Neural Correlates of Task-order Preparation in Dual Tasks: An EEG Study

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Abstract

Dual-task scenarios require a coordinated regulation of the processing order of component tasks in light of capacity limitations during response selection. A number of behavioral and neuroimaging findings suggest a distinct set of control processes involved in preparing this task order. In this study, we investigated electrophysiological correlates of task-order preparation in a variant of the overlapping dual-task paradigm with cue-determined task order that resulted in trials with blockwise fixed task order as well as trials with repeated and switched task order in blocks with variable task order. During the cue–stimulus interval, we found an earlier centro-parietal order-mixing positivity and a later parietal order-switch positivity. A decoding approach based on multivariate pattern analysis showed that the order-mixing positivity is a necessary prerequisite for successful order selection, whereas the order-switch positivity appears to facilitate the implementation of a new task order after its selection. These correlates of order preparation share striking similarities to commonly found potentials involved in the preparation of individual tasks in the (single-)task-switching paradigm, which is strong empirical support for the account that the underlying preparatory processes are to be considered as higher-level control signals that are implemented independently of specific task representations.

INTRODUCTION

In many dual-task situations, participants execute two choice-response tasks in close temporal succession (Telford, 1931). Usually, in these situations, RTs, error rates, or both are increased compared to single task situations. These decrements in performance are commonly attributed to a bottleneck at the response selection stage (Schubert, 1999; Pashler, 1994; Welford, 1952). According to this perspective, a bottleneck causes that response selection processes will operate only for one task at a time resulting in the serial processing of the two tasks. As a consequence of this serial processing, both task streams compete for access to the bottleneck and the order of task processing at the response selection stage has to be regulated. Although for several decades, research has mainly focused on whether the bottleneck is a rather structural (Pashler, 1994; McCann & Johnston, 1992) or a strategic one (Fischer & Plessow, 2015; Meyer & Kieras, 1997), or whether flexible and shared resource allocation is possible in dual-task situations (Tombu & Jolicoeur, 2003), still little is known how the processing order of the two component tasks is regulated (Steinhauser & Steinhauser, 2018; Schubert, 2008). In recent years, a number of psychological (Luria & Meiran, 2003, 2006; De Jong, 1995) as well as psychophysiological studies (Kübler, Soutschk, & Schubert, 2019; Steinhauser & Steinhäuser, 2018; Szameitat, Schubert, Müller, & von Cramon, 2002) proposed that order regulation in dual tasks relies on additional order information. Several authors proposed that, additionally to the representation of the component tasks, temporal aspects related to the conjoint execution of the two tasks, that is, task order, are represented in a distinct task-order set that guides the order processing of the component tasks in dual-task situations (see also Hirsch, Nolden, & Koch, 2017). This task-order set contains explicit information about the processing sequence of both tasks in analogy to a do-do list (“first perform Task A and then Task B”). The task sets of the component tasks, on the other hand, do not represent order but instead specific task information, such as stimulus and response information and the stimulus–response (S–R) mappings.

In this study, we utilize ERPs to investigate how cognitive control processes accomplish the preparation and implementation of this task-order set during dual-task processing, and how these processes are related to control processes previously found when individual tasks are prepared in the task-switching paradigm. To this aim, we analyze neural correlates for the preparation of the task order in dual-task situations with constant and with variable task order. In the latter situation, we further analyze neural correlates in a more fine-grained fashion by comparing trials in which the order of the component tasks either repeats or switches compared to that in the previous trial. In addition, we examine how errors in order preparation are reflected in brain activity while the...
component tasks are nonetheless executed correctly. This allows us to thoroughly distinguish the preparation of the individual component tasks as well as the preparation of the task order—and their potential ERP correlates.

**Electrophysiological Evidence for Task Preparation**

A considerable portion of prior work investigating task preparation with electrophysiological parameters applied the task-switching paradigm. In this paradigm, participants work on only one of usually two discrete tasks at a time (Kiesel et al., 2010; Vandierendonck, Liefooghe, & Verbruggen, 2010). Random alternations of the currently relevant task, usually indicated by a cue stimulus, produce task switches (different task as in the previous trial) and task repetitions (same task as in the previous trial). A multitude of studies has shown that successful task preparation rests on the interaction of two distinct preparatory processes reflected by dissociable ERP components. One process is mirrored by a P3b-like posterior positivity during the cue-stimulus interval that is found in task switches relative to task repetitions, hence named the *switch positivity* (Karayanidis & Jamadar, 2014; Karayanidis et al., 2010; Kieffaber & Hetrick, 2005; Rushworth, Passingham, & Nobre, 2002). This ERP component peaks about 400–800 msec after cue presentation over posterior electrodes and is assumed to reflect a context updating mechanism that is initiated in task switches when the internal model of the task environment does not fit the factual requirements indicated by the cue (Kieffaber & Hetrick, 2005, see also Donchin & Coles, 1988).

When experiments feature not only these mixed-task blocks but also single-task blocks in which the same task is repeated throughout the whole block, an additional *mixing positivity* can be observed. This ERP is obtained by comparing repetition trials in the regular mixed-task blocks with trials from the single-task blocks. The mixing positivity peaks about 300–500 msec after cue presentation at centro-parietal electrode sites and represents general task preparation that occurs in both task switches and task repetitions of mixed-task blocks. Research suggests that it is linked to a generic form of task readiness that sets the currently relevant goal based on the prevailing cue (Karayanidis, Whitson, Heathcote, & Michie, 2011; Goffaux, Phillips, Sinai, & Pushkar, 2008; Kray, Eppinger, & Mecklinger, 2005; see also Rubin & Meiran, 2005).

