

Electrophysiological evidence against parallel motor processing during multitasking

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Abstract

We combined behavioral measures with electrophysiological measures of motor activation (i.e., lateralized readiness potentials, LRPs) to disentangle the relative contribution of premotor and motor processes to multitasking interference in the prioritized processing paradigm. Specifically, we presented stimuli of two tasks (primary and background task) in each trial, but participants were instructed to perform the background task only if the primary task required no response. As expected, task performance was substantially influenced by a task probability manipulation: Background task responses were faster, psychological refractory period effects were smaller, and interference from the second task (i.e., backward compatibility effects) was larger when there was a larger probability that this task required a response. Critically, stimulus-locked and response-locked LRP analyses indicate that these behavioral effects of parallel processing were not driven by background task motor processing (e.g., motoric response activation) taking place during primary task processing. Instead, the LRP results suggest that these effects were exclusively localized during premotor stages of processing (e.g., response selection). Thus, the present results generally provide evidence for multitasking accounts allowing parallel task processing during response selection, whereas the task-specific motor responses are activated in a serial manner. One plausible account is that multiple task information sources can be processed in parallel, with sharing of limited cognitive resources depending on task relevance, but a primary and still active task goal prevents motor activation related to the goals of other tasks in order to avoid outcome conflict.

KEYWORDS

cognitive control, dual task performance, EEG, event-related potentials (ERPs), lateralized readiness potential, multitasking

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1 | INTRODUCTION

When people are required to perform two or more cognitive tasks simultaneously, their performance on these tasks is usually worse compared with working on the tasks separately (e.g., Levy et al., 2006). Many behavioral studies have provided important insights into the causes of such multitasking interference, thereby providing fundamental clues to the architecture of our information processing system (for reviews, see; e.g., Fischer & Plessow, 2015; Janczyk & Kunde, 2020; Koch et al., 2018; Musslick & Cohen, 2021; Pashler, 1994). However, there still exists much uncertainty about the relative contribution of premotor and motor processes to multitasking interference—presumably because it is difficult to clearly interpret the effects of experimental manipulations within the processing stream by relying only on behavioral measures (i.e., reaction time, RT, and percentage errors, PE). In order to tackle this question more directly, the present study combined behavioral measures with online electrophysiological measures of motor activation (i.e., lateralized readiness potentials, LRP_s; e.g., Eimer & Coles, 2003; Smulders & Miller, 2012).

1.1 | Overview of dual-task models and relevant behavioral findings

The classic approach to investigate the nature of multitasking interference is by using a dual-task experimental paradigm called the psychological refractory period (PRP) paradigm (Pashler, 1984; Welford, 1952). In this paradigm, the stimuli (S_1 and S_2) of two tasks (T_1 and T_2) are presented sequentially, with S_2 presented after an interval known as the stimulus onset asynchrony (SOA). Participants are required to respond to each stimulus with a separate response (R_1 and R_2). For example, participants could be instructed to respond first to the identity of a letter as T_1 with their left versus right hand (e.g., H = left, S = right) followed by responding to the color of a square as T_2 with their left versus right hand (e.g., red = left, green = right). One typical finding is that the response latencies for the second task (T_2) increase approximately linearly with a + 1 slope as SOA decreases.

Many theoretical accounts agree that this so-called PRP effect mainly arises due to limitations occurring during premotor processing, but these accounts inherently differ in how the flow of T_1 and T_2 information from premotor stages (e.g., perception, response selection) to motor stages (e.g., motoric response activation, initiation, and execution) should be conceptualized. According to response selection bottleneck (RSB) accounts, the

response selection stage of T_2 has to wait until the response selection stage of T_1 has been finished—that is, structural limitations only allow serial processing at this stage (e.g., Han & Marois, 2013; Marois & Ivanoff, 2005; Pashler, 1994; Ruthruff et al., 2001). In contrast, resource-sharing accounts assume that the system is in principle able to select multiple responses in parallel but that the limited cognitive resources needed for response selection must be strategically shared between the two tasks depending on task requirements (e.g., Boag et al., 2019; Lieder & Griffiths, 2020; Mittelstädt & Miller, 2017; Navon & Miller, 2002; Palada et al., 2019; Tombu & Jolicœur, 2003).

Unfortunately, it has been in general difficult to clearly distinguish premotor and motor sources of dual task interference—including the PRP effect—when considering in more detail the requirement to produce two overt responses (R_1 and R_2) in the PRP paradigm. First, T_1 motor processes might at least partially contribute to the PRP effect, because there is evidence that the initiation of the T_1 motor response temporarily prevents the initiation of the T_2 motor response and that the initiation of the T_1 motor response might be also accompanied by a monitoring processes that taps the same resource that is used for response selection (e.g., Bratzke et al., 2008, 2009; De Jong, 1993; Keele, 1973; Klapp et al., 2019; Ulrich et al., 2007). Second, participants may adopt additional strategies to coordinate the two motor responses (e.g., Meyer & Kieras, 1997b; Miller & Alderton, 2006; Ruiz Fernández et al., 2013; Ruiz Fernández & Ulrich, 2010; Ulrich & Miller, 2008), and such strategic adjustments could additionally obscure the underlying causes of dual-interference. These issues may also partly explain why the few electrophysiological studies reviewed later provide inconclusive evidence concerning the relative contribution of premotor versus motor processes in producing the PRP effect in the standard PRP paradigm.

With respect to these issues, it is especially attractive to consider that several key findings characteristic of the PRP paradigm can also be observed in another dual-task paradigm, the prioritized processing (PP) paradigm—including the PRP effect (e.g., Miller & Durst, 2014, 2015; Mittelstädt & Miller, 2017; Rieger & Miller, 2020; Rieger et al., 2021). As can be seen in Figure 1, the PP paradigm is similar to the PRP paradigm in that it also includes two independent tasks, each with its own S-R assignments. The crucial difference is that the participants never make more than one response per trial in the PP paradigm. Specifically, in the PP paradigm one task is designated as the high priority “primary” task (T_p) and the other task as the low priority “background” task (T_b). Participants are instructed to respond only to the primary task stimulus (S_p) when this task requires a

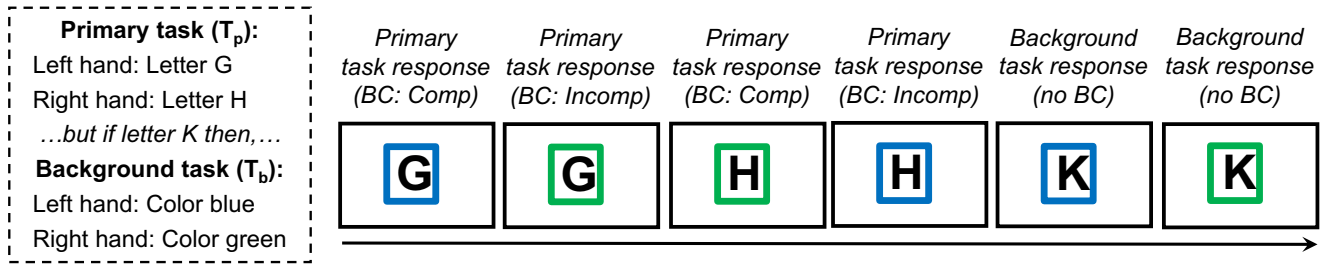


FIGURE 1 Central instructions and trial sequence with possible stimulus displays using the prioritized processing paradigm. The row over the stimulus displays indicates whether a primary versus background task response was required and the backward compatibility (BC) condition. Note that in the actual present experiment there were also fixation displays, feedback displays, intertrial intervals, and the background task stimulus (here: colored square) appeared with an stimulus onset asynchrony of 0 versus 300 ms

response. A response to the background task stimulus (S_b) is required only in trials for which T_p requires no overt response (i.e., no-go T_p trials). Because no-go responses also need to be selected (e.g., Logan et al., 2014; Wühr & Heuer, 2020), in no-go T_p trials both the primary and the background tasks involve task-specific *limited* response selection processes, with these limitations producing substantial PRP effects in these trials (e.g., Miller & Durst, 2015; Mittelstädt & Miller, 2017).¹

Obviously, the finding of PRP effects with only one overt response refutes a pure motor limitation account of dual-task interference. However, it is still a much debated question whether motor processes of a secondary task (i.e., T_b in the PP and T_2 in the PRP paradigm) contribute to dual-task interference. The causes of another type of interference, the *backward compatibility* effect (BCE), have primarily been the subject of this debate (e.g., Hommel, 1998; Janczyk, 2016; Watter & Logan, 2006). The BCE reflects a tendency for primary task response latencies (RT_p) to be affected by the compatibility of S_b or R_b with R_p (e.g., Miller & Durst, 2014; Rieger & Miller, 2020; Rieger et al., 2021). For example (see also Figure 1), left versus right T_p hand responses are faster in the PP paradigm when R_p is compatible with the response required for T_b (e.g., a left hand response for T_p and for T_b) compared to incompatible (e.g., a left hand response for T_p and a right hand response for T_b), and analogous BCEs have been also found in the PRP paradigm (e.g., Fischer et al., 2014; Janczyk et al., 2018; Thomson et al., 2021).

