

# Evidence of Resource Sharing in the Psychological Refractory Period (PRP) Paradigm

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Performance is generally worse when performing multiple tasks than when performing a single task, but there is debate about whether this multitasking interference arises due to a structural bottleneck that requires serial central processing or due to resource limitations that slow processing of 2 tasks when they are carried out in parallel. The present study used a novel approach of comparing first- and second-task reaction times (RTs) within the psychological refractory period (PRP) paradigm to contrast these 2 possibilities. Counterbalancing task order across participants to control for differences in task difficulty, we found that second-task responses were faster than first-task responses at long stimulus onset asynchronies (SOAs). This second-task advantage is difficult to explain within bottleneck models, which allow the first task to be processed at full speed while the second task waits for access to the bottleneck process. Instead, the effect suggests that processing of the first task is slowed because some cognitive resources are held back in case they are needed for second-task processing. At long SOAs, all resources can be allocated to second-task processing because the first task is already completed. Thus, we propose that cognitive control processes flexibly coordinating the sharing of limited central resources may better explain dual-task performance in the PRP paradigm than bottleneck-based waiting due to structural limitations.

## Public Significance Statement

It is well known that the concurrent performance of 2 or more tasks is impaired when compared to performing the tasks separately, but there remains debate about the causes of these multitasking costs. The present findings demonstrate that these costs probably do not emerge from structural bottleneck-type limitations in the human cognitive system that require serial processing of 2 tasks. Instead, the results suggest that these costs arise because the system shares limited cognitive processing resources to process 2 tasks in parallel.

**Keywords:** resource sharing, bottleneck models, psychological refractory period (PRP), multitasking

In our technologically advanced world, we are constantly bombarded with information associated with multiple task demands. Although the simultaneous performance of two or more cognitive tasks is impaired when compared to performing the tasks separately, it seems impossible to avoid concurrent multitasking in many real-world situations (for multitasking reviews, see; e.g., Fischer & Plessow, 2015; Janczyk & Kunde, 2020; Koch et al., 2018; Musslick & Cohen, 2021; Pashler, 1994). Thus, uncovering the causes of multitasking

decrements has important practical implications (e.g., Levy, Pashler, & Boer, 2006). Furthermore, a better understanding of these decrements would provide important insights into the architecture of human cognition: Overloading the cognitive system with simultaneous processing requirements is helpful to clarify how different parts work together (e.g., Miller & Durst, 2014; Pashler & Johnston, 1998). To date, there is some general agreement regarding the crucial role of control processes attempting to optimize human multitask performance under cognitive and external processing constraints (e.g., Boag, Strickland, Loft, et al., 2019; Fischer et al., 2014). However, as is elaborated below, it is still unclear whether performance, at its core, is impaired due to structural bottleneck-type limitations that require serial processing or due to resource limitations that reduce the speed of parallel processing. Many empirical findings are in principle compatible with both views (e.g., Janczyk, Renas, & Durst, 2018; Koch et al., 2018; Miller & Durst, 2015; Verbruggen, Schneider, & Logan, 2008).

In the present study, we examine a novel diagnostic of the extent to which resources are shared between two tasks within the psychological refractory period (PRP) paradigm—a paradigm typically regarded as providing evidence in favor of bottleneck

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models. Specifically, we compared performance across the two tasks used in this paradigm, reasoning that task 1 performance should be impaired *relative to task 2 performance* if some resources are withheld from task 1 for parallel processing of task 2. The results provide evidence that cognitive limitations in dual-tasking probably do not emerge from bottleneck-based waiting but can better be conceptualized within processing architectures that incorporate the idea of cognitive control processes flexibly coordinating the sharing of limited central resources to process two tasks in parallel.

### Serial Versus Parallel (Resource-Limited) Processing in Dual-Tasking

Beginning with Telford (1931), the PRP paradigm has become the most widely used approach to study dual-task limitations (e.g., Durst & Janczyk, 2018; Pashler, 1984; Schubert & Strobach, 2018; Watter & Logan, 2006; Welford, 1952). In classic PRP studies, stimuli ( $S_1$  and  $S_2$ ) associated with two separate tasks ( $T_1$  and  $T_2$ ) are usually presented in close temporal succession, and participants are required to respond to each of the two tasks in a fixed order (e.g., Langsdorf et al., 2022; Mattes et al., 2021; Pashler, 1994; Wirth et al., 2020). For example, participants may be instructed to first decide whether a tone ( $S_1$ ) is high or low pitched by pressing the index or middle finger of the left hand and then to decide whether a letter ( $S_2$ ) is an H or S by pressing the index or middle finger of the right hand (e.g., Beste et al., 2013; Jentsch et al., 2007; Ruthruff, Johnston, et al., 2001). When the time interval between  $S_1$  and  $S_2$  (i.e., the stimulus onset asynchrony, SOA) varies unpredictably across trials, the reaction time (RT) of  $T_2$  usually decreases markedly when the SOA increases, and this finding is strong evidence of cognitive limitations in selecting responses for two tasks simultaneously (e.g., McCann & Johnston, 1992; Pashler, 1993).