The cognitive processes that underlie the switch positivity and the mixing positivity appear to constitute successful task preparation as a fixed set of stages that first select and activate the goal of which task to pursue at the moment (mixing positivity) and subsequently update the task set as the concretized internal representation of that goal in case of a task switch (switch positivity; Jamadar, Hughes, Fulham, Michie, & Karayanidis, 2010; Jamadar, Michie, & Karayanidis, 2010a, 2010b). In a conventional task-switching environment, Steinhauser and Steinhauser (2019) investigated whether impairments in any of the two preparatory processes would lead to task-confusion errors, that is, trials in which participants gave a correct response to the currently irrelevant task. In this study, the authors found only a reduced mixing positivity before such task-confusion errors, whereas the switch positivity was unaffected here. This suggests that the mixing positivity is the actual constituent for successful goal activation and thus task selection, whereas the switch positivity appears to represent a subordinate process that only supports efficient switches, possibly by adjusting task parameters and increasing the receptivity toward the newly relevant internal representation of the current task, the task set (see also Steinhauser, Maier, & Ernst, 2017). Furthermore, a recent line of argument links switch-related ERPs to the general family of P300-like potentials (Barceló & Cooper, 2018a, 2018b). It is argued that the amount of information conveyed by the cue and the resulting novelty of the actual task stimulus is directly connected to the amplitude and spatial topography of these ERPs (Friston, 2005; Donchin, 1981). This appears in line with previous accounts, particularly on the mixing positivity, which saw this ERP component as a correlate of cue processing (Karayanidis & Jamadar, 2014; Karayanidis, Provost, Brown, Paton, & Heathcote, 2011; Jamadar, Michie, et al., 2010a).

**Evidence for Task-order Preparation**

In dual-task situations with temporally overlapping component tasks (Pashler, 1994; Welford, 1952; Telford, 1931), preparation differs from that in task switching in several regards. Here, participants are explicitly not meant to execute one of the tasks alone. Instead, they have to process and respond to two component tasks in each trial according to a given task order. As a result, optimal preparation needs to activate the representations of both component tasks while also taking into account their processing order, that is, which task is processed as the first task (T1) and which task is processed as the second task (T2; De Jong, 1995; Gottsdanker, 1979). It was previously suggested that this order information is represented in a distinct task-order set, which is prepared in addition to the individual task sets of the component tasks (Kübler, Reimer, Stroback, & Schubert, 2018; Hirsch et al., 2017; Luria & Meiran, 2003, 2006).

Evidence for the employment of such a task-order set stems from studies that apply a specific dual-task paradigm, in which participants are presented two target stimuli in quick succession and are instructed to respond to both tasks according to the order of stimulus presentation (Schubert & Szameitat, 2003). Importantly, the order of stimuli can either be held constant or be varied from trial to trial. This results in three types of trials (Kübler et al., 2019; Schubert & Szameitat, 2003; De Jong, 1995). Blocks with a constant task order only feature *fixed-order trials* with the same task order throughout the block. Blocks with variable task order, so-called mixed-order blocks, however, feature *order-repetition trials*, in which
the order of the component tasks is repeated in a given trial \( n \) compared to the previous trial \( n - 1 \) (\( A \rightarrow B \rightarrow A - B \)) as well as order-switch trials, in which the order of tasks in a given trial \( n \) is reversed compared to the previous trial \( n - 1 \) (\( A \rightarrow B \rightarrow B - A \)).

On a behavioral level, several authors demonstrated increased RTs in order-repetition trials of variable-order blocks compared to the fixed-order trials in fixed-order blocks, although both have the same succession of task orders and component tasks (Kübler et al., 2019; Schubert & Szameitait, 2003; De Jong, 1995), as well as increased RTs on order-switch trials compared to order-repetition trials (Luria & Meiran, 2003, 2006; Szameitait, Lepsien, von Cramon, Sterr, & Schubert, 2006; De Jong, 1995). Both findings are interpreted as strong evidence for a distinct representation of a task-order set, because traditional views of (single) task preparation would make different predictions. First, increased RTs for order-repetition trials than for fixed-order trials cannot be accounted for if no distinct task order representation is postulated (Kübler et al., 2018; Stelzel, Kraft, Brandt, & Schubert, 2008). Second, increased processing demands because of switching between single, independent component tasks would predict larger RTs in order-repetition trials, which are characterized by a switch on the component tasks level (\( A \rightarrow B \rightarrow A - B \)), than in order-switch trials.

Neuroscientific studies support this account of a distinct representation of the task-order set. A number of fMRI studies have found increased activation in regions in the lateral prefrontal cortex (lPFC), involving the inferior frontal sulcus and the middle frontal gyrus in mixed-order blocks compared to fixed-order blocks as well as in order-switch trials compared to order-repetition trials (Stelzel et al., 2008; Stelzel, Schumacher, Schubert, & D’Esposito, 2006; Szameitait et al., 2006; Schubert & Szameitait, 2003). The causal role of the inferior frontal sulcus on task order preparation was substantiated in subsequent studies that used TMS or transcranial direct current stimulation of the inferior frontal junction to selectively influence performance in trials from blocks with variable task order relative to trials from fixed-order blocks (Kübler et al., 2019; Strobach, Soutschek, Antonenko, Flöel, & Schubert, 2015). Recently, first evidence on a distinct preparation of the task-order set has also been provided in an ERP study (Steinhauser & Steinhauser, 2018). A posterior positivity (equivalent to the switch positivity found in single-task-switching paradigms) was found in task-order switches of a PRP paradigm despite the repetition of task sets on the component task level.

**Current Study**

In this study, we used EEG and aimed to elucidate different types of preparatory processes associated with task order processing in dual-task situations. In more detail, per analogy to task switching, we hypothesized to find two distinct ERP components reflecting two different types of preparatory processes. When contrasting fixed-order trials with order-repetition trials, we expected to find an ERP resembling the mixing positivity in task switching, that is, an order-mixing positivity. In addition, by comparing order-repetition and order-switch trials, we anticipated to observe an ERP that is similar to the switching positivity, that is, an order switching positivity (Steinhauser & Steinhauser, 2018).

Furthermore, we aimed to elucidate the relative roles of the two processes for the successful selection of the correct task order. For this purpose, we investigated the involvement of a potential order-mixing positivity and order-switch positivity in the emergence of task-order reversals, that is, trials in which correct responses are given to both component tasks but in reversed order relative to the order determined by the cue stimulus. Thus, these task-order reversals serve as an indicator for failed task-order preparation.

For both research questions, a thorough differentiation of the mixing positivity and switch positivity is of key importance, because evidence from studies on task switching indicate that both ERP components partially overlap in the temporal and spatial domains. To this end, we implemented conventional ERP analysis as well as a decoding approach based on multivariate pattern analysis (MVPA). The latter approach yields robust estimates of the respective ERP components that can subsequently be transferred to conditions with smaller trial numbers such as task order reversals, thus improving the signal-to-noise ratio considerably (Steinhauser & Steinhauser, 2019; Steinhauser, Maier, & Steinhauser, 2017; Parra et al., 2002).

