks with separate task performance (Koch et al., 2018). Numerous studies have also identified neural structures linked to the coordination of the dual-task scenario and to the control of the temporal sequence of the individual tasks, that is, the task order (Kübler et al., 2019; Strobach et al., 2015; Szameitat et al., 2006). Of considerable interest in understanding task order coordination is whether its underlying control processes are carried out in an all-or-nothing way or whether task order coordination is modulated in a gradual way based on the requirements of the current task environment. Recent studies suggest that behavioral measures of task order coordination are in fact modulated by the succession of the task order in previous dual-task trials, with reduced behavioral costs after a previously costly trial (Strobach et al., 2021; Strobach & Wendt, 2022). Although, to our knowledge, no such finding has yet been reported on the neurophysiological level, two data sets previously published by the authors allow for a detailed analysis of the most prominent neural correlate of task order coordination in dual-task scenarios, the order-switch positivity (Steinhauser et al., 2021; Steinhauser & Steinhauser, 2018), with regard to a modulation by preceding trials. Demonstrating that the characteristics of order-switch positivity depend on trial history would contribute important insights into the functional significance of this event-related potential and would provide evidence for a gradual adjustment of task order coordination based on current demands.

1.1 | Dual tasks and their task order control

Prior research on dual-tasking primarily focused on identifying the nature of the serial processing of central-cognitive operations that is frequently observed in dual-task situations and is commonly attributed to a hard-wired or strategic processing bottleneck located at the response selection stage (see Koch et al., 2018; Meyer & Kieras, 1997; Pashler, 1994, for reviews). This research on serialization investigated how the cognitive processing architecture deals with capacity-limited processes when they occupy the bottleneck at the same time (Figure 1). However, recent studies have emphasized questions of task coordination and task order control under conditions
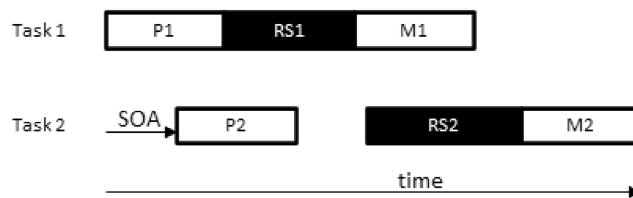

FIGURE 1 Dual-task processing architecture with a dual Task 1 and a Task 2, separated by a SOA (stimulus onset asynchrony). In this models, central response selection (RS1; RS2) stages in Task 1 and Task 2 are processed serially (this is commonly attributed to a hard-wired or strategic processing bottleneck), although perception (P1; P2) and response (R1; R2) stages are processed in parallel.

of rapid, successive administration of stimuli for different tasks (for an exemplary task situation, see Figure 2). Among others, this research demonstrated that changing the task order presentation from the preceding trial N-1 to the current trial N (i.e., different task orders in successive trials and therefore a task order switch) yields a performance impairment for both tasks in comparison with the same task order and therefore a task order repetition across these trials (henceforth, task order switch costs, e.g., Kübler et al., 2018; Szameitat et al., 2006). Task order switch costs have been observed even when regular sequences of order repeat and order-switch trials provided foreknowledge concerning the task order of the upcoming trial (e.g., Luria & Meiran, 2003; Strobach et al., 2021), suggesting a robust processing limitation that cannot easily be overcome by anticipation or preparation.

On the neural level, the task order switch costs have recently been found to be mirrored by a distinct event-related potential (ERP) component, the order-switch positivity (Steinhauser et al., 2021; Steinhauser & Steinhauser, 2018). This P3b-like positivity over posterior electrodes in order switches compared to order repetitions peaks about 400–800 ms after the presentation of a cue that indicates the upcoming task order. It bears strong similarities with the more frequently investigated switch positivity of (single-)task switching paradigms (Karayanidis et al., 2010; Karayanidis & Jamadar, 2014; Kieffaber & Hetrick, 2005; Rushworth et al., 2002). This switch positivity is assumed to reflect a context updating mechanism that is initiated in task switches when the internal model of the task environment does not match the factual requirements indicated by the cue (Kieffaber & Hetrick, 2005; see also Donchin & Coles, 1988). Due to the strong similarities between the order-switch positivity of dual-task paradigms and the switch positivity of task-switching paradigms in terms of time course and topography, Steinhauser et al. (2021) suggested that both ERPs mirror the same underlying higher-order control process that is implemented independently from specific task representations (single-task sets vs. dual-task sets).
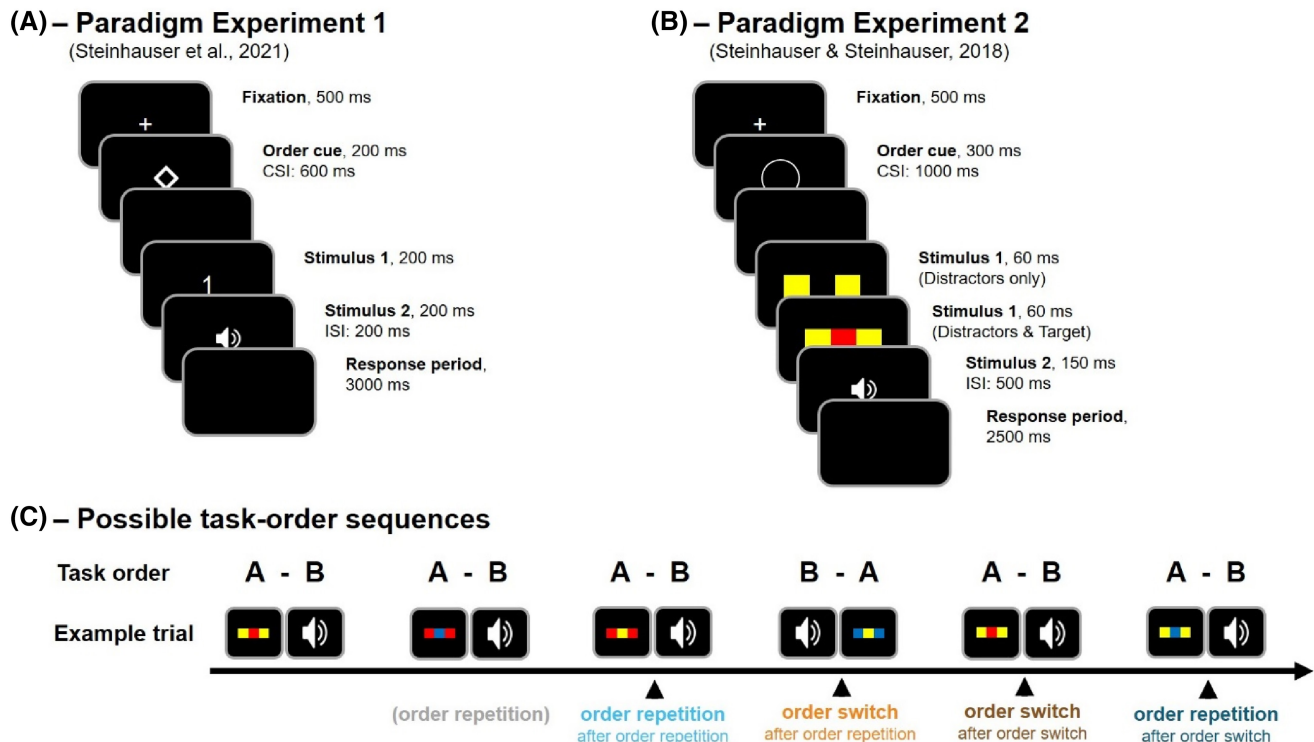
(A) – Paradigm Experiment 1
(Steinhauser et al., 2021)

(B) – Paradigm Experiment 2
(Steinhauser & Steinhauser, 2018)

(C) – Possible task-order sequences

FIGURE 2 Paradigms of the previously published experiments that were reanalyzed (Panels a, b) and the four possible task order sequences that were considered in the present study (using exemplary stimuli of Experiment 2; Panel c). In Experiment 1, participants were instructed to manually respond according to the identity of visual digits and the pitch of tones. In Experiment 2, participants were instructed to manually respond according to the pitch of tones and the color of centrally presented visual squares. CSI, cue-stimulus interval; ISI, inter-stimulus interval.