Several qualitative and quantitative accounts have been proposed to explain these limitations (e.g., Byrne & Anderson, 2001; Logan & Gordon, 2001; Navon & Miller, 1987; Pashler, 1994; Salvucci & Taatgen, 2008; Smith, 1967). These accounts differ in several important respects, but at the core, they can be distinguished by whether or not they allow central resources to be divided concurrently between tasks (for an overview of such a classification, see Musslick & Cohen, 2021). Thus, parallel processing of two tasks might be possible even when central operations (e.g., response selection) are required for both tasks at the same time, and the PRP effect could be a consequence of  $T_2$  receiving only a small amount (if any) of the limited cognitive resources prior to the completion of  $T_1$  (e.g., McLeod, 1977; Mittelstädt & Miller, 2017; Navon & Miller, 2002). Note that the finite pool of cognitive resources involved in task processing may be linked to concepts like working memory (e.g., Cowan & Morey, 2007; Hazeltine & Wifall, 2011; Oberauer & Bialkova, 2009; Redick et al., 2016), selective attention (e.g., Lavie, 2005) or both—considering that these two concepts may be considered as a single system and hence tap on the same limited resources (cf. Cowan, 1988, 2008; Kiyonaga & Egner, 2013; Oberauer, 2019). In contrast to resource-sharing accounts, however, it might also be possible that structural constraints only allow central processes to operate serially on simultaneous task inputs (e.g., due to serial focus of attention, cf. Garavan, 1998). Thus, according to bottleneck accounts, the PRP effect is a consequence of the waiting time of  $T_2$  until  $T_1$  central processing has finished (e.g., Pashler & Johnston, 1989; Ruthruff, Pashler, et al., 2001; Sigman & Dehaene, 2006).

Unfortunately, there are in particular two reasons why it is quite difficult to provide decisive empirical evidence regarding these fundamentally different processing accounts (i.e., resource-sharing vs. bottleneck). First, these accounts often make the same predictions regarding the effects of experimental manipulations—including the PRP effect (e.g., Navon & Miller, 2002; Tombu & Jolicoeur, 2003). Consider also that resource-sharing accounts can even act as a strategic bottleneck by allocating all resources to  $T_1$ —a strategy which often also improves overall performance (e.g., Miller et al., 2009). Second, findings of parallel processing do not necessarily provide decisive evidence for *resource-limited* parallel processing. For example, the finding of backward-compatibility effects (BCEs) indicates that first-task processing is affected by the compatibility of  $T_2$  characteristics ( $S_2$  or  $R_2$ ) with  $T_1$  responses, suggesting that  $T_1$  and  $T_2$  processing features are at least partially activated in parallel (e.g., Hommel, 1998; Naefgen et al., 2017; Rieger & Miller, 2020; Thomson et al., 2021). However, extended bottleneck accounts can explain BCEs by assuming that parallel automatic (i.e., resource-unlimited)  $T_2$  response activation interferes with  $T_1$  processing but central (i.e., resource-limited)  $T_2$  processing still has to wait for access to the bottleneck (e.g., Hommel, 1998; Janczyk et al., 2018; Schubert et al., 2008; Thomson et al., 2015). As is reviewed next, these problems also make it difficult to clearly favor one account over the other when people adapt their dual-task processing to environmental constraints.

### Proactive and Reactive Cognitive Control in Dual-Tasking

Data from several studies suggest that people are able to proactively (i.e., in advance of stimuli, cf. Braver, 2012) bias their dual-task processing based on anticipated processing requirements (for example, Boag, Strickland, Heathcote, et al., 2019; Boag, Strickland, Loft, et al., 2019; De Jong, 1995; Koch & Prinz, 2002; Palada et al., 2019; Steinhauser et al., 2021; Strobach et al., 2021). For example, the size of the BCE decreases following backward-incompatible trials (e.g., Janczyk, 2016), and it also decreases in a context with a high proportion of backward-incompatible trials (e.g., Fischer et al., 2014). Within extended bottleneck accounts, for example, these findings could be interpreted to mean that automatic  $T_2$  activation is more strongly shielded from spilling over to  $T_1$  processing (e.g., Fischer et al., 2014; Janczyk, 2016) when it was just harmful or is expected to be harmful—similar to suggestions made in the conflict task literature (cf. Gratton et al., 1992). Alternatively, however, these findings could also be conceptualized within resource-sharing accounts according to which the cognitive system will preallocate more limited processing resources to  $T_2$  (and hence less to  $T_1$ ) in these two situations (e.g., Janczyk, 2016). Thus, it is usually ambiguous whether proactive control is actually applied to prevent between-task interference by biasing resource-limited parallel processing or by adjusting the amount of task shielding (cf. Fischer et al., 2014).