**METHODS**

**Participants**

Twenty-six healthy participants (22 female; 4 left-handed; mean (m) age = 23.3 years, SD = 4.9 years) took part in the experiment. Sample size was based on an a priori power analysis using the G*Power software (Faul, Erdfelder, Lang, & Buchner, 2007). For this end, we estimated a large effect size of \( \eta^2_p = .29 \) (which corresponds to an effect size of \( f = .63 \)) based on the results of Kübler et al. (2019; Experiment 1) who showed a large effect of task-order switching on dual-task performance by comparing conditions with variable and fixed task order. This analysis yielded a required sample size of \( N = 19 \) (a err prob: .05; Power (1 – β err prob): .95). Previous studies investigating task-order switching indicate that implementing an order cue (see below) results in a substantial reduction of task-order reversals compared to a dual-task situation without an order cue indicating the sequence of stimuli (Kübler et al., 2019). Because these task-order reversals are a critical measure in this study, we increased the required sample size to 26 to guarantee sufficient power in our analyses. All participants were
German native speakers, had normal or corrected-to-normal vision, and were paid 8 euros per hour or course credit for their participation. The experimental protocol conformed to the Declaration of Helsinki, and written informed consent was obtained from each participant before the commencement of the study. The study was approved by the ethics committee of the Catholic University of Eichstätt-Ingolstadt. One participant was excluded from the analyses because of a very high amount of errors (36.8% discrimination errors and 40.4% task-order reversals), differing more than 3 SDs from the mean error rate across all participants.1

Task and Procedure

Participants performed a dual task consisting of an auditory and a visual three-choice RT task (Figure 1A). In the visual task, one of three different digits (1, 5, or 9) was presented centrally on the computer screen and subtended .52° × .35° of the visual angle at a viewing distance of 70 cm. Participants were instructed to respond to 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 by 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. Visual stimuli were presented in white on a black background. Stimuli of the auditory task consisted of three sine-wave tones with different frequencies (200, 650, or 1100 Hz), which participants responded 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. Each trial started with a fixation cross (.48° × .48°) presented for 500 msec, which was then followed by a task-order cue. We presented this order cue so that participants would prepare task-order before target presentation and, thus, temporally isolate order preparation from other cognitive processes that are necessary for performing both component tasks (De Jong, 1995). The task-order cue remained visible for 200 msec and provided information about the order of stimuli in the upcoming trial (a square [.82° × .82°] for trials on which the auditory task was presented first, and a diamond [1.14° × 1.14°] for trials on which the visual task was presented first). The order indicated by the instructional cue was always congruent with the order of stimulus presentation. After a cue–target interval (CTI) of 600 msec, the target stimuli were presented for 200 msec each separated by a stimulus onset asynchrony of 200 msec (see also Kübler et al., 2019; Szameitat et al., 2006). The two stimuli were presented in sequential fashion (rather than simultaneously) in order to avoid any uncertainty concerning task order or competition between both tasks for access to a capacity-limited bottleneck stage. Subsequently to the stimuli, the screen was cleared for a maximal response period of 3000 msec. After an intertrial interval of 500 msec, which started with the execution of the second response, the next trial began. Participants were instructed to respond to both tasks as quickly and as accurately as possible and, importantly, according to the order of target stimuli, which was indicated by the order cue.

Dual-task trials were presented in two types of blocks (Figure 1B). In fixed-order blocks, the presentation order of the target stimuli remained constant throughout the entire block. In half of these blocks, the visual task was always presented first, whereas in the other half, the auditory task was always presented first. In mixed-order blocks, on the contrary, the order of stimulus presentation

Figure 1. (A) The time course of an exemplary dual-task trial in which the digit task was presented as the first task (top to bottom). After a fixation cross, an order cue (here: diamond) provided information of the presentation order of both stimuli in the upcoming trial. After a CTI of 600 msec, both stimuli were presented for 200 msec, each with an ISI of 200 msec. The maximum response period for both responses was set to 3000 msec. (B) Order sequences during the experiment. Fixed-order blocks only feature fixed-order trials. Mixed-order blocks feature order-repetition trials and order-switch trials. ISI = interstimulus interval.
varied randomly from trial to trial. Within each mixed-order block, the number of trials, in which the auditory or visual stimulus was presented first, as well as the number of order-repetition and order-switch trials were equal. Furthermore, all combinations of variables occurred with equal probability, that is, all stimulus combinations occurred equally frequently in order repetitions, in order switches and in fixed-order blocks. The length of runs of the same task order was limited to a maximum of four to reduce a possible impact of trial sequences (but see Strobach, Kübler, & Schubert, 2021, Exp. 3, who found no effect of sequence length on order preparation). The task-order cue was presented in both, fixed-order and mixed-order blocks.

At the beginning of the experimental session, we implemented a practice phase that started with four single-task blocks with 18 trials each. Subsequently, participants performed six dual-task blocks with 18 trials each. Four of those blocks were fixed-order blocks (two for each task order), and two of these blocks were mixed-order blocks. Then, the actual EEG recording was started and four fixed-order blocks (two for each task order) as well as eight mixed-order blocks with 72 trials each were conducted. In total, this yielded 288 trials for each trial type. Half of the participants performed the dual-task blocks in the following sequence: two fixed-order blocks, four mixed-order blocks, two fixed-order blocks, and four mixed-order blocks. For the other half or participants, this sequence was reversed.

Data Acquisition

The EEG was recorded using a BIOSEMI Active-Two system (BioSemi) with 64 Ag-AgCl electrodes from channels Fp1, AF7, AF3, F1, F3, F5, F7, FT7, FC5, FC3, FC1, C1, C3, C5, T7, TP7, CP5, CP3, CP1, P1, P3, P5, P7, P9, PO7, PO3, O1, 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 Common Mode Sense and Driven Right Leg electrodes were used as reference and ground electrodes. Vertical and horizontal EOG was recorded from electrodes above and below the right eye and on the outer canthi of both eyes. All electrodes were off-line rereferenced to linked mastoids. EEG and EOG data were continuously recorded at a sampling rate of 512 Hz.

Data Analysis

Behavioral Data

We analyzed participants’ mean RTs and response error rates (separately for Task 1 and Task 2) as well as order reversal rates as a function of trial type. Response errors are defined as trials in which the correct task order was applied but an incorrect response was executed upon the presented target stimulus. Order reversals are defined as trials in which participants gave correct responses to the presented target stimuli, however, in a reversed order compared to the order indicated by the cue. RTs, error rates, and order reversals for all three trial types were pooled across trials with the auditory and the visual stimulus presented first. For RT analyses, trials with RTs longer or shorter than ±3 SDs (separately for each participant and condition) as well as trials with incorrect responses, order reversals or omitted responses were excluded.