1.2 | Task order control: All-or-nothing or gradual?

One central question on the nature of dual-task order co-ordination is whether this aspect of cognitive control is carried out as all-or-nothing or whether it varies gradually with contextual demands. Generally, some aspects of cognition, such as access to consciousness or a central processing bottleneck, are commonly suggested to be carried out in an all-or-nothing way (Raffone & Pantani, 2010; Sergent & Dehaene, 2004), whereas for others, such as conflict-driven adaptive control, graded trial-by-trial variations have been proposed (Botvinick et al., 2001; Gratton et al., 1992; Von Gunten et al., 2018). As for task selection in (single-)task switching paradigms, both alternatives have their advocates (for an overview, see Kiesel et al., 2010). Some authors (e.g., De Jong, 2000; Lavric et al., 2008) argue for complete activation of the correct task in some trials and failed task activation in others (the failure-to-engage hypothesis). Others suggest in the context of task-switching paradigms that switch positivity represents a graded control process linked to strategic variations from trial to trial (Karayanidis et al., 2010; Karayanidis, Provost, et al., 2011). In line with this, Steinhauser and Steinhauser (2019) found that graded

variations in the size of the switch positivity were able to predict behavioral errors.

Intriguingly, behavioral task order switch costs in dual tasks have recently been found to be modulated by the "order sequence" status of the predecessor trial (for this sequence, see Figure 2c). Specifically, Strobach and colleagues (Strobach, 2024; Strobach et al., 2021; Strobach et al., 2023; Strobach & Wendt, 2022) demonstrated that task order switch costs in the current trial N were reduced when trial N-1 itself involved a switch of task order compared to when this trial N-1 involved a repetition (for a review, see Strobach, 2023). This reduction occurred for both tasks of the trial and is indicated in RTs, error rates, and response reversal rates (i.e., the rate of trials where the response order is different from the order of stimulus presentation). It was observed for tasks with different difficulty levels (i.e., two-choice tasks and three-choice tasks), for relatively short and relatively long stimulus onset asynchronies (SOAs), for relatively short or long inter-trial intervals, as well as tasks/task orders with different dominances and priorities. According to the authors of these studies, this modulation could be due to adaptive adjustments of cognitive control comparable to what had previously been found for other aspects of cognitive control (Botvinick et al., 2001; Gratton et al., 1992; Gratton

et al., 2018; Stürmer et al., 2002; Von Gunten et al., 2018; Yeung et al., 2004). If this sequence-related difference in behavioral task order switch costs is mirrored by a corresponding difference in order-switch positivity during a cue-task interval, this would provide evidence for the operation of graded and adaptive control during task order coordination based on contextual demands.

1.3 | The present study

To investigate sequence effects on order-switch positivity, we analyzed two data sets that were previously published as Steinhauser and Steinhauser (2018) and Steinhauser et al. (2021). These studies implemented variants of the dual-task paradigm with random but cued task order and featured robust behavioral as well as electrophysiological findings. In both studies, considerable task order switch costs in RTs and error rates were present, and both studies feature a prominent order-switch-related positivity over posterior electrodes. Together, this makes them well suited for a reanalysis with regard to the sequential effects of the task order. In line with the reduction of behavioral task order switch costs in previous studies (Strobach et al., 2021; Strobach & Wendt, 2022), reduced amplitude differences between the order-switch positivity in order repetitions and order switches after order switches in trial N-1 (in comparison with after order repetitions in trial N-1) would demonstrate that the underlying control process takes into consideration the previous order sequence as a specific feature of contextual demands. Furthermore, this would imply that task order coordination is adjusted in a gradual and adaptive way. In contrast, comparable amplitude differences between the order-switch positivity of order repetitions and order switches (1) after order switches and (2) after order repetitions in trial N-1 would be predicted by a control of task order coordination in an all-or-nothing manner.

2 | EXPERIMENT 1

Experiment 1 is a reanalysis of the data set previously published (Steinhauser et al., 2021). This experiment featured a dual-task paradigm with cued task order and a cue-stimulus interval (CSI) of 600 ms.

2.1 | Method

2.1.1 | Participants

We reanalyzed the data of the 25 participants that were entered into the analysis of the original study (i.e.,

Steinhauser et al., 2021; one participant had been excluded from that study due to a very high number of task errors and order reversals). They had a mean age of 23.3 years (4 left-handed, 3 male). Written informed consent was obtained from all participants, and the study was approved by the ethics committee of the Catholic University of Eichstätt-Ingolstadt.

2.1.2 | Tasks and procedure

The dual-task paradigm of the present experiment featured a visual three-choice digit discrimination task and an auditory three-choice pitch discrimination task with a random task order that was indicated by a visual cue (Figure 2a). Stimuli for the visual task were the digits 1, 5, and 9, of which one per trial was displayed centrally at a visual angle of 0.52°°×0.35° at a viewing distance of 70 cm. Participants were instructed to respond according to the identity of the digits by pressing response keys of a QWERTZ keyboard with the fingers of their right hand. In particular, they responded to the digit 1, pressing the "," key with the index finger, to the digit 5 by pressing the "." key with the middle finger, and to the digit 9 by pressing the "−" key with the ring finger. Stimuli for the auditory tasks were sine-wave tones of 200, 650, and 1100 Hz, of which one per trial was presented over loudspeakers and on which participants responded by pressing response keys of a QWERTZ keyboard with the fingers of their left hand. Participants were instructed to respond to the 200-Hz tone by pressing the "Y" key with the ring finger, to the 650-Hz tone by pressing the "X" key with the middle finger, and to the 1100-Hz tone by pressing the "C" key with the index finger. The two isoluminant visual cues that indicated the upcoming task order were either a square with a white outline at 0.82°°×0.82° (indicating auditory task first, visual task second) or an equivalent diamond at 1.14°°×1.14° (indicating visual task first, auditory task second). Trials started with the presentation of a fixation cross for 500 ms, which was followed by the task order cue for 200 ms and a CSI of 600 ms. The stimulus of the first task followed for 200 ms and was then succeeded by the respective other task stimulus for another 200 ms after an SOA of 200 ms. The screen remained black during the response period (3000 ms max.) and the subsequent trial started 500 ms after the response to the second task. After a practice phase that consisted of 4 single-task blocks à 18 trials (to train the stimulus–response mappings of the two tasks; 2 blocks per task) and 6 dual-task blocks à 18 trials (2 blocks to train the order sequence visual–auditory, 2 blocks for auditory–visual, and 2 blocks with mixed task order), participants

worked on 12 test blocks à 72 dual-task trials, of which 8 blocks had mixed task orders and 4 blocks had fixed task orders (the latter blocks had to be excluded from this reanalysis). As a result, we here reanalyzed a total of 8 dual-task blocks, that is, 576 mixed task order trials for Experiment 1. At the beginning of every block throughout the experiment, participants were instructed to respond to both tasks in the order determined by the cue and as fast and accurately as possible.