RSB models need additional assumptions about how information generated for a secondary task (T_b

or T_2) can influence primary task processing (T_p or T_1) to produce the BCE, since according to these models the two response selection processes do not overlap. The standard assumption is that S_b (S_2) produces *automatic* (i.e., capacity-unlimited) early response activation without requiring access to the bottleneck before a final controlled (i.e., capacity-limited) response selection process takes place (extended RSB models; see e.g., Hommel, 1998; Janczyk et al., 2014; Lien & Proctor, 2002; Schubert et al., 2008). As a result, parallel automatic T_b (T_2) response activation might interfere with the response selection process of T_p (T_1 ; e.g., Hommel, 1998; Janczyk et al., 2018; Thomson et al., 2015). Critically, it is not clear whether this response activation reflects parallel automatic *motor* activation or some kind of generic activation that is not related to motor cortex activity and could arise due to parallel automatic *premotor* response selection processes (e.g., Maquestiaux et al., 2020). It is also unclear whether the BCE should be attributed to premotor or motor processes within resource-sharing models. Assuming that at least some cognitive resources are used for T_b (T_2) response selection, the BCE could arise quite naturally because two parallel premotor response selection processes simply interfere with each other. Intuitively, however, if responses can be selected in parallel, this might also allow activation of the corresponding motor responses in parallel.

In sum, it is still not known whether secondary-task (T_b or T_2) motor activation can take place in parallel with primary-task (T_p or T_1) processing. Notably, if secondary-task motor activation operates at least partially in parallel with primary task processing, it is possible that motor processes would contribute not only to the BCE but also to the PRP effect. Specifically, T_b (T_2) motor response demands could additionally interfere with T_b (T_1) premotor processing due to a resource-limited central process involved in monitoring T_b (T_2) motoric response activations.

¹Note that substantial PRP effects have been also found after no-go T_1 trials (i.e., when T_1 requires a no-go/go decision, see e.g., De Jong, 1993; Jung, Martin, & Ruthruff, 2020; Röttger & Haider, 2017) in the PRP paradigm. However, these studies are more similar to a PRP paradigm than a PP paradigm because participants *always* had to respond to T_2 (even when T_1 required a go-response), whereas in the PP paradigm they can completely ignore T_b (T_2) if T_p (T_1) requires a response.

1.2 | Rationale of the Study: Separating parallel premotor versus motor processing with the lateralized readiness potential (LRP)

The goal of the present study was to use electrophysiological data to examine the possibility that secondary-task motor processes take place in parallel with primary task processing and thus contribute to observed dual-task interference (i.e., PRP effect and BCE). More precisely, we used the lateralized readiness potential (LRP) because this event-related potential component has proved to be the most fruitful measure of selective motor activation (e.g., Coles, 1989; Martens et al., 2010; Miller & Hackley, 1992; Miller & Ulrich, 1998; Smulders & Miller, 2012): When a participant is preparing to initiate a motor response with the left versus right hand, the motor cortex activity in the contralateral hemisphere of the corresponding response hand is stronger than the activity in the ipsilateral hemisphere, and the LRP reflects this activity difference. The view that the LRP indexes selective motor activation accords with the LRP's neuroanatomical origin mainly within the primary motor cortex (MI; cf. Leuthold & Jentzsch, 2002) as well as its functional relation to motor preparation and response priming processes (for a review, see Smulders & Miller, 2012). It is only under specific presentation conditions (i.e., unilateral stimulus presentation, bilateral presentation demanding attentional selection of a lateral target stimulus, stimuli containing directional information such as arrows)—none of which were used in the present study—that early sensory or attentional ERP activity might overlap with or mimic LRP activation (cf. Leuthold, 2011). The LRP can be calculated relative to the onset of the stimulus (S-LRP) or relative to the onset of the response (LRP-R) (e.g., Masaki et al., 2004) and this allows one to dissect premotor from motor processing: The S-LRP interval reflects the duration of premotor stages (perception and response selection) whereas the LRP-R interval reflects the duration of motor stages (motoric activation, initiation, and execution). Thus, an RT effect of an experimental manipulation can be localized to premotor and/or motor processing stages by examining whether this manipulation influences the duration of the S-LRP and/or LRP-R interval.

To provide a strong test regarding the dissociation of parallel premotor and/or motor processing, we manipulated the relative probability of responding to T_p versus T_b in the PP paradigm, because this manipulation has been shown to strongly encourage parallel task processing to optimize task performance in a previous study (Miller & Tang, 2021)—an obvious prerequisite to meaningfully investigate the processing locus/loci of

parallel processing. This is an important experimental design feature, because without such performance incentives participants are implicitly encouraged to strategically process two tasks serially to improve overall performance—as is typically the case in a PRP setting—even though they might be capable of parallel processing when it is efficient (e.g., Fischer et al., 2018; Meyer & Kieras, 1997a; Miller et al., 2009). Thus, in “high-background” (HiBac) blocks of the present experiment, most trials had no-go stimuli in the primary task, so T_b responses were required in most trials of these blocks, whereas the corresponding task probabilities were reversed in “high-primary” (HiPri) blocks.

On a behavioral level, we measured reaction time (RT) and percentage errors (PE) and we expected to replicate the three behavioral markers indicating parallel processing observed by Miller and Tang (2021) in the modified experimental set up of the present experiment. First, BCEs should be larger in HiBac compared to HiPri blocks. Second, PRP effects (i.e., reduced RT_b with longer SOA) should be smaller in HiBac compared to HiPri blocks. As the third and strongest marker of parallel processing, we also expected to replicate the surprising finding of this earlier study that T_b responses were even faster than T_p responses (Miller & Tang, 2021): Considering that participants can actually only execute T_b responses after making the T_p no-go decision, this behavioral marker suggests that they must have processed T_b to a large degree in parallel during T_p processing.

The main question of the present study is whether these three markers of increased parallel processing with larger background task probabilities were at least partly driven by background T_b motor processing (e.g., motor activation) that might have taken place during primary T_p processing. To see how the present LRP analyses can help to disentangle parallel premotor from motor processing, consider how the two standard accounts of dual-task interference could accommodate the behavioral effects in the idealized stage diagram in Figure 2.² For the sake of simplicity, we assume that the strong focus on T_p in HiPri blocks will encourage participants to *strategically* process the two tasks in serial order in those blocks (even if they could in principle process the two tasks in parallel). Thus, Figure 2a can be seen as a baseline condition, because this condition cannot by itself distinguish between serial and parallel processing (and serial processing is in principle compatible with both resource-sharing and RSB models).