In a similar vein, it is unclear whether the finding of slower  $T_1$  responses in the PRP paradigm compared to a pure single-task setting (cf. Pashler, 1994) is due to sharing of resources or not. Specifically, it seems plausible that a division of processing resources between the two tasks occurs in advance of a trial to meet the anticipated *dual-task* processing requirements. This would slow down subsequent  $T_1$  processing (compared to single task performance), but this does not provide evidence that  $T_1$  and  $T_2$  actually share processing resources during the trial. Indeed, early advocates of

bottleneck accounts have already proposed that dual-task  $T_1$  slowing can be explained in terms of preparatory processes (i.e., proactive control) that take place before the onset of task stimuli (e.g., Gottsdanker, 1979; Pashler, 1994; Schubert, 1999; Smith, 1967).

Critically, resource-sharing accounts can also quite naturally explain findings suggesting reactive processing adjustments in dual-tasking (i.e., online processing adjustments made after the trial has already started, cf. Braver, 2012). For example, in addition to  $T_2$  performance,  $T_1$  performance is often impaired when SOA decreases (e.g., Strobach et al., 2015). This is consistent with the idea that  $S_2$  withdraws some additional limited processing resources from  $T_1$  in order to process  $T_2$  in parallel (cf. Navon & Miller, 2002; Tombu & Jolicoeur, 2003). Furthermore,  $T_1$  performance is worse in trials when  $S_2$  is presented than in trials when it is omitted (Mittelstädt & Miller, 2017), suggesting that resources are shifted from  $T_1$  to  $T_2$  when  $S_2$  appears. Moreover, this detrimental effect of  $S_2$  presentation on  $T_1$  is larger when  $T_2$  always requires a response than when it does not. Although bottleneck accounts might argue that the unpredictable onset of  $S_2$  produces a distracting effect, it is not clear which further assumptions are required to explain why such a distracting effect depends on the response-relevance of  $T_2$ . Instead, resource-sharing accounts provide a parsimonious explanation for this finding by assuming resources are reallocated after  $S_2$  onset based on the relative importance of task goals (cf. Mittelstädt & Miller, 2017).

Thus far, there seem to be good reasons to assume that cognitive control processes adjust resource-limited parallel processing because this assumption helps to explain why secondary tasks or stimuli modulate  $T_1$  performance. Importantly, the PRP effect in  $T_2$  performance could actually also reflect an interplay between cognitive control and resource sharing (cf. McLeod, 1977; Navon & Miller, 2002; Tombu & Jolicoeur, 2003). Specifically,  $T_2$  would receive only a small amount of resources for the time  $T_1$  central processing is still under way (i.e., primarily at short SOA) due to the much stronger emphasis on  $T_1$  than  $T_2$ . When  $T_1$  central processing has been completed all resources can be reallocated to  $T_2$ , so the remaining  $T_2$  processing could speed up by using full resources. The goal of the present study is to empirically assess whether the PRP effect may actually reflect such resource allocations between  $T_1$  and  $T_2$ .

### Logic of the Present Study

In each of the four experiments of this study, participants were tested in a classic PRP paradigm using two SOAs (50 ms vs. 1000 ms). In contrast to previous studies, however, we directly compared the performance between  $T_1$  and  $T_2$ . Thus, we also counterbalanced task order across participants to make sure that this comparison was not contaminated by differences in task difficulty. Our primary focus was the comparison of  $T_1$  and  $T_2$  performance at the long SOA, for which resource-sharing and bottleneck models seem to make distinct predictions. According to bottleneck accounts,  $T_1$  performance should be as good as or better than  $T_2$  performance.  $T_1$  performance should be good because this task is definitely processed with all resources. Performance of an equally-difficult  $T_2$  might be just as good since this task would also have full resources at long SOA, but  $T_2$  performance might also be worse because this task's processing might suffer from

residual activations left over from just having processed  $T_1$  (cf. Allport, Styles, & Hsieh, 1994; Altmann & Gray, 2002; Lien et al., 2003; Sohn & Carlson, 2000). Obviously, resource-sharing accounts would make similar predictions if  $T_1$  gets 100% of resources (i.e., strategic bottleneck). As mentioned above, however, although participants presumably (proactively) preallocate most processing resources to  $T_1$ , they might also save some resources for  $T_2$  processing (i.e., to be prepared for both  $T_1$  and  $T_2$ ), in which case  $T_1$  processing would not actually use 100% of resources. In contrast, under resource-sharing accounts,  $T_2$  processing could in principle use all resources if resources can flexibly be reallocated during a trial (i.e., after  $T_1$  and before  $T_2$  processing) as assumed by these accounts. Accordingly,  $T_2$  performance could be better than  $T_1$  performance at long SOAs within resource-sharing accounts, whereas bottleneck accounts would only be compatible with  $T_1$  performance being better than or equal to  $T_2$  performance.