2.1.3 | Data acquisition and analysis

Data were recorded and analyzed as described in detail in Steinhauser et al. (2021). We recorded the EEG with a 64-channel BIOSEMI Active-Two system with linked mastoids as the reference electrodes and a sampling rate of 512 Hz. Utilizing customized MATLAB v8.3 (The Mathworks) scripts and EEGLAV v13.5 (Delorme & Makeig, 2004) functions, we bandpass filtered (0.1–40 Hz), epoched (−500 to +1000 ms around the onset of the cue), and baseline-corrected (−200 to 0 ms before the cue) the data. Defective electrodes were interpolated with EEGLAB's pop_rejchan.m, and epochs were removed if they exceeded ±300 μV or had a joint probability beyond 5 SDs from the mean of all epochs. An independent component analysis was computed to correct for recurring artifacts, and in this regard, we differed from the original publication: To increase the replicability of our data preprocessing pipeline, we by now refrain from visual inspection for the removal of independent components (ICs) as in the original study and rather utilize EEGLAB's new implementation of the ICLabel project (Pion-Tonachini et al., 2019). For the present reanalysis of this data set, we automatically removed ICs if they were classified as "Muscle," "Eye," "Heart," "Line Noise," or "Channel Noise" with a probability over 90% by the ICLabel toolbox and simultaneously were classified as "Brain" with a probability below 5%. On average, 4.9% of extracted ICs (M = 3.12 ICs, SD = 2.01) per participant were excluded in this way.

All statistical tests were implemented as two-way repeated-measures ANOVAs on the variables Current Transition (order repetition vs. order switch in the current dual-task trial) and Previous Transition (order repetition vs. order switch in the previous dual-task trial). These ANOVAs were separately performed on all behavioral measures, that is, the RTs and error rates of Task 1 (T1, firstly presented task, irrespective of either auditory or visual task) and Task 2 (T2, secondly presented task, irrespective of either auditory or visual task), as well as the response reversals, and on our electrophysiological

measure, that is, the order-switch positivity. The latter was quantified as the mean amplitude between 450 and 600 ms relative to cue onset at electrode Pz (Karayanidis, Whitson, et al., 2011), but taking into consideration the shorter CSI of 600 ms.

2.2 | Results

2.2.1 | Behavioral data

As can be seen in Figure 3, RTs of T1 were considerably longer in current order switches compared to order repetitions, as highlighted by a main effect of Current Transition, $F(1,24) = 48.59$, $p < .001$, $\eta^2_{part.} = .67$. The significant main effect of Previous Transition, $F(1,24) = 11.24$, $p = .003$, $\eta^2_{part.} = .32$, demonstrates a general slowing after previous order switches (Strobach & Wendt, 2022), and this effect is further explained by the interaction of the two variables, $F(1,24) = 6.37$, $p = .019$, $\eta^2_{part.} = .21$, which indicates a larger difference between current order repetitions and order switches after an order repetition in the previous trial (mean difference of 133 ms, $t(24) = 6.41$, $p < .001$, $d = 0.50$) than after an order switch (mean difference of 77 ms, $t(24) = 5.02$, $p < .001$, $d = 0.29$). RTs to T2 feature the same pattern, with significant main effects of Current Transition, $F(1,24) = 44.50$, $p < .001$, $\eta^2_{part.} = .65$, as well as Previous Transition, $F(1,24) = 25.21$, $p < .001$, $\eta^2_{part.} = .51$, and an interaction effect, $F(1,24) = 7.61$, $p = .011$, $\eta^2_{part.} = .24$. In particular, the interaction indicates a larger difference between current order repetitions and order switches after an order repetition in the previous trial (mean difference 141 ms, $t(24) = 5.85$, $p < .001$, $d = 0.47$) than after an order switch (mean difference 73 ms, $t(24) = 4.78$, $p < .001$, $d = 0.24$).

T1 error rates, however, were not affected at all by any of these variables, all $Fs(1,24) < 0.88$, all $ps > .35$, and all $\eta^2_{part.}s < .01$. Likewise, we found no effect for T2 error rates, all $Fs(1,24) < 0.17$, all $ps > .68$, and all $\eta^2_{part.}s < .01$. Nonetheless, the rate of order reversals again showed a similar pattern as what we found for RTs, with a main effect of Current Transition, $F(1,24) = 16.00$, $p = .001$, $\eta^2_{part.} = .40$, as well as an interaction of Current Transition and Previous Transition, $F(1,24) = 8.22$, $p = .008$, $\eta^2_{part.} = .26$. Also, for the order reversal rate, we found a considerable difference between current order repetitions and order switches only after an order repetition in the previous trial (mean difference 3.55%, $t(24) = 4.43$, $p < .001$, $d = 1.14$) and only a marginally significant one after an order switch (mean difference 1.00%, $t(24) = 1.92$, $p = .067$, $d = .38$).
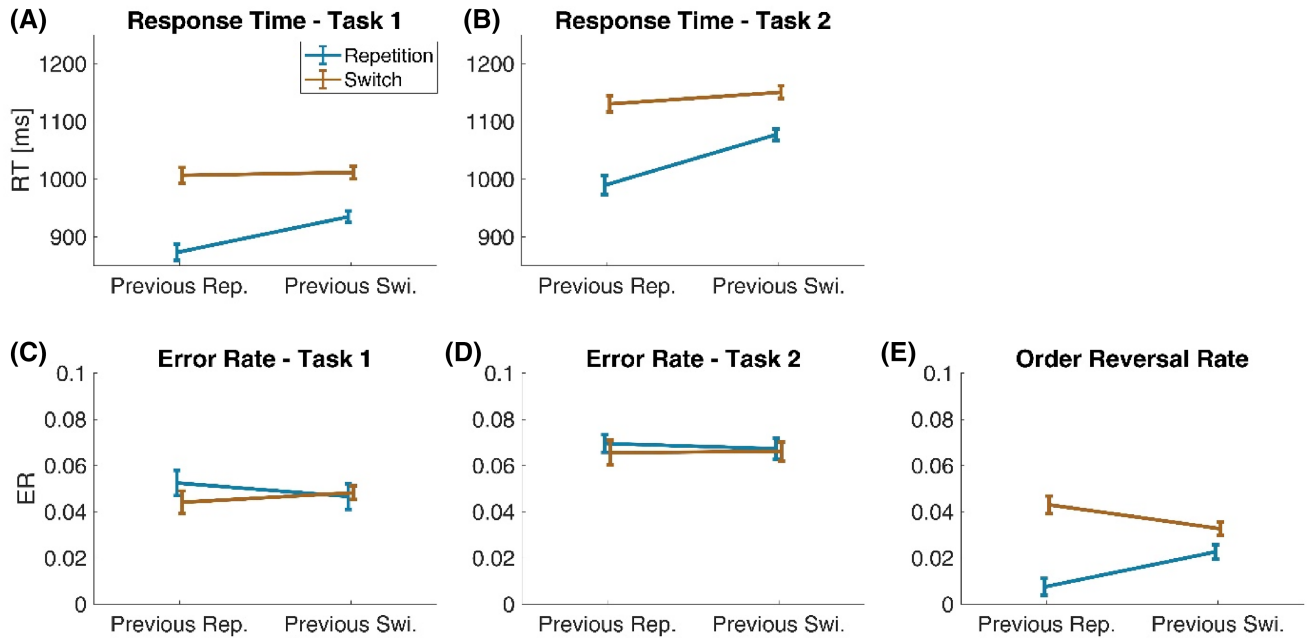
FIGURE 3 Behavioral results of Experiment 1, that is, response times to Task 1 (Panel a) and Task (Panel b) as well as error rates of Task 1 (Panel c) and Task 2 (Panel d) as well as the rate of order reversals (Panel E). Previous Rep., previous order repetition; Previous Swi., previous order switch; Repetition, current order repetition; Switch, current order switch; RT, reaction time; ER, error rates.
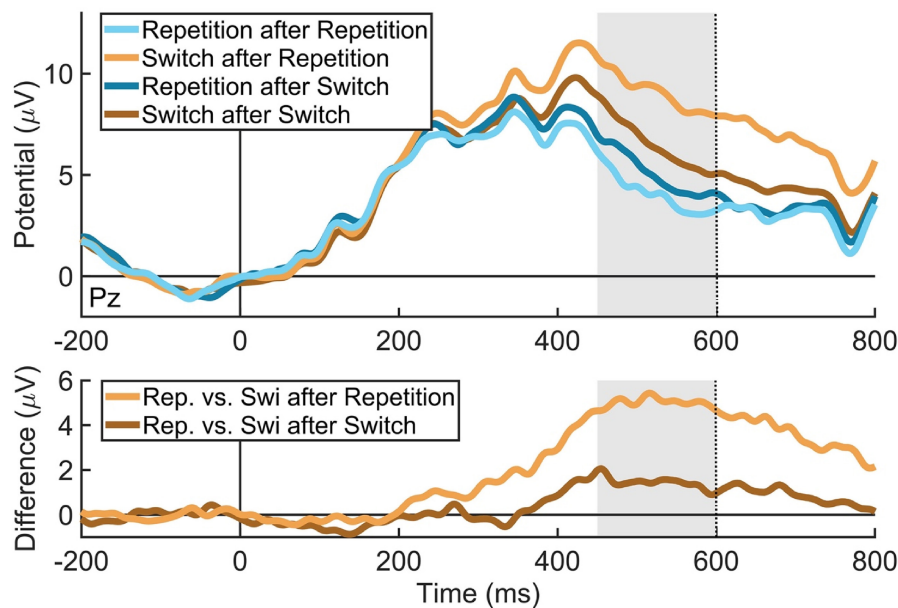