Critically, both RSB (Figure 2b) and resource-sharing (Figure 2c) models could with some additional

²Preregistered hypotheses and planned analyses are available at <https://osf.io/ba29r>

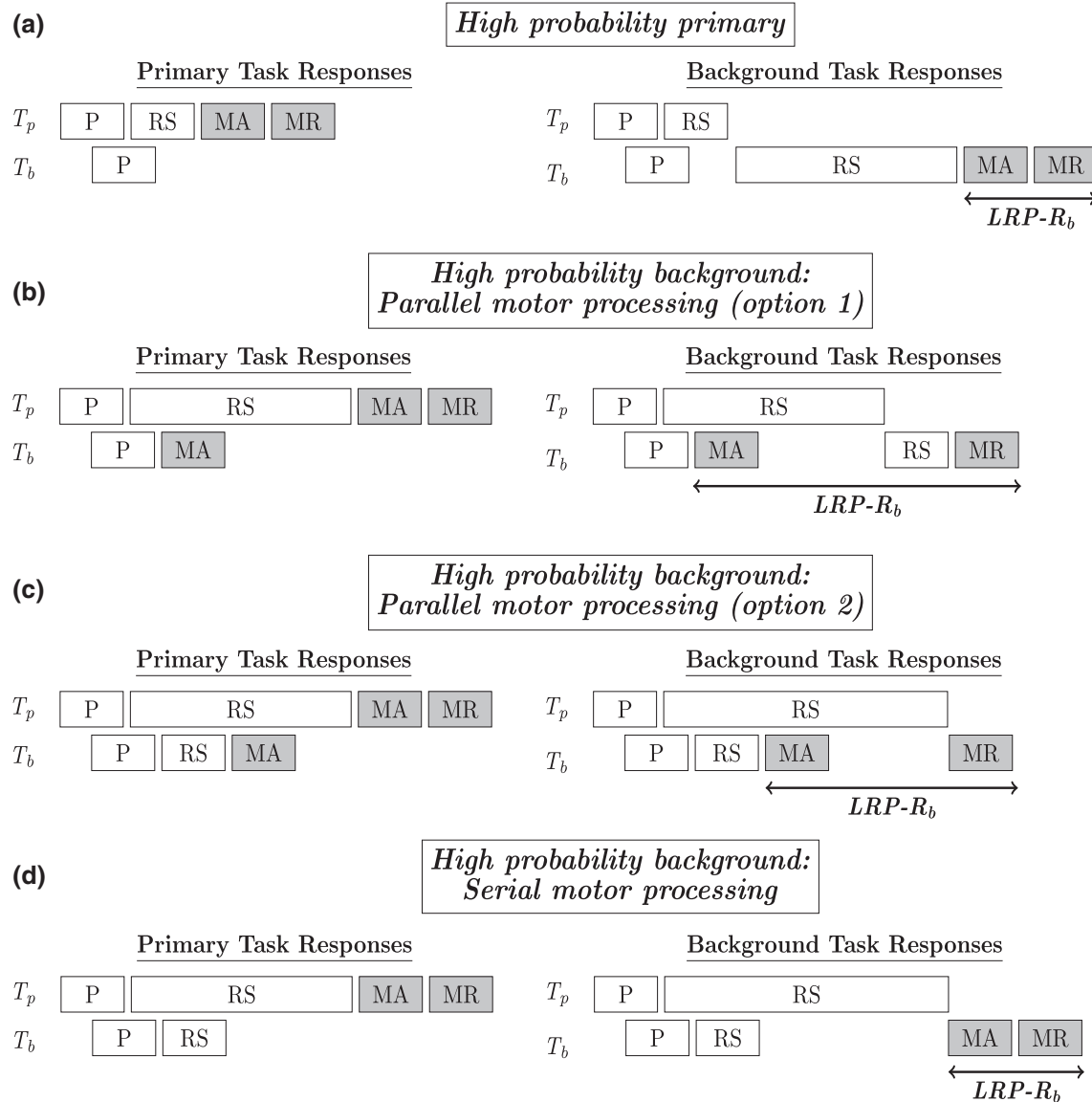


FIGURE 2 Depictions of idealized processing sequences for the primary task (T_p) and background task (T_b) with different premotor (i.e., perception [P] and response selection [RS]) and motor stages (i.e., motor response activation [MA] and motor response execution [MR]) intervening between stimuli and overt responses. The processing sequences on the left (right) side reflect trials in which a primary (background) task response was required. The length of the double-arrow lines reflect the predicted response-locked interval from the onset of lateralized readiness potential (LRP) to an overt T_b response (i.e., LRP- R_b). (a) Predicted processing sequences in blocks in which primary task responses have a high probability. (b) Predicted processing sequences in blocks in which background task responses have a high probability and parallel T_b motor activation during T_p response selection automatically begins after perceptual processing of T_b . (c) Predicted processing sequences in blocks in which background task responses have a high probability and parallel T_b motor activation during T_p response selection begins after a resource-limited response selection process of T_b . (d) Predicted processing sequences in blocks in which background task responses have a high probability and serial T_b motor activation begins after the T_p response selection has been completed

assumptions related to motor processing explain the behavioral differences that are observed between the HiPri and HiBac conditions. For example, within extended RSB models, the strength of automatically triggered T_b motor activation might be modulated by the task proportion manipulation—potentially in an analogous manner as task-irrelevant motor activation in conflict task paradigms is sensitive to experimental manipulations like

conflict proportion (e.g., Gratton et al., 1992; Logan & Zbrodoff, 1979; Stürmer et al., 2002). Alternatively, within resource-sharing models, most resources would presumably be used to select T_b responses in parallel to T_p processing in HiBac blocks, so T_b motor activation might also start before the T_p response selection process has been completed. Thus, within both types of models, it is conceivable that stronger T_b motor activation in

HiBac than HiPri blocks more strongly interferes with ongoing T_p response selection processes. When the T_p response selection process finishes and a T_b response is required (i.e., a no-go T_p response was selected), this response could already have been prepared, which in turn would speed up motor processing times leading to faster RTs for T_b . As is illustrated in Figure 2b,c, this implies that the LRP- R_b interval (i.e., in trials with T_b responses) should be shorter in the HiPri compared to HiBac condition. Furthermore, if T_b motor responses can be activated in parallel with T_p processing, the analyses of stimulus-locked LRP of T_p of the backward-incompatible condition should show evidence for early incorrect motor/LRP activation before the correct T_p motor response is activated. In particular, in the HiBac condition, there should be evidence for an initial positive-going deflection indicating incorrect motor activation analogous to the so-called Gratton dip for T_p responses that has been repeatedly observed in conflict task paradigms (e.g., Gratton et al., 1992; Stürmer et al., 2002).

Alternatively, as is illustrated in Figure 2d, motor processing may take place in a serial manner—that is, there is only some overlap of parallel automatic (RSB models) or capacity-limited (resource-sharing) premotor response selection. Since this cognitive process is not related to motor activity, the LRP- R_b results should not differ between the HiPri and HiBac conditions. For example, no early incorrect motor/LRP activation would be observed in T_p trials because background-task response activation would not be carried out during primary-task processing.

As mentioned above, it is difficult to predict the outcome of this study when considering previous LRP dual-task studies using the standard PRP paradigm, because these studies do not allow clear inferences concerning the roles of premotor and motor sources of interference in producing the PRP effect and BCE.³ The major problem is that these studies required participants to first produce an overt T_1 response, so that participants may have strategically withheld the build-up of T_2 motor activation—and with that a measurable LRP of T_2 —until a T_1 response has been initiated. Furthermore, findings concerning the modulation of the LRP- R_2 interval by SOA are mixed, so the interpretation of these findings is even more problematic. Specifically, some studies have observed that this interval is increased at short compared to long SOAs (e.g., Lien et al., 2007; Sangals et al., 2004; Sommer et al., 2001) whereas others have not (e.g., Jentzsch et al., 2007; Osman & Moore, 1993). Some researchers interpret observed LRP- R_2

lengthening based on additional interference due to T_1 motor processes (e.g., Sangals et al., 2004; Sommer et al., 2001). Others rely on a purely premotor account by arguing that this modulation reveals that a parallel T_2 response selection process leads to earlier T_2 motor activation, but the execution of T_2 has to wait until the response selection process of T_1 is terminated (e.g., Lien et al., 2007).

Interestingly, however, there are two LRP studies using dual-task paradigms in which the LRP was measured in trials with only one overt T_2 response. First, Jung et al. (2020) used a PRP paradigm in which T_1 sometimes required an overt response and sometimes a no-go response. Second, Miller (2017) used a PP paradigm in which a T_b response only had to be made when T_p required no response. Across the two studies, the same pattern was found: specifically, the S_2 -LRP interval (Jung et al., 2020) and the S_b -LRP interval (Miller, 2017) increased with decreasing SOA, whereas the corresponding response-locked intervals remained relatively stable across SOAs. Interestingly, because Miller (2017) also found BCEs, the most straightforward interpretation is that both the PRP effect and the BCE occur during parallel response selection processing. Unfortunately, these two studies do not provide decisive evidence against the possibility that T_b (T_2) motor processes can take place during T_p (T_1) premotor response selection. In both of these studies (as in all other LRP dual-task studies), the instructions were to focus initially on the first task (i.e., T_1 or T_p) and to process the secondary task (i.e., T_2 or T_b) only after that task was completed. As mentioned above, such instructions implicitly encourage serial processing (e.g., Meyer & Kieras, 1997a), but T_2 motor activation during T_1 response selection might only be evident when the two tasks are processed in parallel.