Electrophysiological Data

We computed all analyses using customized MATLAB v8.3 scripts (The Mathworks) together with EEGLAB v13.5 functions (Delorme & Makeig, 2004). First, EEG frequencies below 0.1 Hz and above 40 Hz were excluded through a band-pass filter and the continuous data stream was epoched for each trial from −500 to +1000 msec around the onset of the cue. Electrodes were interpolated using spherical spline interpolation if it met the joint probability criterion (threshold 5) or the kurtosis criterion (threshold 5) in EEGLAB’s channel rejection routine (pop_rejchan.m). Epochs were removed that contained activity exceeding ±300 μV in any channel except AF1, Fp1, Fpz, Fp2, and AF8 (to prevent exclusion of blink artifacts, which were corrected at a later stage) or whose joint probability deviated more than 5 SDs from the epoch mean. To correct for eye blinks and muscular artifacts, an infomax-based independent component analysis (Bell & Sejnowski, 1995) was computed and components with time courses and topographies typical of these artifacts were removed after visual inspection. Following Karayanidis, Whitson, et al. (2011) but taking into account the shorter CTI of 600 msec, we quantified both the mixing positivity and the switch positivity at electrode Pz, the former ERP component from 300 to 550 msec and the latter one from 450 to 600 msec.

To analyze neural correlates of failed task-order preparation in task-order reversals, we had to restrict ourselves to mixed-order blocks, as this error type was too infrequent in fixed-order trials (M = 0.1%; only five participants committed pure task-order reversals in this condition). Order reversals were rather infrequent also in the other conditions, but 21 participants could be considered for these analyses with, on average, m = 4.9 order reversals in order-repetition trials per subject and m = 11.9 order reversals in order-switch trials. Conventional ERP analysis is limited in its informative value when it comes to measure the relative contribution of the switch positivity and the mixing positivity to the emergence of order reversals, because both components are quantified as the difference between two contrasting conditions (for the switch positivity: order-repetition vs. order-switch; for the mixing positivity: order-repetition vs. fixed-order) and the magnitude of this difference cannot be transferred to individual
order reversal trials. For this reason, we additionally used MVPA to decode the two preparatory processes that are the basis of these ERP components (Steinhauser, Maier, & Steinhauser, 2017; Mansfield, Karayanidis, & Cohen, 2012; Steinhauser & Yeung, 2010; Parra, Spence, Gerson, & Sajda, 2005; Parra et al., 2002). For that purpose, we implemented the linear integration method by Parra et al. (2002) and trained two separate sets of classifiers on partially overlapping time windows of 50 msec, separated by 10 msec during the CPT (0–600 msec after cue onset). Each classifier was trained on an equal-sized, randomly drawn number of correct trials per participants and is represented by a weight vector v. The first weight vector set, v_{mix}, was computed by discriminating between order-repetition trials and fixed-order trials, and decodes the process underlying the order-mixing positivity. The second set of weight vectors, v_{switch}, was computed by discriminating between order-switch trials and order-repetition trials. This latter classifier set analogously decodes the process underlying the order-switch positivity. To describe sensitivity of each resulting classifier, we report the area under the receiver operating characteristic curve (Az score), of which an Az of 0.5 would indicate classification at chance level. To prevent overfitting, leave-one-out cross-validation was applied so that each weight vector was the mean of T=(N−1) samples of N−1 trials to predict the T samples of the remaining trial (with N as the number of trials and T as the number of time windows). To visualize the spatial distribution of each classifier, we computed the coupling coefficient vector, which represents the activity at each electrode site that correlates with the respective discriminating component and thus can be thought of as the sensor projection of that component (Parra et al., 2002, 2005).

For each time window t, this MVPA approach allows to assign an averaged prediction value \(\hat{y}_v(t)\) to any trial. Importantly, as this is also possible for trials that were not part of the training set, the classifiers can hence be applied to order reversals. The averaged prediction value reflects the probability of the trial to belong to the event e and ranges from 0 to 1, as it represents the predicted value of a logistic regression. Computed over v_{mix} (i.e., an \(\hat{y}_v(t)\) is assigned to each trial based on the classifier set v_{mix}), this classifier output represents how well the respective trial resembles a prototypical order-repetition trial in contrast to a fixed-order trial, and thus is a single-trial measure for the order-mixing positivity. Likewise, computed over v_{switch}, this output mirrors a measure for the order-switch positivity. For our analyses, we calculated such averaged prediction values for all correct trials and order reversals in order-repetition trials and order-switch trials, separately based on v_{mix} and v_{switch}. Statistical testing of differences between the conditions was conducted at time windows at the peak of the respective underlying ERP component, that is, at 400 msec for the order-mixing positivity and at 520 msec for the order-switch positivity.

RESULTS

Behavioral Data

Task 1
To test for effects of task-order preparation on the RTs in Task 1 (RT1), we performed an ANOVA with the within-subject variable trial type (fixed-order, order-repetition, and order-switch trials). For this analysis, we found a significant main effect, \(F(2, 48) = 58.81, p < .001, \eta^2_p = .71\), indicating the operation of task-order preparation (Figure 2). Pairwise comparisons revealed that RT1 increased from fixed-order trials \((m = 789 msec)\) to order-repetition trials \((m = 906 msec)\), \(t(14) = 6.07, p < .001, d = 0.53, \) and from order-repetition trials to order-switch trials \((m = 1009 msec)\), \(t(24) = 7.18, p < .001, d = 0.39\), replicating earlier findings (Kübler et al., 2018; Luria & Meiran, 2003, 2006). Also for the response error rate in Task 1, we found a significant effect of trial type, \(F(2, 48) = 6.01, p < .01, \eta^2_p = .20\). Response error rates were significantly increased from fixed-order trials \((m = 4.9\%)\) to order-repetition trials \((m = 7.8\%)\), \(t(24) = 3.10, p < .01, d = 0.62\). A similar trend was observable for the comparison between fixed-order trials and order-switch trials \((m = 6.9\%)\), \(t(24) = 2.00, p = .06, d = 0.4\). Response error rates for Task 1 did not differ between order-repetition and order-switch trials, \(t(24) = 1.61, p = .12, d = 0.32\).