FIGURE 4 Raw ERP waveforms (top) and difference waves (switch minus repetition, bottom) of Experiment 1 at electrode Pz, time-locked to the onset of the task order cue. Gray areas indicate the time intervals used for statistical testing, which were adopted from Steinhauser et al. (2021). The dotted black line at 600 ms indicates the onset of the task stimulus.

2.2.2 | Electrophysiological data

Inspection of the ERP waveforms highlights the typical P3-like positivity over posterior electrodes that is commonly found in task-(order-)switching (Figure 4), and the respective topographies (Figure 5) confirm its posterior spatial distribution. Mirroring what has previously been found on the behavioral level, statistical analysis

revealed a significant main effect of Current Transition, $F(1,24)=59.19$, $p<.001$, $\eta^2_{part.}=.71$, as well as a marginally significant main effect of Previous Transition, $F(1,24)=3.56$, $p=.071$, $\eta^2_{part.}=.13$, which is further specified by an interaction of the two variables, $F(1,24)=33.10$, $p<.001$, $\eta^2_{part.}=.58$. Difference waves confirm that the order-switch-related posterior positivity is far more pronounced after order repetitions in the previous trial (mean
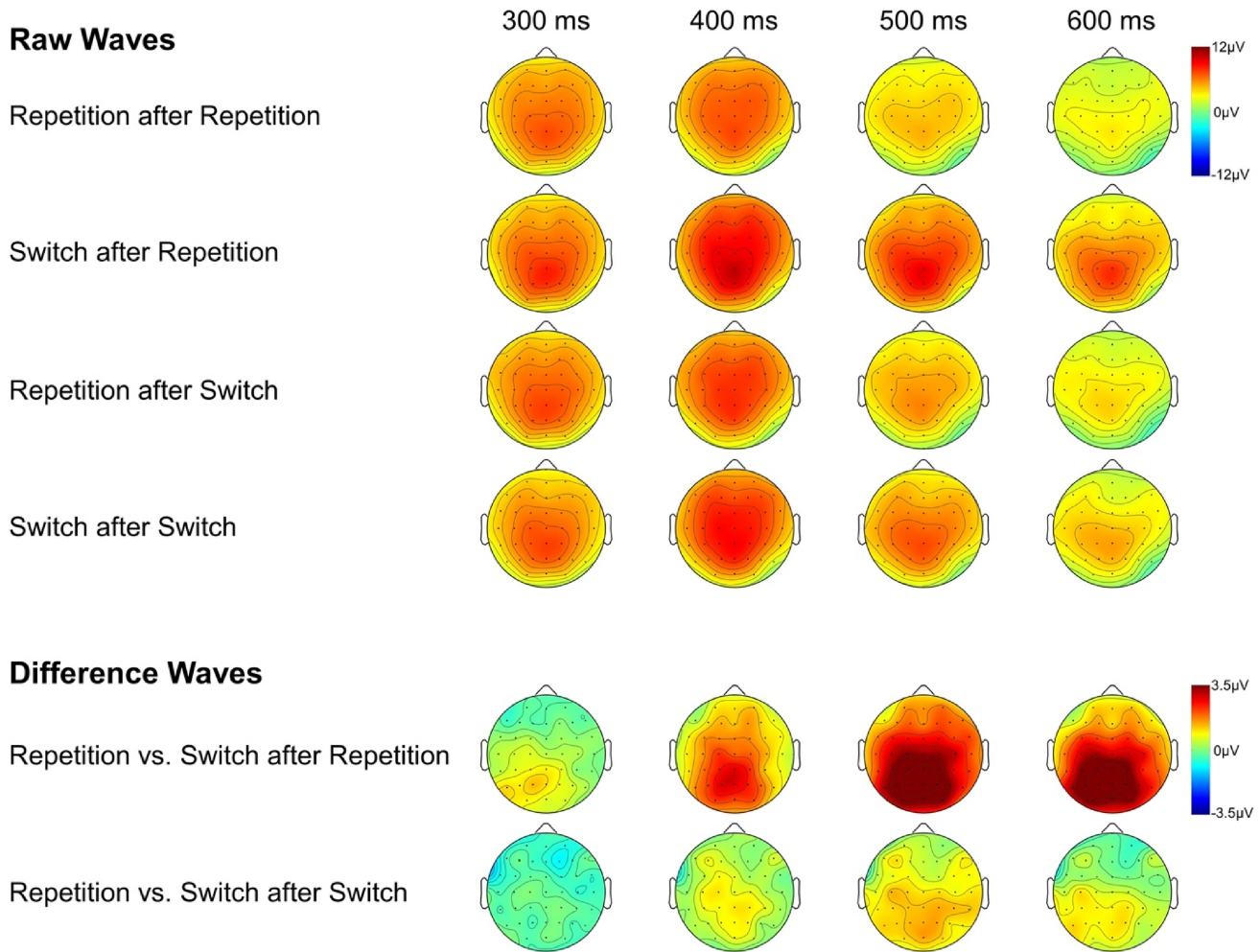
FIGURE 5 Scalp topographies from Experiment 1. Topographies of raw waveforms show the distribution of the averaged activity across the scalp for selected time points in each condition. Topographies of the difference waves show the distribution of the averaged difference between repetition trials and switch trials.

difference 5.02 μV, $t(24) = 9.58$, $p < .001$, $d = 1.19$) than after order switches (mean difference 1.46 μV, $t(24) = 2.79$, $p = .010$, $d = 0.37$).