As explained earlier, the present LRP experiment will address this concern by building on the recent study of Miller and Tang (2021). In each trial, a letter surrounded by a colored square was presented and these two stimuli were associated with two independent tasks (Figure 1). The probability of responding to T_p versus T_b was the main experimental factor manipulated within-subjects across blocks. In high primary blocks (HiPri), two thirds (i.e., 66.7%) of trials required T_p responses and in high background (HiBac) blocks, one third (i.e., 33.3%) of trials required T_p responses. The second within-subjects factor SOA (0 ms vs. 300 ms) was manipulated within blocks. On a behavioral level, we measured reaction time (RT) and percentage errors (PE) and we expected to replicate the behavioral findings, indicating increased parallel processing in HiBac compared with HiPri blocks observed by Miller and Tang (2021). On an electrophysiological level, we measured electroencephalogram (EEG) activity

³To our knowledge, no previous PRP study has actually examined the BCE in T_1 using EEG.

recorded over left and right motor cortices to calculate LRPs. The main question is whether the RT_p and RT_b differences that are observed between the HiPri and HiBac conditions are partly driven by T_b motor processing that is assumed to take place during T_p processing (Figure 2b,c) or not (Figure 2d).

2 | METHOD

2.1 | Participants

Thirty five⁴ people were tested at the University of Tübingen, but the data of two participants were not included in the data analyses due to not showing clear lateralized motor activity in the averaged waveform and/or poor EEG data quality (e.g., excessive number of artifacts). The remaining 33 healthy participants (22 women) ranged in age from 18 to 42 years ($M = 23.9$) and 26 were right handed. Each participant was tested in a single experimental session lasting approximately 70 min and either received course credits or money (20e) for participation. The experiment was in accordance with the ethical standards of the institutional and national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. Informed consent was obtained from all individual participants included in the study.

2.2 | Apparatus and stimuli

Stimulus presentation and recording of behavioral responses were controlled by MATLAB 2018a using the Psychophysics Toolbox extensions (Brainard, 1997; Kleiner et al., 2007; Pelli, 1997). All visual stimuli were presented on a black background on a 21 inch (1,280 × 960) CRT monitor running at 100 Hz, viewed from a distance of approximately 75 cm. In each trial, a letter was presented in white font surrounded by a colored outline square (1.8 cm in height and width). A centrally positioned white plus sign served as fixation point. For each participant, two letters and two colors were randomly

selected out of a letter set (i.e., all consonants except L and R) and a color set (i.e., red, green, blue) and assigned to the left and right response, respectively. For half of the participants, the letter task was T_p and the color task T_b whereas this mapping was reversed for the other half of participants. Depending on whether responding to color or letter was T_p , one additional color or letter was assigned to the T_p no-go response. Responses were made with the left and right index fingers by pressing the left and right keys on an external response box.

2.3 | Procedure

Each participant was tested in 20 blocks of trials, with the first ten blocks in the HiPri condition and the last ten blocks in the HiBac condition, or the reverse (counterbalanced across participants). In HiPri blocks, two third (i.e., 66.7%) of trials required T_p responses and in HiBac blocks, one third (i.e., 33.3%) of trials required T_p responses. The first block in each task probability condition (i.e., block 1 and block 11) was a practice block with 48 trials, whereas the remaining 20 experimental blocks (i.e., 9 blocks for each task probability condition) had 96 trials each (i.e., 1728 experimental trials in total). Each block consisted of multiple (i.e., depending on task probability condition) presentations of each of the 12 possible stimulus displays/trial types (i.e., 3 stimuli for T_p , 2 stimuli for T_b , 2 SOA). Trial order was randomized separately for each block.

At the beginning of each trial, the fixation cross appeared on the screen and after 500 ms, S_p was presented on the screen. S_b appeared either simultaneously (i.e., SOA = 0 ms) or after an SOA of 300 ms. The stimuli (or stimulus) remained on the screen until the participant responded, up to a maximum of 3 s. Following correct responses, a blank screen was presented (i.e., intertrial interval, ITI) for a randomly selected time between 500 and 1,000 ms (uniform distributed) before the fixation cross of the next trial appeared. In the practice blocks, additional 500 ms were added to the ITI after correct responses. Following incorrect responses, an error screen was presented for 2 s indicating the type of error: “Error!” if the wrong key was pressed, “Too slow!” if participants did not respond within the response deadline, “Too fast!” if participants did respond in T_b trials before S_b was presented.

Participants were instructed that they should respond only to T_p in trials where S_p was assigned to the left or right response, ignoring S_b in those trials. They were told to respond to S_b in trials where the no-go S_p was presented. For example, one participant with letter task as T_p received the following written instructions which were paraphrased by the experimenter:

⁴As can be seen in our preregistration, we had initially planned to test 40 participants. However, we had decided to stop data collection when Covid-19 happened. Note that the sample size of 40 participants was somewhat arbitrarily yet conservatively set, because we had no information about the possible effects size and we wanted to compensate for potential dropouts. Note also that a power analysis to detect a medium sized effect ($d = 0.50$) of longer LRP- R_b intervals in HiBac compared with HiPri blocks (as described in our preregistration) with a power level of 80% and a significance level of 5% would have suggested 27 (one-sided) participants.

The first priority is to respond to the letter: If the letter is Z, respond with the left index finger. If the letter is K, respond with the right index finger. If the letter is P, respond based on the square (second priority): If the square is green, respond with the left index finger. If the square is blue, respond with the right index finger.

2.4 | Electrophysiological recording

The EEG and the electrooculogram (EOG) recordings were sampled at 512 Hz. We used a BioSemi Active-Two amplifier system and followed our standard laboratory routine in recording activity continuously from 72 Ag-AgCl electrodes, including C3 and C4 electrodes for LRP calculation, which are roughly located over the left and right hand area of the primary motor cortex, respectively. All ERP analyses were performed using EEGLAB (Delorme & Makeig, 2004), FieldTrip (Oostenveld et al., 2011), and custom MATLAB scripts. One analysis epoch was chosen for all analyses starting 500 ms before the onset of the task stimulus requiring a response and lasting 3.5 s. Off-line, all EEG channels were recalculated to an average reference and high-pass filtered (0.1 Hz, 30 dB/oct). Next, using a procedure similar to that by Nolan et al. (2010), (ocular) artifacts were removed and EEG data were corrected. The exact steps involved in this procedure are described next. A predefined z -score threshold of ± 3 was used for outlier identification (relating to channels, epochs, independent components, and single channels in single epochs). First, epochs containing extreme values in single electrodes (values larger than $\pm 1,000 \mu\text{V}$) were removed, as were trials containing values exceeding $\pm 75 \mu\text{V}$ in multiple electrodes if independent of the EOG activity. Second, z -scored variance measures were calculated for all electrodes, and noisy EEG electrodes (z score $> \pm 3$) were removed if their activity was uncorrelated to EOG activity. Third, this EEG data set was subjected to a spatial independent components analysis (ICA) (see infomax algorithm: Bell & Sejnowski, 1995). ICA components representing ocular activity were automatically identified using z -scored measures of the absolute correlation between the ICA component and the recorded hEOG and vEOG activity and confirmed by visual inspection before removal. Fourth, previously removed noisy channels were interpolated using the average EEG activity of adjacent channels within a specified distance (4 cm, ≈ 3 –4 neighbors).

The LRP is a measure of selective response preparation and is calculated as follows: $(\text{Mean}[C4 + C3] + \text{Mean}[C3 - C4])/2$. The stimulus-locked epoch (S-LRP) was as described above, whereas for the response-locked

epoch (LRP-R), the ERP waveforms were realigned to the response onset. For the LRP analysis, the signal at each electrode site was low-pass filtered (4 Hz, 36 dB/oct). The S-LRP waveforms were aligned to 200 ms baseline before the onset of the critical stimulus. The LRP-R waveforms were aligned to a 200 ms baseline starting 600 ms before response execution. LRP onsets were measured and analyzed by applying the jackknife-based procedure suggested by Miller et al. (1998) and Ulrich and Miller (2001). Specifically, n different grand average LRPs for each of the experimental conditions were computed by omitting from each grand average the data of another participant. S-LRP onsets were measured aligned to a 200 ms pre-stimulus baseline using a 50% of max peak amplitude within the time-window 200–500 ms post stimulus onset. LRP-R onsets were measured aligned to a 200 ms baseline that started 500 ms before the response using a 90% of max peak amplitude within the time-window -300 – 0 ms before overt response. All statistical analyses were performed by means of repeated-measures analysis of variance (ANOVA) and paired t -tests. For the LRP onsets, the F values were corrected as follows: $F_c = F/(n-1)^2$, where F_c denotes the corrected F -value and n the number of participants (Ulrich & Miller, 2001).