### Experiment 1

The basic tasks used in this experiment were modeled after those used previously (e.g., Miller & Durst, 2015; Mittelstädt & Miller, 2017). In each trial, a letter surrounded by a colored square was presented and these two stimuli were associated with two independent task sets. These stimuli were presented sequentially in each trial (i.e., SOA of 50 ms or 1000 ms) and participants were required to respond to both the letter and color task stimuli in each trial. Importantly, stimulus (i.e., task) order was counterbalanced between-subjects (letter then color vs. color then letter) in order to eliminate any difference in task difficulty from the overall  $RT_1$ - $RT_2$  difference. Thus, half of the participants responded first to the letter stimulus and afterward to the color stimulus presented following the SOA, whereas the other half of participants responded first to the color stimulus and afterward to the letter stimulus presented following the SOA. Our main question related to the comparison of means between  $RT_1$  and  $RT_2$ , averaging across the color and letter tasks. As discussed in the introduction, if participants can reallocate freed-up resources after they have finished resource-limited processing of  $T_1$ , mean RT of  $T_2$  should be less than mean RT of  $T_1$ , especially at long SOA.

### Method

#### Participants

As preregistered<sup>1</sup>, 40 people were tested online, but data of two participants was excluded due to error rates larger than 30%. The final sample consisted of 38 people (33 women). They ranged in age from 18 to 28 years ( $M = 21.5$ ) and 36 were right-handed. In this and the other three experiments, participants gave informed

<sup>1</sup> Preregistration is available via the Open Science Framework (OSF) at <https://osf.io/5u6rc>. Note that a power analysis indicated we would have over 80% power to detect a significant main effect of at least  $\eta_p^2 = .18$  for the  $RT_1$  vs.  $RT_2$  comparison at the long SOA. Although the actual effect size in Experiment 1 was substantially larger (i.e.,  $\eta_p^2 = .78$ ), we proceeded with testing 40 participants in each experiment to allow for the possibility that the effect might be smaller with other tasks and in order to more meaningfully consider potential trade-offs in RTs and error rates. Note that raw data of all experiments are available via the OSF at <https://osf.io/5u6rc>.

consent before testing. Furthermore, all experiments were 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.

### Apparatus and Stimuli

This and the other three experiments reported subsequently were conducted online using the JavaScript library jsPsych (De Leeuw, 2015). All visual stimuli were presented on a gray background. In each trial, a letter was presented in black font surrounded by a colored outline square. A centrally positioned white plus sign served as fixation point. For each participant, two letters were randomly selected out of a letter set (i.e., all consonants except L, Q, P, R, Q) with one each assigned to the left index and left middle finger response. Similarly, two colors were randomly selected out of a color set (i.e., red, green, blue) with one each assigned to the right index and right middle finger response, respectively. For half of the participants, the letter task was the first task and the color task the second task whereas this mapping was reversed for the other half of participants. Responses were key presses on the “Q,” “W,” “O,” and “P” keys of a standard QWERTZ computer keyboard.

### Procedure

Each participant was tested in 1 practice block with 32 trials followed by 4 experimental blocks of 64 randomly ordered trials per block (288 trials in total). Specifically, each experimental block included eight presentations of each of the eight possible stimulus displays defined by the combinations of the two possible letters (assigned to index vs. middle fingers), the two possible squares (assigned to index vs. middle fingers) and the two possible SOAs (50 vs. 1000 ms). At the beginning of each trial, the fixation cross appeared on the screen for 500 ms.  $S_1$  (i.e., a letter or a colored square) was displayed immediately at the offset of the fixation cross and  $S_2$  was added to the display at the end of that trial's SOA. The stimuli remained on the screen until the participant responded, up to a maximum of 4 s (i.e., 4 s from onset of the first stimulus). Furthermore, each individual response had to be given within 2 s. After both required responses had been made in a trial or the maximum time had elapsed, feedback was displayed for 1 s to indicate correct responses or for 3 s indicating the type of error: “Error!” if the wrong key was pressed for at least one of the two tasks, “Too slow!” if participants did not respond within the response deadline for at least one of the tasks, and “Too fast!” if participants did respond faster than 100 ms for at least one of the two tasks. RT was measured from the onset of the stimulus to which each response was made.