3 | EXPERIMENT 2

For Experiment 2, we reanalyzed the data set previously published in Steinhauser and Steinhauser (2018), which featured a dual-task paradigm with cued task order and a longer (as compared to Experiment 1) CSI of 1000 ms.

3.1 | Method

3.1.1 | Participants

We reanalyzed the data of all 25 participants of the original study (i.e., Steinhauser & Steinhauser, 2018) with a mean age of 22.2 years (4 left-handed, 5 male). Written

informed consent was obtained from all participants, and the study was approved by the ethics committee of the Catholic University of Eichstätt-Ingolstadt.

3.1.2 | Task and procedure

The paradigm consisted of a three-choice color flanker task and a two-choice pitch discrimination task with a random task order that was again indicated by a cue stimulus, as outlined in Figure 2b and described in detail in Steinhauser and Steinhauser (2018). As in Experiment 1, trials started with the presentation of a fixation cross for 500 ms, which was then succeeded by a task order cue of 300 ms, an outlined white square or circle with a visual angle of 2.1°°×2.1°. After a CSI of 1000 ms, the stimulus of the first task, either the three colored squares of the flanker task (red, blue, or yellow; 60 ms flankers, 200 ms flankers, and target combine, only incongruent stimuli), or the sine-wave tone of the pitch discrimination task (400 or 900 Hz; 150 ms) followed.

The second task then followed after a fixed SOA of 500 ms, and the subsequent trial started 1000 ms after the second response. The experiment consisted of two sessions: one practice session with 3 blocks à 24 trials to practice the stimulus–response mapping of the color flanker task alone, 1 block à 24 trials for the pitch discrimination task alone, 2 blocks à 24 trials for both tasks in fixed task order, 2 blocks à 24 trials for both tasks in random order, and finally, 6 blocks à 96 trials to adjust individual speed pressure for higher error rates in the two tasks (error trials were omitted for the present reanalysis, though). The actual data recording session consisted of 11 dual-task blocks à 96 trials in mixed task order, resulting in 1056 total trials for Experiment 2.

3.1.3 | Data acquisition and analysis

Data were recorded and analyzed as described in Steinhauser and Steinhauser ([2018](#)). Recording was conducted using the same 64-channel BioSemi system as described in Experiment 1. The EEG signal was bandpass filtered analogously from 0.1 to 40 Hz. With an interval of −300 to +1500 ms around the cue onset (and baseline-corrected for −200 ms to 0 ms before cue onset), epochs were longer to account for the increased CSI, though. Defective electrodes were again interpolated by using EEGLAB's pop_rejchan.m routine, and epochs were removed if they exceeded ±250 μV or their joint probability deviated more than 5 SD from the mean across all epochs. The same change from the original publication as for Experiment 1 was conducted with regard to the independent component analysis: To increase replicability, we switched from visual inspection for the removal of ICs to the ICLabel toolbox, with the same parameters as reported for Experiment 1. On average, 6.3% of extracted ICs (M = 4.04 ICs, SD = 2.76) per participant were excluded in this way.

All statistical tests were implemented as two-way repeated-measures ANOVAs on the variables Current Transition (order repetition vs. order switch in the current dual-task trial) and Previous Transition (order repetition vs. order switch in the previous dual-task trial). These ANOVAs were separately performed on behavioral measures, that is, the RTs and error rates of T1 and T2, as well as the response reversals and the order-switch positivity, which was quantified as the mean amplitude at electrode Pz from 400 to 600 ms[1] (Karayanidis & Jamadar, [2014](#)).

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[1]Please note that we used slightly different time intervals for quantifying the switch positivity in the two experiments, because these were the intervals used in the original studies. However, when reanalyzing Experiment 1 with the longer interval (400–600 ms) from Experiment 2, all results remained the same.

3.2 | Results

3.2.1 | Behavioral data

Experiment 2 showed only a very small number of the behavioral effects reported in Experiment 1. As illustrated in Figure 6, RTs of T1 did not feature any effects, all Fs(1,24) < 2.04, all ps > .16, all $\eta^2_{part.}$s < .08. The ANOVA on RTs of T2 only yielded a main effect of Current Transition, $F(1,24) = 16.10$, $p = .001$, $\eta^2_{part.} = .40$, with slower responses on order switches (437 ms) than on order repetitions (424 ms). All other effects were non-significant, all Fs(1,24) < 1.45, all ps > .23 all $\eta^2_{part.}$s < .06.

A main effect of Current Transition was also found for T1 errors, $F(1,24) = 8.71$, $p = .001$, $\eta^2_{part.} = .27$. More T1 errors occurred on order switches (7.13%) than on order repetitions (5.56%). No other effects were significant, all Fs(1,24) < 0.95, all ps > .33 all $\eta^2_{part.}$s < .04. For T2 errors, no effects were significant, all Fs(1,24) < 0.47, all ps > .50 all $\eta^2_{part.}$s < .02. Order reversals finally showed only a marginally significant main effect of Current Transition, $F(1,24) = 3.59$, $p = .07$, $\eta^2_{part.} = .13$, with slightly more order reversals on order switches (0.49%) than on order repetitions (0.18%).

3.2.2 | Electrophysiological data

Although the basic morphology of the raw ERP waveforms differs considerably from those in Experiment 1, Figures 7 and 8 highlight that the order-switch-related posterior positivity features a very similar time course and scalp topography in Experiment 2. A main effect of Current Transition, $F(1,24) = 17$, $p < .001$, $\eta^2_{part.} = .43$, as well as an interaction of Current Transition and Previous Transition, $F(1,24) = 5.60$, $p = .026$, $\eta^2_{part.} = .19$, confirmed the same pattern as found in Experiment 1: The order-switch related positivity is pronounced after order repetitions in the previous trial (mean difference 2.36 μV, $t(24) = 5.43$, $p < .001$, $d = 0.81$) but fails to reach statistical significance after order switches (mean difference 0.92 μV, $t(24) = 1.69$, $p = .10$, $d = .30$).