3 | RESULTS

3.1 | Behavioral results

First, the two practice blocks were excluded from any analyses and the remaining trials were used for percentage error (PE) analyses. For RT analyses, we only included correct trials (95.1% of all trials). From the correct trials, we additionally identified and excluded trials with RTs longer than 2 s (0.7%) as outliers. For percentage error (PE) analyses, only correct and choice error trials were included (99.6% of all trials).⁵

3.1.1 | Overall RT and PE analyses

Figure 3a,b show the overall mean RT for the primary and background tasks as a function of task probability separately for the two SOA conditions. A $2 \times 2 \times 2$ ANOVA with the within-subject factors of response task (T_p vs. T_b), task probability (HiPri vs. HiBac), and SOA (0, 300) on these means revealed a significant main effect of response task, $F(1, 32) = 32.53$, $p < .001$, $\eta_p^2 = 0.50$. T_p responses (642 ms) were on average slower than T_b

⁵Very similar behavioral results were also obtained when using the same trials used for the electrophysiological analyses.

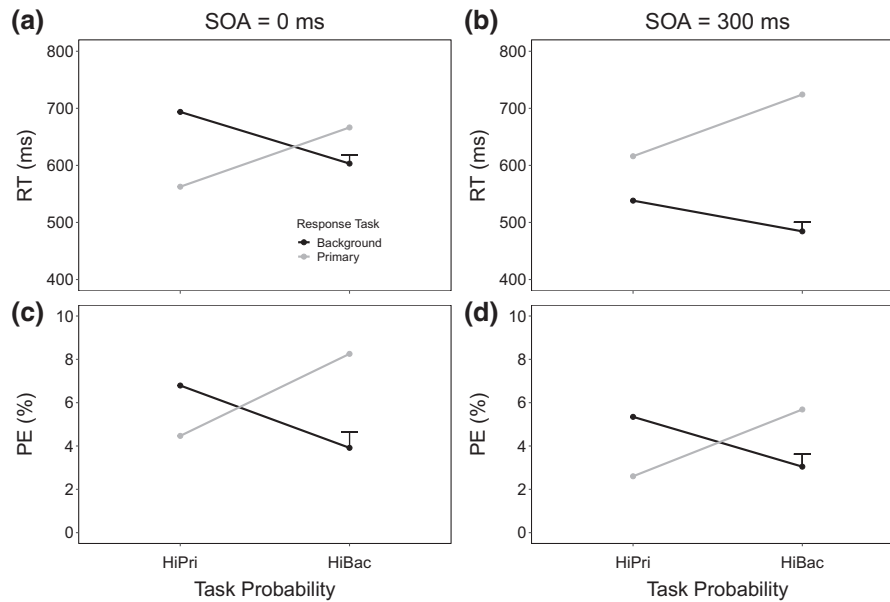


FIGURE 3 (a) Mean reaction time (RT) as a function of response task (primary, background) and task probability (High Primary, High Background) for the stimulus onset asynchrony (SOA) = 0 ms condition. (b) Mean RT as a function of response task and task probability for the SOA = 300 ms condition. (c) Mean percentage errors (PE) as a function of response task and task probability for the SOA = 0 ms condition. (d) Mean PE as a function of response task and task probability for the SOA = 300 ms condition. The error bars in A, B, C, and D indicate 1 SE (standard error) based on the pooled error terms of the two main effects and the interaction for the specific SOA condition

responses (580 ms). The main effect of SOA was also significant, $F(1, 32) = 63.02$, $p < .001$, $\eta_p^2 = 0.66$, indicating on average faster responses for SOA = 300 (591 ms) compared with SOA = 0 (632 ms). Furthermore, there was a significant two-way interaction between SOA and response task, $F(1, 32) = 483.81$, $p < .001$, $\eta_p^2 = 0.94$. For SOA = 0, T_p responses (615 ms) were faster than T_b responses (670 ms). For SOA = 300, T_p responses (648 ms) were considerably slower than T_b responses (511 ms). Viewed from another perspective, the SOA effect was reversed for T_p as compared with T_p responses. There was also a significant two-way interaction between SOA and task probability, $F(1, 32) = 11.45$, $p = .002$, $\eta_p^2 = 0.26$. For SOA = 0, responses were on average only slightly faster in HiPri blocks (628 ms) than in HiBac blocks (635 ms), whereas for SOA = 300, the difference in RT between HiPri blocks (577 ms) and HiBac (604 ms) was larger. Most important, the two-way interaction between response task and task probability was also significant, $F(1, 32) = 151.80$, $p < .001$, $\eta_p^2 = 0.83$. In HiPri blocks, T_p responses (589 ms) were slightly faster than T_b responses (616 ms). In HiBac blocks, T_p responses (695 ms) were considerably slower than T_b responses (544 ms). Finally, there was also a significant three-way interaction between all factors, $F(1, 32) = 11.07$, $p = .002$, $\eta_p^2 = 0.23$. Separate ANOVAs were conducted for each SOA condition. For SOA = 0, there was a significant main effect of response task ($p = .003$, $\eta_p^2 = 0.24$)

and a significant interaction ($p < .001$, $\eta_p^2 = 0.83$). For SOA = 300, there were significant main effects of response task ($p < .001$, $\eta_p^2 = 0.83$) and task probability ($p = .041$, $\eta_p^2 = 0.12$) as well as a significant interaction ($p < .001$, $\eta_p^2 = 0.79$).

Figure 3c,d show that the corresponding mean PE pattern mirrors the one found for RTs. A $2 \times 2 \times 2$ ANOVA parallel to the one on mean RTs revealed a significant main effect of SOA with more errors at SOA = 0 (5.9%) than at SOA = 300 (4.2%), $F(1, 32) = 26.79$, $p < .001$, $\eta_p^2 = 0.46$. There was also a significant interaction between response task and task probability, $F(1, 32) = 63.08$, $p < .001$, $\eta_p^2 = 0.66$. In HiPri blocks, T_p responses (3.6%) were less error-prone than T_b responses (6.1%), whereas in HiBac blocks, T_p responses (6.9%) were more erroneous than T_b responses (3.5%).

3.1.2 | Primary task: RT_p and PE_p analyses

Figure 4a shows mean RT_p as a function of SOA, task probability and backward compatibility. A $2 \times 2 \times 2$ ANOVA with the three within-subject factors of task probability, backward compatibility, and SOA was conducted on these means. All main effects were significant with all $ps < .001$ and all $\eta_p^2s > 0.63$. Furthermore, the interaction of SOA with compatibility was significant,

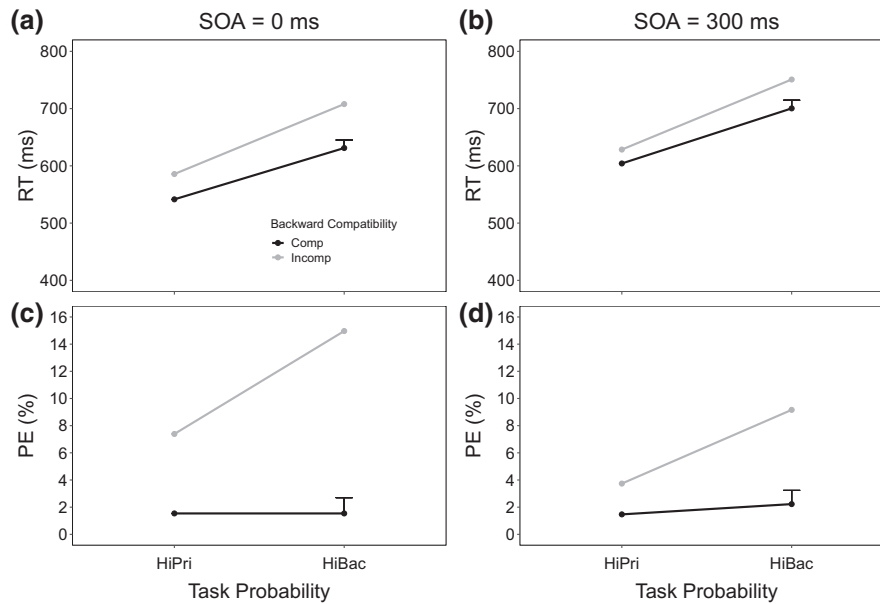


FIGURE 4 A. Mean reaction time (RT) as a function of task probability (High Primary, High Background) and backward compatibility (compatible, incomp) for the stimulus onset asynchrony (SOA) = 0 ms condition. (b) Mean RT as a function of task probability and backward compatibility for the SOA = 300 ms condition. (c) Mean percentage errors (PE) as a function of task probability and backward compatibility for the SOA = 0 ms condition. (d) Mean PE as a function of task probability and backward compatibility for the SOA = 300 ms condition. The error bars in A, B, C, and D indicate 1 SE (standard error) based on the pooled error terms of the two main effects and the interaction for the specific SOA condition

$F(1, 32) = 7.83, p = .009, \eta_p^2 = 0.20$, reflecting a larger BCE at SOA = 0 (61 ms) than at SOA = 300 (38 ms). Importantly, the BCE was also strongly modulated by task probability, $F(1, 32) = 15.10, p < .001, \eta_p^2 = 0.32$. As predicted, the BCE was larger in HiBac blocks (66 ms) than in HiPri blocks (34 ms).