Task 2
Similar to RT1, we found a significant main effect of trial type on RT for Task 2, \(F(2, 48) = 56.38, p < .001, \eta^2_p = .70\). RT for Task 2 increased from fixed-order trials \((m = 889 msec)\) to order-repetition trials \((m = 1036 msec)\), \(t(24) = 6.66, p < .001, d = 0.61, \) and from order-repetition to order-switch trials \((m = 1140 msec)\), \(t(24) = 8.24, p < .001, d = 0.35\). In addition, response error rates for Task 2 varied as a function of trial type, \(F(2, 48) = 5.52, p < .01, \eta^2_p = .19\). Response error rates significantly increased from fixed-order trials \((m = 8.2\%)\) to order-repetition trials \((m = 10.5\%)\), \(t(24) = 2.67, p = .01, d = 0.54, \) and to order-switch trials \((m = 10.1\%)\), \(t(24) = 2.32, p = .03, d = 0.47\). The latter two trial types did not differ significantly, \(t(24) = 0.83, p = .42, d = 0.17\).

Task-order Reversals
Order reversal rates were rather low \((m = 1.82\%)\). Nevertheless, we analyzed reversal rates using an ANOVA analogously to RTs and error rates. This analysis revealed that the rate of order reversals varied as a function of the factor trial type, \(F(2, 48) = 14.91, p < .001, \eta^2_p = .38\) (Figure 3). Although hardly any order reversals occurred on fixed-order trials \((m = 0.1\%)\), they were more frequent on order-repetition trials \((m = 1.53\%)\), \(t(24) = 2.40, p = .025, d = 0.67, \) and again more frequent on order-switch trials \((m = 3.82\%)\), \(t(24) = 3.63, p < .001, d = 1.21\).
To sum up the behavioral data, by observing performance decreases from fixed-order trials to order-repetition trials as well as from order-repetition trials to order-switch trials, we found evidence for the operation of task-order preparation in dual-task situations.

ERPs

In a next step, we examined whether the pattern of behavioral results is also reflected on the neural level by analyzing ERPs during the cue–stimulus interval, that is, after presentation of the cue but before the onset of the actual stimulus of Task 1. Investigating the potential occurrence of an order-switch positivity (Steinhauser & Steinhauser, 2018), we contrasted order-repetition trials and order-switch trials (Figure 4). The latter condition was linked to a posterior positivity (order-switch positivity, Po-switch) peaking around electrode Pz at 520 msec after cue onset, $t(24) = 8.27, p < .001, d = 0.87$. Contrasting fixed-order trials and order-repetition trials, we found a mixing positivity (Po-mix) that peaked over the centro-parietal electrode CPz and had a slightly earlier time course, reaching its maximum around 400 msec, $t(24) = 9.11, p < .001, d = 1.92$. In terms of time course and scalp topography, both the Po-switch and Po-mix closely resembled the switch and mixing positivity commonly found in task-switching studies (Steinhauser & Steinhauser, 2019; Karayanidis & Jamadar, 2014; Karayanidis, Provost, et al., 2011). In summary, we found two distinct preparatory ERP components when comparing fixed-order trials with order-repetition trials and order-repetition trials with order-switch trials, the Po-switch and the Po-mix.

Addressing how these preparatory potentials relate to failed task-order preparation, which is reflected by the occurrence of order reversals, we subjected cue-locked ERPs to a repeated-measures ANOVA on the variables order correctness (correct order vs. order reversal) and order transition (order repetition vs. order switch). This was done on a subset of 21 participants, as four participants did not exhibit any order reversals in order-repetition trials, order-switch trials, or both. Visual inspection of the ERPs
and topographies (Figure 5) suggests a reduced posterior positivity on order reversals compared to correct order trials both in order-repetition trials and order-switch trials, which is confirmed by a main effect of order correctness around the peak of the P_{o-mix} (400 msec), \( F(1, 20) = 9.42, p = .006, \eta^2_p = .32 \). Around the peak of the P_{o-switch} (520 msec), a main effect of order transition, \( F(1, 20) = 12.61, p = .002, \eta^2_p = .39 \), indicates that the posterior positivity was reduced in order repetitions independent of the order correctness and a main effect of order correctness, \( F(1, 20) = 7.62, p = .012, \eta^2_p = .28 \), indicates that also, in this time range, the posterior positivity is reduced on order reversals. The interaction of the two variables was nonsignificant for both time intervals, \( F_s(1, 20) < 1.26, p_s > .27, \eta^2_{ps} < .06 \). These findings can be considered as preliminary evidence that deviations in the P_{o-mix}, the P_{o-switch}, or both are associated with the emergence of order reversals. Because of the spatial and temporal overlap of the two ERPs, however, it is not possible to confidently dissociate their relative contribution to this type of error.

**Decoder Analysis**

The initial analysis of neural correlates of task preparation on order reversals in the preceding paragraph features a fundamental disadvantage. A thorough differentiation of the P_{o-mix} and the P_{o-switch} is hardly possible because of...
the spatial and temporal overlap of the two ERP components. In addition, conventional ERP analysis is subject to a high degree of noise because of the strongly limited number of order reversal trials (after artifact correction for EEG analysis $m = 4.76$ order reversals in order-repetition trials per subject and $m = 11.23$ order reversals in order-switch trials), which greatly decreases statistical power. For these reasons, we utilized MVPA to decode the processes underlying the $P_{O\text{-mix}}$ and the $P_{O\text{-switch}}$ from correct trials. This approach yields robust estimates of the ERP components, which then can be applied to the limited number of order reversal trials leading to a considerably increased sensitivity of the corresponding analysis (Steinhauser & Steinhauser, 2019; Steinhauser, Maier, & Steinhauser, 2017). In this regard, in two such analyses, we contrasted (a) the single-trial ERP waveforms of fixed-order trials and order-repetition trials to obtain a robust estimate for the $P_{O\text{-mix}}$ and (b) contrasted order-repetition trials and order-switch trials to obtain a robust estimate for the $P_{O\text{-switch}}$.