4 | DISCUSSION

To find out whether the task order coordination depends on trial history and, thus, whether it is carried out in an all-or-nothing or gradual way, we reanalyzed the data of two previously published experiments (Steinhauser et al., [2021](#); Steinhauser & Steinhauser, [2018](#)). We did so with regard to whether behavioral measures and the order-switch positivity in the current dual-task trial would be modulated by
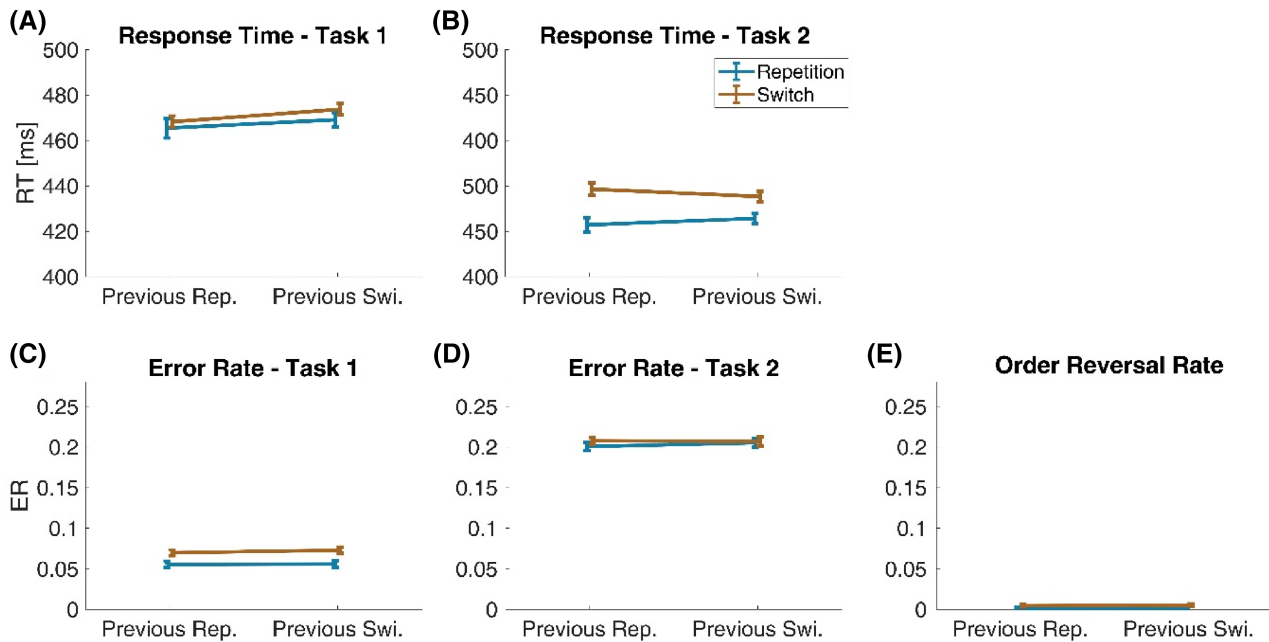
FIGURE 6 Behavioral results of Experiment 2, that is, response times to Task 1 (Panel a) and Task (Panel b) as well as error rates of Task 1 (Panel c) and Task 2 (Panel d) as well as the rate of order reversals (Panel e). Previous Rep., previous order repetition; Previous Swi., previous order switch; Repetition, current order repetition; Switch, current order switch; RT, reaction time; ER, error rates.
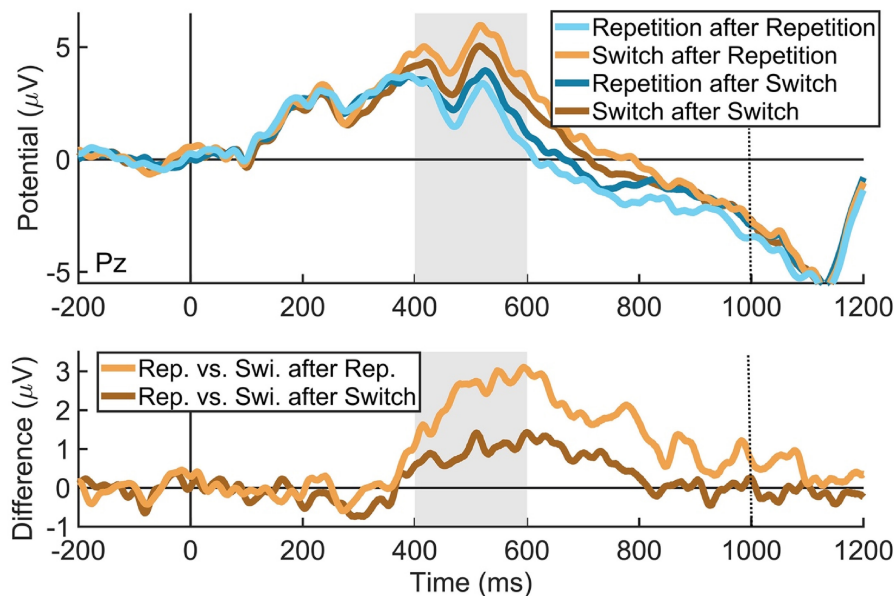

FIGURE 7 Raw ERP waveforms (top) and difference waves (switch minus repetition, bottom) of Experiment 2 at electrode Pz, time-locked to the onset of the task order cue. Gray areas indicate the time intervals used for statistical testing, which were adopted from Steinhauser and Steinhauser (2018). The dotted black line at 1000 ms indicates the onset of the task stimulus.

order switches vs. repetitions in the previous trial (e.g., task order A-B after task order B-A vs task order A-B). The two experiments featured variants of order-cued dual-task paradigms with different stimulus–response mappings (digit classification vs. color flanker combined with a pitch discrimination task) as well as different amounts of time for task order preparation (CSIs of 600 vs. 1000 ms). In sum,

these present findings are consistent with the reviewed findings of Strobach et al. (2023). That is, in Experiment 1, we found a modulation of the task order switch costs in RTs and response reversals; these costs were reduced after an order switch in Trial N-1 compared with order repetitions in Trial N-1. The lack of effect in the error rates does not provide evidence for a speed-accuracy trade-off in these data.
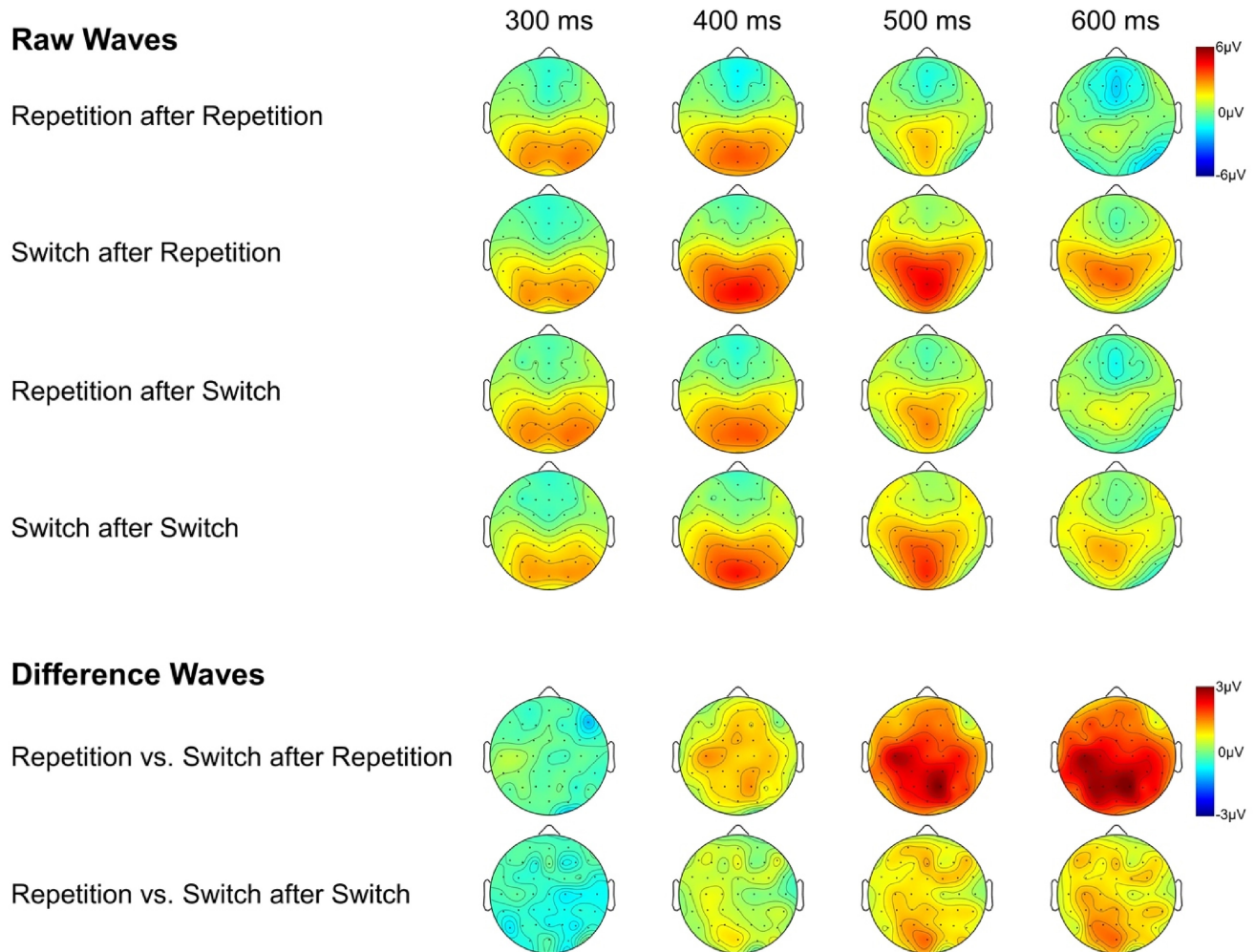
FIGURE 8 Scalp topographies from Experiment 2. Topographies of raw waveforms show the distribution of the averaged activity across the scalp for selected time points in each condition. Topographies of the difference waves show the distribution of the averaged difference between repetition trials and switch trials.