Figure 4b shows the corresponding mean PE_p pattern. All main effects were significant with all $ps < .002$, all $\eta_p^2s > 0.31$. Furthermore, the error-BCE was significantly modulated by SOA, $F(1, 32) = 13.68, p = .001, \eta_p^2 = 0.30$, indicating that the BCE was again larger with SOA = 0 (9.7%) than with SOA = 300 ms (4.7%). There was also an interaction between compatibility and task probability, $F(1, 32) = 41.79, p < .001, \eta_p^2 = 0.57$. As shown in Figure 4b, the BCE was larger in HiBac (10.1%) compared with HiPri (4.1%) blocks.

3.1.3 | Background task: RT_b and PE_b analyses

Figure 5a shows mean RT_b as a function of task probability and SOA. A 2×2 ANOVA with these two factors revealed that all effects were significant: First, the main effect of SOA indicated that responses were slower at SOA = 0 than at SOA = 300 (648 ms vs. 511 ms = PRP effect of 137 ms), $F(1, 32) = 476.01, p < .001, \eta_p^2 = 0.94$. Second, the

main effect of task probability reflected faster responses in HiBac (544 ms) compared with HiPri (616 ms) blocks, $F(1, 32) = 23.50, p < .001, \eta_p^2 = 0.42$. Third, the significant interaction reflected a larger PRP effect (i.e., steeper slope) in HiPri compared with HiBac blocks, $F(1, 32) = 19.35, p < .001, \eta_p^2 = 0.38$.

Figure 5b shows the mean PE_b pattern. The corresponding ANOVA yielded a significant main effect of task probability with fewer errors in HiBac (3.5%) compared with HiPri (6.1%) blocks, $F(1, 32) = 34.87, p < .001, \eta_p^2 = 0.52$. There was also a significant main effect of SOA reflecting more errors at SOA = 0 (5.4%) than at SOA = 300 (4.2%), $F(1, 32) = 13.16, p = .001, \eta_p^2 = 0.29$.

3.2 | Electrophysiological results

We only used correct trials with RTs more than 200 ms and less than 2 s. From these trials, we excluded trials that were contaminated due to EEG artifacts (11%).

3.2.1 | Primary task: S_p -LRP intervals

Figure 6a,b show the stimulus-locked filtered LRP activations for T_p as a function of task probability (HiPri vs. HiBac) and backward compatibility (compatible vs.

FIGURE 5 (a) Mean reaction time (RT) for the background task as a function of task probability (High Primary, High Background) and stimulus onset asynchrony (SOA) (0, 300). (b) Mean error rates (PE) for the background task as a function of task probability and SOA 0, 300. The error bars in A and B indicate 1 SE (standard error) based on the pooled error terms of the two main effects and the interaction

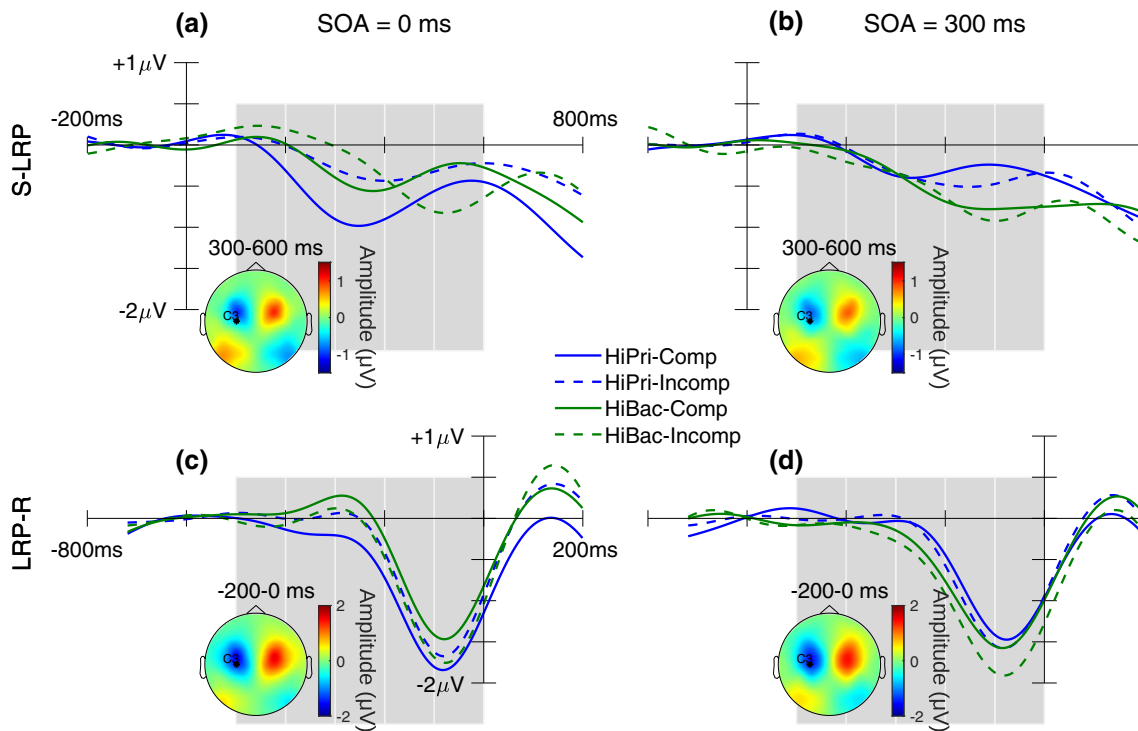
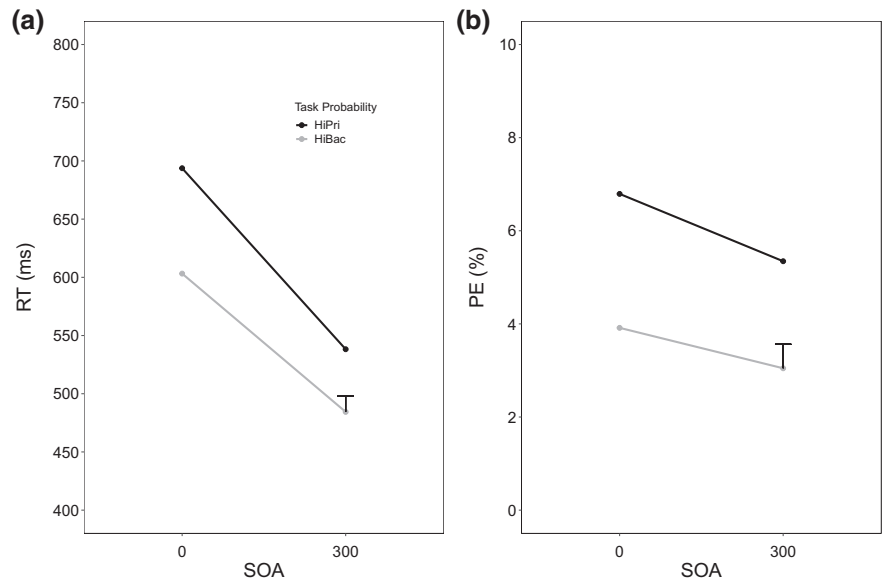


FIGURE 6 (a) Stimulus-locked LRP (S-LRP) activations for the primary task as a function of task probability (High Primary, High Background) and backward compatibility (compatible versus incompatible) for stimulus onset asynchrony (SOA) = 0 ms. (b) S-LRP activations for the primary task as a function of task probability and backward compatibility for SOA = 300 ms. (c) Response-locked LRP (LRP-R) activations for the primary task as a function of task probability and backward compatibility for SOA = 0 ms. (d) LRP-R activations for the primary task as a function of task probability and backward compatibility for SOA = 300 ms. The respective topographic plots represent the combined lateralized activity across the respective conditions within the corresponding plot pane

incompatible) separately for SOA = 0 and SOA = 300. A $2 \times 2 \times 2$ ANOVA with the corresponding three within-subject factors on the jackknifed LRP onsets revealed a significant main effect of task probability, $F(1, 32) = 9.00$, $p = .005$, $\eta_p^2 = 0.22$, indicating smaller S_p -LRP latencies in HiPri (253 ms) compared to HiBac (336 ms) blocks.