Figure 4A depicts the classification accuracies for the two sets of classifiers, which strongly resemble the time courses and topographies of the original ERP components. Whereas the robust $P_{O\text{-mix}}$ reaches its peak of classification accuracy at around 400 msec, the robust $P_{O\text{-switch}}$ peaks slightly later at around 520 msec. The classification accuracies of both sets of classifiers are considerably above the significance threshold as established by a permutation test, for which a test distribution under the null hypothesis was generated for each time point and participant by recomputing the Az values with a random assignment of trials to the respective two contrasting categories (Steinhauser & Yeung, 2010). This is illustrated by the dotted line in Figure 4A and documents the validity of the current MVPA approach. In other words, the MVPA is able to predict the trial type (i.e., for a: fixed-order vs. order repetition, for b: order repetition vs. order switch) of individual trials based on the related EEG activity significantly above chance level. Importantly, this prediction of the trial type is based on EEG activity during the cue–stimulus interval, that is, exclusively before the onset of the actual task stimulus.

Subsequently, we aimed to apply the obtained MVPA weight vectors to analyze the corresponding brain activity in order reversal trials in more detail. For that purpose and on the same subset of 21 participants as described above, we computed the average discrimination activities for trials with correct order preparation and trials with order reversals based on these weight vectors. Subsequently, we subjected those values to two repeated-measures ANOVAs with the variables order correctness (order correct vs. order reversal) and order transition (order-repetition vs. order-switch). Each ANOVA was based on data from the time window of the respective peak of classifier accuracy (robust $P_{O\text{-mix}}$: 400 msec; robust $P_{O\text{-switch}}$: 520 msec). In the first ANOVA, the one with values of the robust $P_{O\text{-mix}}$, a main effect of order correctness, $F(1, 20) = 10.36, p = .004, \eta_p^2 = .34$, shows that the $P_{O\text{-mix}}$ was reduced in order reversals compared to trials with correct order preparation, independently of whether the respective trial has been an order-switch or an order-repetition trial. For illustration, see Figure 6B, all other effects were nonsignificant, $F_s(1, 20) < 0.52, ps > .47, \eta_p^2 < .03$. The second ANOVA with values of the robust $P_{O\text{-switch}}$, on the other hand, only yielded a significant main effect of order transition, $F(1, 20) = 79.45, p < .001, \eta_p^2 = .80$, which replicates that the $P_{O\text{-switch}}$ was reduced in order reversals compared to trials with correct order preparation, independently of whether the respective trial has been an order-switch or an order-repetition trial. Order transition and the interaction of the two variables were nonsignificant here, $F_s(1, 20) < 0.41, ps > .53, \eta_p^2s < .02$ (for details, see Figure 6C).

**Figure 6.** Results of the MVPA-based decoding approach. A depicts the classification accuracies of the two classifiers that were trained on distinguishing order-repetitions and fixed order trials (robust $P_{O\text{-mix}}$, green) and order switches from order repetitions (robust $P_{O\text{-switch}}$, blue) and the topographies of the discriminating topographies at the time points of the respective peak accuracy. B and C depict the average discrimination activity of correct and order reversal trials when the two classifiers robust $P_{O\text{-mix}}$ (B) and robust $P_{O\text{-switch}}$ are applied to the respective conditions.
All in all, the additional MVPA-based decoder approach allows for a more precise separation of the processes underlying the \(P_{o-mix}\) and the \(P_{o-switch}\). The findings of this analysis confirm the above preliminary findings on ERP waveforms in a far more robust manner: Order reversals, that is, trials with failed order preparation, are preceded by a reduction of the \(P_{o-mix}\) whereas the \(P_{o-switch}\) shows no difference between order-reversal trials and trials with correct order preparation.

**DISCUSSION**

In this study, we investigated neural correlates of order preparation in dual-task situations with variable task order. Participants conducted a dual-task consisting of two temporally overlapping component tasks in blocks with fixed task order as well as in blocks with variable task order, with the latter resulting in order-repetition and order-switch trials. This approach allowed us to assess preparatory processes that are necessary to coordinate the processing order of the two component tasks in dual-task situations. On a behavioral level, we found that performance deteriorated from fixed-order trials over order-repetition trials to order-switch trials replicating earlier findings (Kübler et al., 2019; Luria & Meiran, 2003, 2006). Even more important for the current research question, we found two distinct ERP components: an order-mixing positivity (order-repetition trials compared to fixed-order trials) and an order-switch positivity (order-switch trials compared to order-repetition trials). Interestingly, the time course and scalp topography of these two ERP components bear strong similarities to their single-task equivalents in the task-switching paradigm (Karayanidis & Jamadar, 2014; Karayanidis et al., 2010). Subsequent MVPA-based decoder analysis confirmed the finding that order preparation is mirrored by the order-mixing positivity that was linked to the emergence of order reversals, that is, trials with correctly performed component tasks but failed task-order preparation. In contrast, order reversals were not associated with changes to the form of preparation that is represented by the order-switch positivity.

**Neural Correlates of Order Preparation**

Dual-task situations are characterized by the requirement for order coordination processes that prepare and regulate the processing order of the component tasks (Schubert, 2008). Previous studies have already investigated the neural correlates of these preparatory order coordination processes in dual-task situations. In fact, a number of studies using fMRI (Stelzel et al., 2006, 2008; Szameit et al., 2006; Schubert & Szameit, 2003) or noninvasive stimulation techniques (Kübler et al., 2019; Strobach et al., 2015) have linked brain regions in the LPFC to planning and regulating the processing order of the component tasks in dual-task situations. However, these studies have mainly focused on identifying relevant brain structures involved in order coordination. Applying a method like EEG with a high time resolution of neural data analysis in the current study allowed us to focus on different mechanisms involved in order coordination and to separate their neural correlates. In fact, we found two different ERP components that were distinguishable in terms of scalp topography and time course: an order-mixing positivity and an order switching positivity. Whereas the order mixing positivity was observable when comparing fixed-order trials with order-repetition trials, the order-switching positivity was found when contrasting order-repetition trials with order-switch trials. Importantly, the existence of these two distinct ERP components suggests the involvement of different subprocesses of preparatory order coordination. This interpretation is also in line with recent behavioral studies on task scheduling in dual-task situations (Strobach et al., 2021; Kübler et al., 2018).