In Experiment 2, there were some effects on the task order switch costs in the behavioral data (i.e., RT of T2 and errors of T1), whereas there was no evidence of a sequential modulation of these costs. Nonetheless, we found the order-switch positivity to be strongly modulated by the order transition of the preceding trial in both experiments. The order-switch positivity was reduced by a great amount if the previous trial was an order switch (compared to an order repetition) by itself.

4.1 | The origin of behavioral task order switch costs and their modulation

The modulation of the task order switch costs in Experiment 1 and the order-switch positivity in Experiment 1 and 2 are evidence in favor of a gradual adjustment of task order coordination. This modulation takes into account trial-to-trial variations in the need to engage the control process that underlies these costs and the order-switch positivity. To explain this gradual adjustment, in the context of frequent task order alternations, different task orders in a dual-task trial might be represented as distinct task order sets (Hirsch et al., 2018; Hirsch et al., 2017; Kübler et al., 2018, 2022), responsible for *"first-order"* task order control. Such task order sets contain explicit information about the processing sequence of both component tasks in a dual-task trial (e.g., "Task A first and Task B second" or "Task B first and Task A second"), which differs from the task sets of the component tasks that represent specific task information, such as stimulus and response information as well as information on the stimulus–response mappings (Kübler et al., 2022). Any repetition of the task order and thus task order set could result in a performance benefit (explaining reduced task order switch costs) because the task order set is still activated from the previous trial, and thus, an additional re-activation process is required. Similar to this

"first-order" task order control, it is possible that *"second order"* task order control represents different transition types (i.e., task order switch vs. task order repetition) as higher-order task sets. In other words, it would be easier to control for a systematic order of repeated task order changes, that is, A-B, B-A, A-B, B-A, compared to a sequence with an irregular and random order of task order changes, that is, A-B, A-B, B-A. To this end, any repetition of task order transition sets would result in a performance benefit. At the same time, this would also imply that it is not only an advantage to perform a task order switch (vs. repetition) after a task order switch in the previous trial N−1, but there is also an advantage to implement a task order repetition after a task order repetition (vs. switch) in this trial. Conversely, performing a task order repetition (vs. switch) after a task order switch in trials N−1 and performing a task order switch (vs. repetition) after a task order repetition in trial N−1 should be characterized by a performance decrement. A general increase in response caution after order-switch trials could enhance RTs in both current order repeat trials and order-switch trials in Experiment 1; such an increase was indicated by generally increased RTs under conditions of an order switch in previous trials (Strobach & Wendt, 2022). One would therefore expect an amplification versus a masking of the effect of the transition set mechanism in order repeat trials and order-switch trials, respectively.

However, the behavioral modulation of the task order switch costs was exclusively present in Experiment 1 but absent in Experiment 2. This lacking evidence for the modulation of task order switch costs is one of the few examples in the literature, where there is no such modulation, whereas all published studies on this issue so far were able to show a modulation of task order switch costs depending on the previous trial condition (Strobach et al., 2021, 2023; Strobach & Wendt, 2022). So, Experiment 2 is informative in contrast to these previous findings since it might represent a borderline case where no modulation is performed. However, Experiment 2 differs from Experiment 1 and previous studies in several aspects (i.e., it applies task order cues, it has a rather long CSI, it applies component tasks different from previous studies, etc.), which does not allow us to make conclusions about the specific aspect that is responsible for a lacking modulation. To find out about this lack, future studies are required.

4.2 | The functional significance of the order-switch positivity and its modulation

Our results are also in line with previous neurophysiological research from the field of task switching, which demonstrated that the amplitude of the switch positivity can vary from trial to trial. It is increased for trials with fast response times with assumedly more efficient preparation compared to trials with slow response times (Karayanidis, Whitson, et al., 2011; Lavric et al., 2008) and also increased for trials with less preparation time (Mueller et al., 2009). Steinhauser and Steinhauser (2019) could demonstrate that variability in the amplitude of the switch positivity is predictive of the occurrence of performance errors. Based on the highly similar natures of the control processes implemented for *task* preparation in task-switching paradigms and those implemented for *order* preparation in order-switching paradigms (Steinhauser et al., 2021; Steinhauser & Steinhauser, 2018), it is likely that the strongly reduced order-switch positivity after order switches in the preceding dual-task trial results from similar variations in the trial-to-trial balancing of the control processes involved in task order coordination.

Moving onward to pinpoint the neural basis of this modulation of the order-switch positivity, it is necessary to address the question of whether this ERP is considered to be directly quantifying the activity of the underlying control process or whether it represents a rather indirect measure of that process, for example, by mirroring the effort or the costs resulting from the implementation of control. The currently observed decrease in order-switch positivity after switch trials could therefore be interpreted as a reduction of the control process itself or as an increase in control that leads to a reduction of the associated effort or costs. The switch positivity in the task switching literature has previously been interpreted in both ways, either as a direct index of anticipatory task-set reconfiguration itself (Karayanidis et al., 2009; Karayanidis, Whitson, et al., 2011; Lavric et al., 2008) or supporting control processes (Steinhauser et al., 2017, 2021; Steinhauser & Steinhauser, 2019), or as a more indirect marker for control by representing aspects such as facilitated cue processing (Logan & Bundesen, 2003; Mayr & Kliegl, 2003), shifts in attention (Astle et al., 2008), or an adaptation of task-related neural populations in repetition trials (de Baene et al., 2012). It would be particularly interesting to investigate whether the order-switch positivity at least partially reflects facilitated cue processing on cue-repetitions. Although it has been shown that cue processing cannot fully account for the (task-)switch positivity (Jost et al., 2008; Nicholson et al., 2006), such a finding has not yet been established for the order-switch positivity.

An explanation for the modulation might be related to models of conflict adaptation, in which the occurrence of distractor-evoked conflict is assumed to trigger the recruitment of additional cognitive control or attentional adjustment, allowing the system to deal more efficiently with future conflict situations (Botvinick et al., 2001, 2004; for

a current overview, see Braem et al., 2019). In the context of task order control, one might assume that the detection of task order mismatch on consecutive order-switch trials results in the adoption of task order control processes that prepare the system for an upcoming order switch, thus reducing the task order switch costs and the order-switch positivity. This would certainly imply that the (order-)switch positivity is an indirect measure of that process, potentially reflecting a neural equivalent of the effort or resources involved in the process and not a direct correlate of the control process itself (in that case, an increase in the switch positivity would be expected when conflict adaptation recruits additional control). Alternatively, in line with de Baene et al.'s (2012) account that interprets switch-related brain activity as resulting from the adaptive reduction of task-specific neural activity on task repetitions, the larger observed order-switch positivity after previous repetitions could be the result of an additional adaptive repetition benefit that follows from the ongoing repetition of the same task representation on several subsequent trials.