There was also a significant main effect of backward compatibility, $F(1, 32) = 8.30$, $p = .007$, $\eta_p^2 = 0.21$, reflecting an overall BCE of $325 - 263 = 62$ ms. No other effects were significant (with all $ps > .17$ and all $\eta_p^2s < 0.06$). For completeness, we also conducted a 2×2 ANOVA with the factors task probability and compatibility

separately for each SOA condition. For SOA = 0, there were main effects of task probability, $F(1, 32) = 7.43$, $p = .010$, $\eta_p^2 = 0.18$, and compatibility, $F(1, 32) = 12.88$, $p = .001$, $\eta_p^2 = 0.29$, but no significant interaction ($p = .142$ and $\eta_p^2 = 0.07$). Thus, the BCE was only numerically larger in HiBac ($402-274 = 128$ ms) than in HiPri blocks ($275-227 = 48$ ms). For SOA = 300, there was only a significant main effect of task probability, $F(1, 32) = 4.41$, $p = .044$, $\eta_p^2 = 0.12$ (with all other $ps > .26$ and $\eta_p^2s < 0.04$). Note that with this SOA the BCE was numerically rather of similar size in HiBac ($353-315 = 38$ ms) and HiPri blocks ($270-237 = 33$ ms).

3.2.2 | Primary task: S_p -LRP amplitudes

Mean amplitudes were computed in 100-ms intervals from 100 to 600 on unfiltered waveforms.⁶ To check for the presence of a positive dip in the first three intervals, we first directly compared the mean amplitudes of the HiBac-Incomp and HiPri-Incomp in the conditions with larger overlap in processing (i.e., SOA = 0) via t -tests against zero. However, there were no significant effects for either HiBac-Incomp (first interval: $p = .474$ with 95%-CI [-0.18 0.38]; second interval: $p = .243$, [-0.14 0.54]; third interval: $p = .774$, [-0.30 0.40]) or HiPri-Incomp (first interval: $p = .641$, [-0.14 0.22]; second interval: $p = .475$, [-0.17 0.36]; third interval: $p = .345$, [-0.51 0.19]). For completeness, we then also conducted $2 \times 2 \times 2$ ANOVAs on each of the five individual interval amplitude means including the factors task probability, compatibility, and SOA. At the third interval, there was a marginally significant main effect of compatibility ($p = .081$; $\eta_p^2 = 0.09$) and a marginally significant task probability \times SOA interaction ($p = .073$; $\eta_p^2 = 0.10$). At the fourth interval, there was a significant main effect of compatibility ($p = .027$; $\eta_p^2 = 0.14$) and a marginal SOA \times Compatibility interaction ($p = .077$; $\eta_p^2 = 0.10$).

3.2.3 | Primary task: LRP- R_p intervals

Figure 6c,d show the response-locked LRP activations for T_p as a function of task probability (HiPri vs. HiBac) and backward compatibility (compatible vs. incompatible) separately for SOA = 0 and SOA = 300. A $2 \times 2 \times 2$ ANOVA with the corresponding three within-subject factors on the jackknifed LRP onsets revealed no significant effects (with all $ps > .13$ and $\eta_p^2s < 0.07$ and all mean latencies were in a range from 113 to 127 ms).

⁶Very similar results were also obtained in all analyses on filtered waveforms.

3.2.4 | Primary task: LRP- R_p amplitudes

Mean amplitudes were computed in 100-ms intervals from -500 to 0 on unfiltered waveforms. As for the stimulus-locked amplitudes, we then conducted $2 \times 2 \times 2$ ANOVAs on amplitude means of the single intervals. At the second interval, there was a marginally significant task probability \times SOA interaction ($p = .091$; $\eta_p^2 = 0.09$). At the third interval, there was a significant main effect of SOA ($p = .022$; $\eta_p^2 = 0.15$) and a significant interaction of task probability \times SOA ($p = .021$; $\eta_p^2 = 0.16$). At the fourth interval, there was a significant interaction of task probability \times SOA ($p = .040$; $\eta_p^2 = 0.13$). At the fifth interval, there was a significant interaction of task probability \times compatibility ($p = .037$; $\eta_p^2 = 0.13$).

3.2.5 | Background task: S_b -LRP intervals

Figure 7 shows the stimulus-locked LRP activations for T_b as a function of task probability (HiPri vs. HiBac) and SOA (0 ms vs. 300 ms). A 2×2 ANOVA with the corresponding two within-subject factors on the jackknifed LRP onsets revealed only a marginally significant main effect of SOA, $F(1, 32) = 3.23$, $p = .082$, $\eta_p^2 = 0.09$, reflecting larger S_b -LRP latencies at short (298 ms) compared with long SOA (249 ms). No other effects were significant (with all $ps > .27$ and all $\eta_p^2s < 0.04$), but S_b -LRP intervals were numerically larger in HiPri than in HiBac blocks for both SOA = 0 (310-285 = 25 ms) and for SOA = 300 (260-237 = 23 ms).

3.2.6 | Background task: S_b -LRP amplitudes

Mean amplitudes were again computed in 100-ms intervals from 100 to 600 on unfiltered waveforms, and a 2×2 ANOVA was conducted on these interval mean amplitudes. There were (marginal) significant main effects of SOA at the second ($p = .037$; $\eta_p^2 = 0.13$), third ($p < .001$; $\eta_p^2 = 0.42$), fourth ($p < .001$; $\eta_p^2 = 0.34$), and fifth interval ($p = .049$; $\eta_p^2 = 0.12$). There were also significant main effect of task probability at the third ($p = .052$; $\eta_p^2 = 0.11$) and fourth ($p = .013$; $\eta_p^2 = 0.18$) intervals.

3.2.7 | Background task: LRP- R_b intervals

Figure 7 shows the response-locked LRP activations for T_b as a function of task probability (HiPri vs. HiBac) and SOA (0 vs. 300). Critically, a 2×2 ANOVA with the corresponding two within-subject factors on the jackknifed LRP onsets revealed no significant effects (with all $ps > .43$ and all

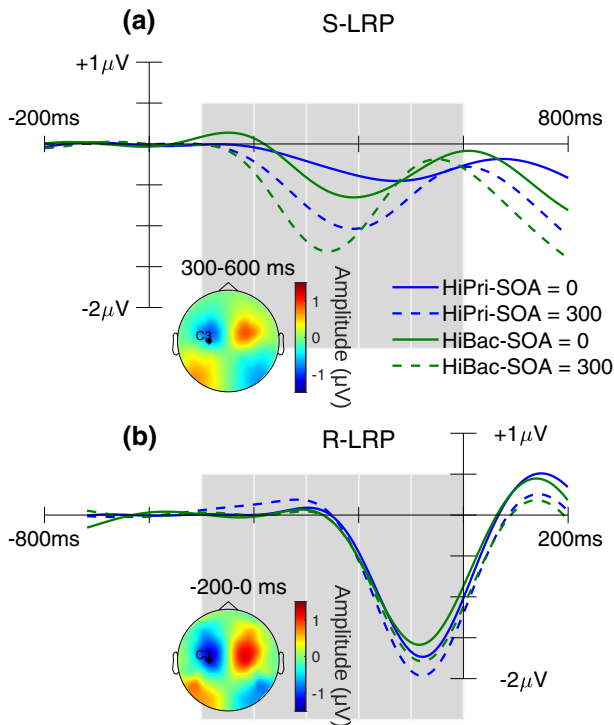


FIGURE 7 (a) Stimulus-locked LRP activations for the background task as a function of task probability (High Primary, High Background) and stimulus onset asynchrony (SOA) (0 ms, 300 ms). (b) Response-locked LRP (LRP-R) activations for the background task as a function of task probability and SOA. The respective topographic plots represent the combined lateralized activity across the respective conditions within the corresponding plot pane

$\eta_p^2 < 0.02$). For SOA = 0, the LRP-R_b interval was numerically only slightly larger in the HiBac (121 ms) than in HiPri (114 ms) blocks and for SOA = 300, these mean interval values were identical (HiBac = HiPri = 115 ms).