The experiment started with an instructional screen describing the assignment of the tasks and stimuli. Furthermore, participants were instructed to respond as quickly and accurately as possible. These instructions were written centrally on a separate instructional screen in order to emphasize their importance. Specifically, they were instructed to respond first to  $S_1$  and then to  $S_2$ . They were explicitly told not to delay  $T_1$  responding by waiting for  $S_2$ .

### Results

The practice block was excluded from any analyses. Trials with too fast (.6%, RT < 100 ms) or too slow responses (1.0%, RT >

2000 ms) were excluded from all analyses. For RT analyses, we additionally excluded trials in which any response error was made (9.2%). For  $T_2$  error analyses, we also excluded trials in which participant responded incorrectly to  $T_1$ . We also reanalyzed the data of all experiments with three additional analyses excluding trials with interresponse stimulus intervals (ITIs) less than 50 ms, less than 100 ms, or less than 150 ms. In all cases, the results of these three additional analyses were very similar to the ones reported in the present results sections, indicating that response grouping effects are very unlikely to have contaminated the reported findings.

### Reaction Time (RT) Analyses

Figure 1A shows the mean RTs for the first and second tasks as a function of SOA separately for the 19 participants with the letter task as  $T_1$  and the color task as  $T_2$  (i.e., task order letter-color) and for the 19 participants with the color task as  $T_1$  and the letter task as  $T_2$  (i.e., task order color-letter).

As preregistered, we first conducted a mixed ANOVA with the within-subject factor of task ( $T_1$  vs.  $T_2$ ) and the between-subjects factor of task order (letter-color vs. color-letter) for trials with long SOA.<sup>2</sup> As predicted, this ANOVA revealed a significant main effect of task,  $F(1, 36) = 124.55, p < .001, \eta_p^2 = .78$ , reflecting longer mean RTs for  $T_1$  compared to  $T_2$  (620 vs. 510 ms). Furthermore, there was a significant interaction between task and task order,  $F(1, 36) = 11.59, p = .002, \eta_p^2 = .24$ . As can be seen in Figure 1A, the RT advantage for  $T_2$  over  $T_1$  was larger for participants with task order letter-color (514 vs. 657 ms) compared to participants with task order color-letter (505 vs. 582 ms), and this presumably reflects a difference in task difficulty with a slightly easier color task.

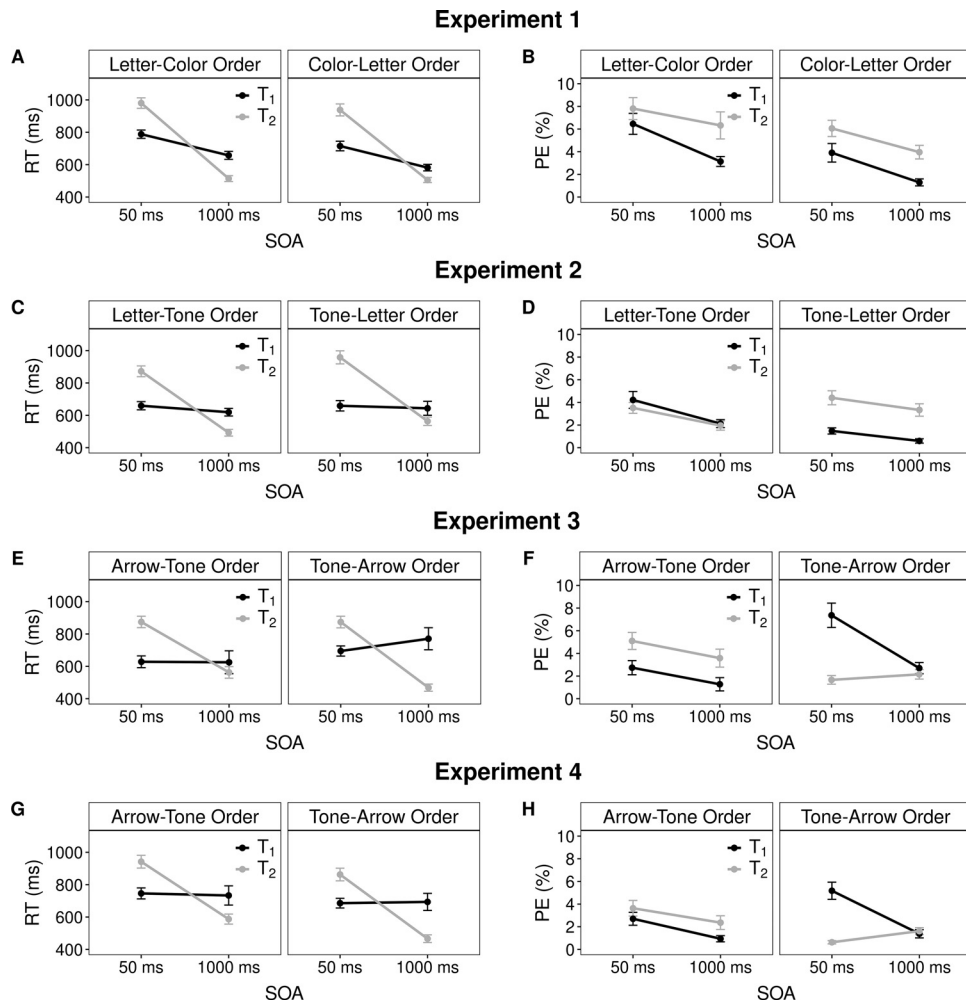
We also conducted separate mixed ANOVAs with the within-subject factor SOA and the between-subjects factor of task order for each of the two tasks. Although these analyses were not preregistered, we felt that including them would fit better with the broader literature in which performance is usually reported separately for each task. For  $T_1$ , this ANOVA yielded a significant main effect of SOA,  $F(1, 36) = 119.19, p < .001, \eta_p^2 = .78$ , reflecting longer mean  $RT_1$  for short compared to long SOA (752 vs. 620 ms). Furthermore, there was a significant main effect of task order,  $F(1, 36) = 4.91, p = .033, \eta_p^2 = .49$ , indicating longer mean  $RT_1$  with task order letter-color than color-letter (723 vs. 648 ms). For  $T_2$ , this ANOVA only yielded a significant main effect of SOA,  $F(1, 36) = 933.04, p < .001, \eta_p^2 = .96$ , reflecting longer mean  $RT_2$  for short compared to long SOA (i.e., PRP effect of  $959 - 510 = 449$  ms).