Another possible explanation for the observed modulation of the order-switch positivity is rooted in the idea that this ERP is a direct index of the underlying control process. Utilizing multivariate pattern analysis, R. Steinhauser and Steinhauser (2019) were able to link the switch positivity to a subordinate control process that supports flexible task selection by enhancing the system's receptivity for new tasks and stimuli. This account draws upon earlier findings that linked this ERP to suppressing the ongoing priming of previously active task sets (Allport et al., 1994; Allport & Wylie, 1999; Friedman et al., 2007; Herd et al., 2014). Receptivity toward the new task (in single-task switching) or task order (in task order switching) is therefore increased by regulating the competitiveness between the alternative tasks and task orders, respectively (see also Goschke, 2000; Hommel, 2015). If the order-switch positivity indeed represented such a process that increases receptivity by regulating the competitiveness in favor of the new task order set on order-switch trials, the need for such an adjustment would be required to a lesser extent in a trial that was preceded by an order-switch trial with already adjusted competitiveness itself. This would therefore explain why the order-switch positivity is strongly reduced on trials that succeed an order switch and is only present to its full extent after an order repetition in the previous trial. Only then does the balancing of control processes need to be majorly adjusted to increase receptivity toward the new task order set.

So far, our discussion on the nature of the order-switch positivity assumed that it reflects a distinct component of the cue-locked ERP represented by the difference wave between switch and repetition trials. However, it is also possible that the order-switch positivity itself reflects a modulation of a posterior P3b and thus has to be interpreted in a framework that explains all P3b-like components with a unitary mechanism. The most popular theory on the P3b assumes that it reflects a context updating mechanism that updates working memory whenever context changes or an unexpected event occurs (Donchin & Coles, 1988). (Barceló & Cooper, 2018a, 2018b) have recently proposed that the P3b to cues as well as to the target stimulus reflects the amount of conveyed information and the resulting unexpectedness of a stimulus. Finally, within the framework of the free energy hypothesis (Friston, 2005), P3-like potentials have been interpreted as reflecting Bayesian surprise, or more specifically, a precision-weighted prediction error representing the mismatch between predicted and observed sensory input, weighted by the prediction error's precision (Barcelo, 2021). This framework has previously been applied to explain repetition priming in behavioral data and repetition suppression in ERPs (for an overview, see Gotts et al., 2012). It could explain our data if one assumes that cues indicating an order switch are less predicted than cues indicating an order repetition. However, given that cue repetition priming alone cannot account for the switch positivity in task switching (Jost et al., 2008; Nicholson et al., 2006), a model would be necessary that specifies Bayesian surprise on the level of tasks, task orders, and cues.

However, although this can account for expectancy effects related to differential stimulus frequencies, it is unclear how it could explain a (task-)switch positivity when each task (and cue) occurs with similar frequency. Karayanidis and Jamadar (2014) provided a detailed discussion on whether the switch positivity in task switching is related to a cue-locked P3b and concluded that several empirical observations are not compatible with this idea. However, it is possible that this conclusion cannot be generalized to the order-switch positivity which makes further research in this direction desirable.

Although both experiments feature the same pronounced reduction of the order-switch positivity after previous order switches, this modulation could be found for behavioral measures only in Experiment 1, not in Experiment 2. One key difference between the two experiments, a shorter CSI of 600 ms (Exp. 1) vs. a longer CSI of 1000 ms (Exp. 2), is likely to play a crucial role here. Visual inspection of the ERPs highlights that the order-switch positivity protrudes considerably into the stimulus–response interval in Experiment 1, whereas its difference wave has returned to zero before the onset of the task stimulus in Experiment 2. This suggests that the associated task order coordination processes are executed before task onset to a smaller degree in Experiment 1. Consequently, these aspects of task order preparation are likely to interfere to a

greater degree with stimulus processing and response execution during the stimulus–response interval, thus creating task order switch costs and their modulation in RTs and order reversal rates to a greater extent in that experiment. Experiment 2, in contrast, features hardly any order reversals at all due to the longer preparation time and, as a result, generally completed task order coordination. This is in line with numerous findings from task switching literature that confirm reduced behavioral switch costs with longer CSIs (e.g., Koch, 2001; Logan & Bundesen, 2003; Monsell, 2003; Arrington & Logan, 2004) and adds to the idea that the observed modulation of task order coordination by preceding order switches is rooted in the preparation process itself. In this regard, it is of particular interest that Experiment 1 yields effects of order-switch cost modulation by the previous trial only for RTs and order reversal rates but not for error rates within the component tasks. This again contributes to the interpretation that this modulation is rooted in task order coordination, which affects order reversals (trials with failed order coordination) as well as the eventual response execution speed but not the correctness of individual component tasks.

The two experiments differ not only with respect to CSI but also in other aspects. In addition to a shorter CSI, Experiment 1 also used a shorter SOA (200 ms in Exp. 1 vs. 500 ms in Exp. 2). Moreover, Experiment 1 includes blocks with constant task order (these data are not reported here but in Steinhauser et al., 2021), which might have led to a contrast effect. It has previously been shown that a within-subject manipulation of preparation demands leads to stronger effects of advanced preparation (Koch, 2001). These differences could explain why the order-switch positivity is generally larger in Experiment 1. Although it is difficult to identify which of these differences in experimental design is responsible for differences in the ERP data, it appears plausible that Experiment 1 is associated with a generally higher preparation demand than Experiment 2, which leads to stronger preparatory brain activity.

Taken together, we could show for the data sets of two studies that order-switch positivity, a most common neural correlate of task order coordination, was strongly influenced by the preceding order sequence. It could be observed prominently after order repetitions in the preceding trial and was starkly reduced after order switches. Taking into account previous findings from the order coordination and task switching literature, we consider this modulation to mirror either an adaptive repetition benefit or an increase in the receptivity toward the new task order set after a series of recurrent task orders. Nonetheless, both ways of interpretation converge on the idea that task order coordination is adjusted in a gradual rather than all-or-nothing way and changes in its extent from trial to trial over the course of experiments due to the demands of the current task environment.

AUTHOR CONTRIBUTIONS

Robert Steinhauser: Conceptualization; data curation; formal analysis; investigation; methodology; project administration; software; visualization; writing – original draft. **Marco Steinhauser:** Conceptualization; funding acquisition; investigation; methodology; project administration; resources; supervision; writing – review and editing. **Sebastian Kübler:** Conceptualization; data curation; methodology; project administration; validation. **Torsten Schubert:** Conceptualization; funding acquisition; project administration; resources; supervision; validation; writing – review and editing. **Tilo Strobach:** Conceptualization; writing – review and editing.

CONFLICT OF INTEREST STATEMENT
The authors declare that they have no competing interests.

DATA AVAILABILITY STATEMENT
The data sets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

ETHICS APPROVAL
All procedures performed in these experiments involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. The experiments were approved by the ethics committee of the Catholic University of Eichstätt-Ingolstadt.

CONSENT TO PARTICIPATE
Written informed consent was obtained from each participant before the commencement of the experiments.

CONSENT FOR PUBLICATION
The manuscript has been approved by the co-authors as well as by the responsible institutions.

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