In single task-switching, when tasks vary randomly from trial to trial, the mixing positivity has been interpreted in terms of a mechanism that updates the currently active task representation based on the given cue (Karayanidis, Whitson, et al., 2011; Goffaux et al., 2008; Kray et al., 2005; see also Rubin & Meiran, 2005). In the present dual task, both tasks have to be performed in combined fashion on each trial. Thus, it is rather unlikely that this positivity reflects exclusively the updating of a particular task representation. Instead, the order-mixing positivity seems to mirror higher-order updating processes required for the selection of the appropriate order set, which involves information about the temporal processing order of the two component tasks in a dual-task situation. Importantly, the updating signal is not only triggered when the current trial requires an order switch. Rather, it is likewise implemented in order-switch and order-repetition trials (see Figure 6C), both trials types that occur in mixed-order blocks (but see Steinhauser, Maier, & Ernst, 2017, and Steinhauser & Steinhauser, 2019, for a more detailed analysis on different time courses of this preparatory process in the two conditions).

The assumption that the order-mixing positivity reflects the selection of the order set is also supported by the observation that it was found to be an indispensable prerequisite for successful order processing. In fact, in this study, an impairment of the order-mixing positivity resulted in order reversals, that is, participants failed to implement the currently relevant goal in terms of task order and consequently executed the component tasks in a reversed order relative to the order that was indicated by the order cue. Interestingly, a similar finding has been found in the field of single task switching by a recent task-switching study (Steinhauser & Steinhauser, 2019), which showed that impairments of the mixing positivity preceded task confusions in mixed-(single) task blocks. It must be noted, though, that the analysis on order reversals was conducted on a small subset of the total trials (\(M = \)
1.52% in order repetitions, $M = 3.82\%$ in order switches). Future studies may need to implement ways to increase the rate of order reversals, potentially by using variable or shorter interstimulus intervals or additional time pressure for responses.

In addition to the mixing positivity, we also observed an order-switch positivity in order-switch trials. This observation provides additional evidence that the preparatory processes in question are associated with control structures that are independent from specific task representations. This finding is notably nontrivial, because order switches feature a repetition of the individual component tasks across two consecutive dual-task trials ($A - B \rightarrow B - A$; Steinhauser & Steinhauser, 2018). Following previous accounts on the switch positivity, one would associate the underlying process with the reconfiguration of particular stimulus sets, response sets, and S–R mappings (Karayanidis et al., 2010; Astle, Jackson, & Swainson, 2008). Consequently, an increased positivity would be expected when a switch of such a concrete task representation occurs from one dual-task trial to the other, that is, in order repetitions ($A - B \rightarrow A - B$). We, however, found a positivity in the opposite case, which indicates that here, the control signal that is mirrored by the switch positivity reflects switch-specific aspects of reconfiguration on a higher-level of task representation, that is, the coordination of the task order.

Furthermore, the order-switch positivity was not related to the emergence of order reversals. This suggests that this ERP component is not primarily involved in the selection of the appropriate task order. Instead, the order-switch positivity must reflect other processes that guarantee successful order preparation. In task-switching, recent accounts propose a subordinate role of the control processes underlying the switch positivity, potentially optimizing efficient task performance by increasing the receptivity toward new tasks and stimuli (Steinhauser & Steinhauser, 2019; Steinhauser, Maier, & Ernst, 2017). Similarly, in dual-task situations with variable task order, the order-switch positivity may reflect processes that promote processes accomplishing order switches after the selection of the appropriate order set has been conducted. Previous studies suggest that, in order-switch trials, the processing order of the previous trial has to be overcome in order to implement a new order, for example, by inhibiting the order set of the previous trial and activating the new appropriate order set according to the perceived stimulus order (Hirsch, Nolden, Declerck, & Koch, 2018; Hirsch et al., 2017; Luria & Meiran, 2003, 2006). Potentially, the order-switch positivity might be an indicator of a related inhibitory process. However, further research is needed to test this assumption.

However, two alternative perspectives accounting for the observed order-switching positivity as well as performance differences between order-repetition and order-switch trials require further consideration. First, the results of the current study could also be explained binding processes as suggested by Hommel (2004, see also Frings et al., 2020). According to this perspective, task features, such as the order of the processed stimuli or of the processed motor response, are automatically encoded and stored as an integrated episodic trace during task processing. Future events that share features with the stored memory trace can result in its automatic retrieval. This retrieval of memory traces from prior task experience can then facilitate or interfere current task performance. Repeating the task order of the preceding trial in order-repetition trials may result in the retrieval of episodic order information from prior task experience, which, in turn, may facilitate performance. Changing task order in order-switch trials, on the other hand, may cause interference, which then might result in the performance benefits for same-order relative to different-order trials as well as the observed order-switching positivity. Although theoretically possible, we argue that this explanation is rather unlikely. From a recent study, there is now empirical evidence that episodic bindings of prior task experience do not include temporal order information (Moeller & Frings, 2019). In particular, in this study, the authors applied a prime-probe design including two targets and two responses (R1 and R2) for each the prime and the probe. In addition, the order of these two targets and, thus, the order of the required responses could either be congruent or incongruent between the prime and the probe. Importantly, as a result, the authors observed the typical binding effects on the processing of the probe irrespective of whether the responses to two probes were congruent or incongruent compared to the responses to two previously presented primes. Importantly, this observation is at odds with the assumption that our results can be explained by binding processes. However, in future research, the potential influence of binding processes in order switching during dual-tasking should be further investigated.

Second, order-switch trials are characterized not only by a switch in task order but also by a switch of the order cue. As a result, the observation of the order-switch positivity as well as performance differences between order-repetition and order-switch trials could also be because of differences in cue processing rather than the processing of an order set (Grange & Houghton, 2010; Mayr & Kliegl, 2003). Importantly, the majority of studies investigating order switching in dual tasks did not implement order cues in their experimental designs (e.g., Kühler et al., 2018; Szameitat et al., 2006). Nevertheless, in these studies, substantial behavioral as well as neurophysiological differences could still be observed between same-order and different-order trials. Importantly, because these studies did not implement order cues, the described order-switch costs cannot be accounted for by cue switches. Based on these findings, we argue that, in the current study, cue switches may have contributed to the observed performance differences between order-repetition and order-switch trial. However, in our view, it is rather unlikely that
cue switches alone can account for the observed behavioral results. Nevertheless, in future studies, it might be interesting to further disentangle the effects of cue and task-order switches on dual-task performance.