### Percentage Error (PE) Analyses

Figure 1B shows the mean PE for the corresponding conditions. The mixed ANOVA at long SOA with the factors of task and task order revealed a significant main effect of task,  $F(1, 36) = 26.32, p < .001, \eta_p^2 = .42$ . Contrary to the mean RT

<sup>2</sup>For completeness, as preregistered, we also conducted  $2 \times 2 \times 2$  mixed measures ANOVAs on both reaction time (RT) and percentage error (PE) with the within-subject factors task and SOA and the between-subject factor of task order for each experiment (see Appendix).

**Figure 1**  
*Mean Reaction Time (RT) and Mean Percentage Error (PE) as Function of Task (Task 1 [T<sub>1</sub>], Task 2 [T<sub>2</sub>]), Stimulus-Onset Asynchrony (SOA; 50 Ms, 1000 ms), and Experiment-Specific Task Order Separately for Experiment 1 (Panels A and B), Experiment 2 (Panels C and D), Experiment 3 (Panels E and F), and Experiment 4 (Panels G and H)*



*Note.* The error bars in A–H indicate standard errors of the means.

pattern, this main effect indicated smaller PEs for T<sub>1</sub> compared to T<sub>2</sub> (2.2% vs 5.1%). Furthermore, there was a significant main effect of task order, reflecting larger PEs for participants with task order letter-color compared to participants with task order color-letter (4.7% vs. 2.6%),  $F(1, 36) = 6.22, p = .017, \eta_p^2 = .15$ .

Finally, mixed measures ANOVA were conducted separately for each task. For T<sub>1</sub>, this ANOVA yielded a significant main effect of SOA,  $F(1, 36) = 30.10, p < .001, \eta_p^2 = .46$ , reflecting larger PEs for short compared to long SOA (5.2% vs. 2.2%). Furthermore, there was a significant main effect of task order,  $F(1, 36) = 7.86, p = .008, \eta_p^2 = .18$ , indicating larger PE<sub>1</sub> with task order letter-color than color-letter (4.8% vs. 2.6%). For T<sub>2</sub>, there was only a significant main effect of SOA,  $F(1, 36) = 9.06, p = .005, \eta_p^2 = .20$ , reflecting larger PE<sub>2</sub>s for short compared to long SOA (i.e., PRP effect of 6.9 – 5.1 = 1.8%).