3.2.8 | Background task: LRP-R_b amplitudes

Mean amplitudes were again computed in 100-ms intervals from 0 to -500 on unfiltered waveforms, and 2×2 ANOVAs were conducted on these interval mean amplitudes. There was a marginally significant effect of SOA at the first interval ($p = .080$; $\eta_p^2 = 0.09$). At the fifth interval, there were marginally significant effects of task probability ($p = .079$; $\eta_p^2 = 0.09$) and SOA ($p = .107$; $\eta_p^2 = 0.08$).

4 | DISCUSSION

In the present study, we monitored motor-related EEG activity when people performed two tasks concurrently to evaluate the hypothesis that dual-task interference arises

at least partially due to parallel motor activation. To this end, we dissociated premotor from motor processing via stimulus-locked and response-locked LRP analyses in a dual-task environment in which participants were required to perform a background task (T_b) only when the primary task (T_p) required no response. Importantly, the behavioral effects of a task probability manipulation showed clear signs of parallel processing—that is, T_b responses were faster, PRP effects were smaller, and BCEs were larger when there was a larger probability that this task required a response. Critically, the LRP results were generally consistent with parallel processing during premotor stages but there was no evidence of parallel motor processing. Specifically, the stimulus-locked analysis of T_p showed no evidence for incorrect motoric response activation when the T_b response was incompatible, and the response-locked analysis of T_b showed no evidence of motor activation associated with this task during T_p processing.

Thus, the present behavioral and psychophysiological results provide evidence for multitasking interference (i.e., BCE and PRP effect) arising solely during premotor processes when potential extra motor-level interference caused by coupling two overt responses is eliminated. Since there was no evidence of parallel motor activation even when there was no overt primary task response, it seems likely that cognitive control processes serve to prevent the concurrent activation of motor responses related to a not-yet relevant (background) task goal. As elaborated next, these findings have implications for studies conceptualizing multitasking decrements in terms of response selection and response activation within bottleneck versus resource-sharing accounts.

4.1 | Response selection and response activation in multitasking: Implications for bottleneck and resource-sharing accounts

To reconcile the standard RSB model with BCEs, extended RSB models have been proposed according to which early automatic response activation produced by a background task stimulus can take place in parallel with primary task processing. However, it is somewhat ambiguous whether response activation reflects activation of a general (premotor) response code or *motoric* response activation. Inspired by LRP findings across a variety of different conflict paradigms (e.g., Dudschig & Kaup, 2018; Eimer, 1995; Freitas et al., 2009; Fröber et al., 2017; Gratton et al., 1992; Jost et al., 2017; Logan & Zbrodoff, 1979; Mattler, 2003; Stürmer et al., 2002), we expected to observe early incompatible motor activation in the present study. Critically, however, there were

no signs of any incorrect early LRP activation related to T_b during stimulus-locked intervals of T_p , even though the size of BCE was substantial (i.e., 128 ms in HiBac). Furthermore, there was no evidence that the finding of faster T_b compared with T_p RTs in HiBac blocks was at least partially due to parallel motor preparation, since there was little if any effect of the probability manipulation on the time from LRP onset of T_b to the key press. Thus, it appears that T_b -related motor activation did not begin automatically after the perceptual stage finished but before the serial response selection stage began, as could be assumed by extended RSB models.

Thus, to reconcile the present findings with extended RSB models, it seems necessary to assume that automatic response activation is not related to motor cortex activity and instead reflects automatic premotor activation produced by S_b that precedes a controlled T_b response selection but overlaps with the controlled T_p response selection process. Of course, this assumption would have to include the idea that participants had some kind of control over this automatic non-motor response activation, because the behavioral effects were strongly influenced by the anticipated processing requirements (i.e., task probabilities). Furthermore, it may be also possible that at least some dual-task interference occurs during early perceptual processing (e.g., Brisson & Jolicœur, 2007; Duncan et al., 2021; Wirth et al., 2020), but this explanation would be also at odds with the assumption of extended RSB models that serial response selections and parallel motor response activations are responsible for all interference.

Instead of adding additional assumptions to RSB models, however, it seems that resource-sharing accounts allow a more parsimonious explanation to reconcile BCEs with the finding that T_b motor response activation only began after a T_b response was selected. Contrary to extended RSB models, these accounts allow parallel processing of two tasks during response selection (cf. Figure 2d). Thus, these models could account for the LRP findings that compatibility and task probability affected the duration of processes operating before the beginning of either T_p or T_b motoric response activation by assuming that processing resources needed for response selection are divided based on task probabilities.⁷

⁷It also seems that resource-sharing models provide a plausible post-hoc explanation for the finding that T_b responses in HiBac blocks were even faster than T_p responses in HiPri blocks when the SOA was 300 ms. Specifically, it seems conceivable that participants preallocate (“save”) processing resources to T_b in both HiPri blocks and HiBac blocks. For example, they can allocate 90% (10%) of processing resources to T_p and the remaining 10% (90%) resources to T_b in HiPri (HiBac) blocks. Assuming that a T_p no-go response selection is made within 300 ms, they can quickly reallocate all resources to the T_b meaning that with SOA = 300 T_b is actually sometimes processed with 100% of processing resources.

Considering that motoric response activation directly follows response selection (or might even take place before a response selection process is fully completed), however, it would also have been possible that parallel response selection processes would be followed by parallel task-specific motor activations. However, the present findings suggest that T_b is only processed during premotor stages in parallel with T_p and that the required T_b response is not activated by the motor system before T_p response selection is completed. Importantly, the progress made by processing T_b in parallel is not lost when T_p requires no response (as reflected in the T_b RT advantage in HiBac blocks). Instead, parallel T_b response selection only pauses—presumably in order to hold the build-up of motor activation in check to prevent outcome conflict (e.g., Navon & Miller, 1987).

Interestingly, there are also more detailed models of multitasking which all have in common that they assume that parallel processing is possible but constrained and coordinated by task goals (e.g., Logan & Gordon, 2001; Meyer & Kieras, 1997a, 1997b; Salvucci & Taatgen, 2008; Verbruggen et al., 2008). For example, the Executive Process/Interactive Control (EPIC) model (Meyer & Kieras, 1997a, 1997b) and the Threaded Cognition model (Salvucci & Taatgen, 2008) share the idea that multitasking reflects parallel processing of multiple sources of information with task goals strategically coordinating these multiple processing streams. Thus, it seems that these models are compatible with the finding that activating the background motor response is strategically deferred until the primary task goal is deactivated. Viewed from the response selection versus response activation stage conception applied in this study, it therefore seems that (multi-) task performance optimization is achieved via a) parallel premotor response selection processing with limited central resources allocated according to the relevance of task goals, and b) serial activation of potential motor responses based on the required task order.

4.2 | Conclusion

In sum, we narrowed the possible sources of multitasking interference to premotor rather than motor processes by monitoring movement-related ERPs. Specifically, the present results suggest that there is parallel processing of the two tasks during premotor response selection with processing resources shared based on task probabilities, but that the corresponding motor responses are activated in a serial manner according to the order of task goals (i.e., primary task goal followed by background task goal). Thus, mental representations of task goals play a crucial role in coordinating parallel multiple processing streams. These

results are thus inconsistent with accounts extending the RSB to explain the BCE in terms of automatic motor response activation, and they help to further constrain theorizing in terms of multitasking accounts that allow resource-sharing as a function of processing requirements and task goals (e.g., Logan & Gordon, 2001; Meyer & Kieras, 1997a, 1997b; Navon & Miller, 1987; Salvucci & Taatgen, 2008).

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.


AUTHOR CONTRIBUTIONS

Victor Mittelstädt: Conceptualization; Formal analysis; Methodology; Writing-original draft; Writing-review & editing. **Ian G Mackenzie:** Conceptualization; Formal analysis; Methodology; Visualization; Writing-review & editing. **Hartmut Leuthold:** Conceptualization; Methodology; Writing-review & editing. **Jeff Miller:** Conceptualization; Methodology; Writing-review & editing.

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