**Similarities to Task-switching Paradigms**

Our results suggest striking similarities of individual task set preparation in the task-switching paradigm and that of order preparation in dual-tasking. Finding the same neural correlates of preparation in both paradigms, a switch positivity and mixing positivity in the task-switching paradigm and an order-switch positivity and order-mixing positivity in the current dual-tasking paradigm strongly suggests that the same basic processes are involved in both cases (Worringer et al., 2019). We hence argue that preparatory control in fact runs, at least in parts, independent from specific task representations and that the corresponding ERPs are representatives of more abstract, higher-level control signals. The observed link to individual task sets (in task-switching paradigms) or to the order set (in the present dual-task paradigm) may, in turn, only constitute paradigm-driven examples out of a multitude of possibilities for the implementation of such higher-level control signals. This raises the question whether those structures in the IFPC that have previously been argued to implement a rather specific form of order preparation may actually accommodate more general mechanisms of interference control. IFPC activation is indeed equally found in conflict paradigms without a hierarchical task structure of different component tasks, such as the Stroop task (Banich et al., 2001; Zysset, Müller, Lohmann, & von Cramon, 2001), the Simon task (Liu, Banich, Jacobson, & Tanabe, 2004; Fan, Flombaum, McCandliss, Thomas, & Posner, 2005), and particularly also the task-switching paradigm (Braver, Reynolds, & Donaldson, 2003; Dove, Pollmann, Schubert, Wiggins, & von Cramon, 2000). It is, however, also well reasonable that electrophysiological findings such as the mixing positivity and switch positivity and neuroimaging findings from studies using the BOLD method address entirely different processes or stages of preparation.

Our higher-level account of the mixing positivity and switching positivity shares similarities with a recent study by Elchlepp, Lavric, Chambers, and Verbruggen (2016), who found an ERP similar to the switch positivity when a task-related context changed from the previous trial (the instruction to respect or ignore a stop signal), whereas the task itself remained the same. The authors argued that the switch positivity could reflect the reconfiguration of many different components within a task set. Here, we extend this line of reasoning and argue that the ERPs in question are linked to higher-level control structures outside and beyond the individual task representation. In studies that adopt conventional paradigms with switches of single tasks (or, as for Elchlepp et al., 2016, of subcomponents within the respective task representation), such a differentiation of task-specific and task-independent aspects of preparation is hardly possible. More complex task scenarios such as the present dual-task paradigm are necessary to implement aspects of reconfiguration that can be segregated and isolated from the concrete task representation and, in turn, provide evidence for higher-level control signals as the neural basis of preparation.

Numerous neuroimaging studies have shown that different hierarchical levels of task representations, from sensory control and S-R mappings up to relational integrations and episodic goal monitoring, are processed distinctly and consequently represented in separate brain areas on a rostro-caudal axis of the pFC (Badre & D’Esposito, 2007, 2009; Kouniheer, Charron, & Koechlin, 2009; Koechlin & Summerfield, 2007; Koechlin, Ody, & Kouniheer, 2003). In line with this, also proactive control of the task order in dual-task situations was previously linked to specific regions within pFC (Stelzel et al., 2006, 2008; Szameitat et al., 2006; Schubert & Szameitat, 2003). Our findings of order-control-related ERPs over parietal electrodes may extend this account on pFC to more global neural mechanisms. Both the (order-)mixing positivity and the (order-)switch positivity belong to the family of P3-like components, showing similarities in time courses and topographies with the stimulus-locked ERPs P3a and P3b commonly found in oddball tasks and similar paradigms (Barceló, 2020; Barceló & Cooper, 2018a; Karayanidis & Jamadar, 2014; Karayanidis et al., 2010). A recent line of reasoning attributes switch-related potentials to the amount of information that is provided by the cue (Barceló & Cooper, 2018a). This appears at least partially also attributable to the present findings: Cues in fixed-order blocks indeed convey less information than cues in mixed-order blocks (i.e., they do not necessarily indicate a general temporal task readiness). However, within mixed-order blocks, cues for order repetitions and order switches conveyed the same amount of information and occurred equally frequently. Nonetheless, a relative positivity in order switches compared to order repetitions occurred, which clearly indicates that an account solely based on cue-surprisal and informative value cannot fully account for the present pattern of preparatory ERPs.

Besides that, a number of studies have linked P3-like components to a large-scale neuronal network that integrates both prefrontal and parietal areas (Del Cul, Baillet, & Dehaene, 2007; Sergent & Dehaene, 2004; Dehaene, Kerszberg, & Changeux, 1998). In accord to this, the posterior ERP components observed in task-switching studies have previously been argued to be the implementational result of an earlier initiation of the respective underlying processes within pFC (Rushworth, Passingham, & Nobre, 2005; Rushworth, Hadland, Paus, & Sipila, 2002). It therefore appears likely that the posterior positivities observed in this study and in electrophysiological (single-)task-switching studies are eventually associated with the hierarchically structured control signals from pFC that are found in neuroimaging studies (see also Duncan, 2010).
Conclusion
Taken together, in this study, we identified two distinct ERP components that are associated with successful order preparation in dual-task situations. In addition, one of these components, that is, the order mixing positivity, was involved in the occurrence of order reversals, suggesting that this component reflects the selection of the appropriate component task order. The order-switch positivity, in contrast, seems to mirror processes that are specific to order-switch trials and aid in the implementation of a new component task order. Interestingly, both the order-mixing and order-switch positivity resemble preparatory EEG components usually found in the single task-switching paradigm. This provides evidence that the neural correlates of preparatory control processes known from ERP studies with the task-switching paradigm, that is, the mixing positivity and the switch positivity, are independent from individual task sets. We rather suggest that they represent higher-level control signals that can, depending on the paradigm context, be associated with various forms of representations of tasks, component tasks, and also of distinct entities such as the task order.

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Diversity in Citation Practices
A retrospective analysis of the citations in every article published in this journal from 2010 to 2020 has revealed a persistent pattern of gender imbalance: Although the proportions of authorship teams (categorized by estimated gender identification of first author/last author) publishing in the Journal of Cognitive Neuroscience (JoCN) during this period were M(An)/M = .408, W(oman)/M = .355, M/W = .108, and W/W = .149, the comparable proportions for the articles that these authorship teams cited were M/M = .579, W/M = .245, M/W = .102, and W/W = .076 (Fulvio et al., JoCN, 33:1, pp. 3–7). Consequently, JoCN encourages all authors to consider gender balance explicitly when selecting which articles to cite and gives them the opportunity to report their article’s gender citation balance.

Note
1. Including this participant in our analyses did not change the general pattern of results, neither for the behavioral nor for the neurophysiological data.

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