**Discussion**

The results of this experiment revealed that RTs of T<sub>2</sub> were considerably smaller than the ones of T<sub>1</sub> at long SOA. This is in line with the idea that participants reallocate freed-up resources to process T<sub>2</sub> after they have finished resource-limited processing of T<sub>1</sub>. Unfortunately, the higher error rates for T<sub>1</sub> compared to T<sub>2</sub> at long SOA warrant some caution when interpreting this RT pattern since the RT advantage could simply be due to a speed–accuracy trade-off. To address this concern, we reanalyzed all results using several combined measures of speed and accuracy—that is, inverse efficiency score (IES; Townsend & Ashby, 1983), rate-correct score (RCS; Woltz & Was, 2006), and linear-integrated speed–accuracy score (LISAS; Vandierendonck, 2017). The results of these additional analyses indicated that the advantage of T<sub>2</sub> over T<sub>1</sub> was present for each of the combined scores, just as it had been for the pure RT analyses (the same was also true in each of the following

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experiments). Although this suggests that  $T_2$  is truly faster than  $T_1$  even when correcting for the observed SAT, we decided to conduct another experiment using very common PRP tasks (letter and tone tasks) to see whether this pattern would replicate.<sup>3</sup>

## Experiment 2

The goal and hypotheses of this experiment were identical to those of Experiment 1, except that we used different tasks, chosen because they have often been used in previous dual-task studies. Specifically, we combined an auditory task (i.e., deciding whether a tone is high or low) with a visual task (i.e., deciding whether a letter is an W or Q). Furthermore, we implemented some minor experimental changes (described in the method section) that we thought might reduce any potential error rate confounds.

## Method

### Participants

We again tested 40 people (34 female) online. They ranged in age from 18 to 42 years ( $M = 21.3$ ) and 37 were right handed.

### Apparatus, Stimuli, and Procedure

Except as otherwise described, the apparatus, stimuli and procedure were essentially the same as in Experiment 1. We replaced the color task with a tone pitch task, with low and high tones consistently mapped to the right index (“O” key) and right middle (“P” key) fingers, respectively. Furthermore, we used only the letters Q and W for the letter task, with Q and W consistently mapped to the left index (i.e., “Q” key) and left middle (i.e., “W” key) fingers in order to facilitate remembering task rules for participants. Thus, in each trial, a letter was presented and a low (400 Hz) or high tone (1000 Hz) appeared for approximately 100 ms. As in Experiment 1, the first stimulus (i.e., letter or tone) appeared immediately at the offset of the fixation cross, and the second stimulus was presented at the end of that trial’s SOA. The stimuli remained on the screen until the participant responded, up to a maximum of 4 s (i.e., 4 s from onset of the first stimulus). Thus, there were no task-specific RT deadlines (i.e., in Experiment 1 each individual task response had to be given within 2 s). After both required responses had been made in a trial, feedback was displayed for 1 s to indicate correct responses or for 4 s to indicate that an error had been made. Thus, we increased the duration of error feedback (i.e., 3 s in Experiment 1) to increase the emphasis on response accuracy.

## Results

We followed the same data preparation procedure as in Experiment 1. The practice block was excluded from any analyses. Trials with too fast (<100 ms, .7%) responses were excluded from any analyses. We additionally excluded 1.0% of trials in which participant responded too slowly (>2 s) to either  $T_1$  or  $T_2$ . For RT analyses, we additionally excluded trials in which any response error was made. For  $T_2$  error analyses, we again also excluded trials in which participant responded incorrectly to  $T_1$ .

### Reaction Time (RT) Analyses

Figure 1C shows the mean RT for all conditions. The  $2 \times 2$  mixed ANOVA with the within-subject factor of task and the between-subjects factor of task order for trials with long SOA revealed again a significant main effect of task,  $F(1, 38) = 43.01$ ,  $p < .001$ ,  $\eta_p^2 = .53$ , reflecting slower mean RTs for  $T_1$  compared to  $T_2$  (631 vs. 528 ms). No other effects were significant (all  $ps > .143$  and  $\eta_p^2s < .07$ ).

We then conducted separate mixed measures ANOVA with the within-subject factor SOA and the between-subjects factor of task order for each of the two tasks. For  $T_1$ , this ANOVA only yielded a significant main effect of SOA,  $F(1, 38) = 5.18$ ,  $p = .029$ ,  $\eta_p^2 = .12$ , reflecting longer mean  $RT_1$  for short compared to long SOA (659 vs. 631 ms). For  $T_2$ , there was also only a significant main effect of SOA,  $F(1, 36) = 704.85$ ,  $p < .001$ ,  $\eta_p^2 = .95$ , reflecting longer mean  $RT_2$  for short compared to long SOA (i.e., PRP effect of  $915 - 528 = 387$  ms).

### Percentage Error (PE) Analyses

Figure 1D shows the mean PE for the corresponding conditions. The mixed ANOVA with the factors of task and task order at long SOA revealed a significant main effect of task. Contrary to the RT pattern (but as in Experiment 1), this main effect indicated smaller PEs for  $T_1$  compared to  $T_2$  (1.4% vs. 2.7%),  $F(1, 38) = 13.14$ ,  $p < .001$ ,  $\eta_p^2 = .26$ . Furthermore, there was also a significant interaction between task and task order,  $F(1, 38) = 15.80$ ,  $p < .001$ ,  $\eta_p^2 = .29$ , indicating that PEs were generally smaller for the tone task than for the letter task.

For completeness, mixed measures ANOVA were conducted separately for each task. For  $T_1$ , this ANOVA yielded a significant main effect of SOA,  $F(1, 38) = 19.10$ ,  $p < .001$ ,  $\eta_p^2 = .33$ , reflecting larger  $PE_1$ s for short compared to long SOA (2.8% vs. 1.4%). Furthermore, there was a significant main effect of task order,  $F(1, 38) = 16.27$ ,  $p < .001$ ,  $\eta_p^2 = .30$ , indicating larger  $PE_1$  with task order letter-tone than tone-letter (3.2% vs. 1.0%). For  $T_2$ , there were also significant main effects of SOA,  $F(1, 38) = 6.42$ ,  $p = .015$ ,  $\eta_p^2 = .14$ , and task order,  $F(1, 38) = 4.36$ ,  $p = .044$ ,  $\eta_p^2 = .10$ . There were larger  $PE_2$ s for short compared to long SOA (i.e., PRP effect of  $4.0 - 2.7 = 1.3\%$ ) and for tone-letter order than letter-tone order (3.9% vs. 2.7%).

## Discussion

As in Experiment 1, Experiment 2 revealed again faster RTs for  $T_2$  than  $T_1$  at the long SOA suggesting the use of more resources

<sup>3</sup> It is also interesting to note that both  $RT_1$  and  $PE_1$  performance seem quite a bit worse at short than long SOA. On the one hand, this pattern had been observed in some studies (for a review, see Strobach et al., 2015) and could be compatible with the idea that the onset of  $S_2$  withdraws some additional resources from  $T_1$  processing. On the other hand, the particularly large SOA effect on  $RT_1$  may also demonstrate that participants were not following the usual PRP instructions to give priority to  $T_1$ . Instead, they may have switched the bottleneck back and forth between tasks at short SOAs. Such division of attention between tasks when both were available could be responsible for the finding that  $RT_2$  is faster at long SOAs where only  $T_2$  is available. Thus, the next two experiments also allowed us to see whether this pattern would be obtained when other stimuli and tasks are used.

for  $T_2$  than  $T_1$  processing. Interestingly, average error rates were again larger for  $T_2$  than for  $T_1$ . Although speculative, one idea could be that task-specific rehearsal of S-R mappings somehow contributes to the  $T_1$  accuracy advantage. Consider that participants might in general rehearse the mapping for the first task more often—simply because this is the primary “more important” task. As a result, they are more likely in failing to retrieve the correct mapping for  $T_2$  than  $T_1$  on some trials. We reasoned that such rehearsal might be particularly required for more difficult tasks with arbitrary mappings, whereas it is less essential for easier tasks with more natural S-R associations. Thus, in Experiment 3, we will try to avoid the importance of potential rehearsal effects in producing the SAT by using one task that uses compatible S-R mappings.

### Experiment 3

The goal and hypotheses of this experiment were again identical to those of the previous experiments, with the procedure implementing two changes that we thought might eliminate higher  $T_1$  accuracy. First, we replaced the letter task with an arrow task. Second, we mapped each task to different fingers (e.g., arrow task = index fingers, tone task = middle fingers) instead of different hands as in the previous two experiments. Thus, the arrow task used a compatible S-R mappings (i.e., left-pointing arrow = left response, right-pointing arrow = right response).

#### Method

##### Participants

We again tested 40 people (31 female) online. They ranged in age from 18 to 24 years ( $M = 20.6$ ) and 33 were right-handed.

##### Apparatus, Stimuli, and Procedure

The only differences to experiment 2 were that we replaced the letter task with an arrow task and that tasks were mapped to fingers instead of to hands. Thus, for the arrow task left- and right pointing arrows were consistently mapped to the left and right middle fingers, respectively. For the tone task, low and high tones were consistently mapped to the left and right index fingers, respectively.

#### Results

The practice block was excluded from any analyses. Trials with too fast ( $< 100$  ms, .9%) responses were excluded from any analyses. We additionally excluded .8% of trials in which participants responded too slowly ( $> 2$  s) to either  $T_1$  or  $T_2$ . For RT analyses, we additionally excluded trials in which any response error was made. For  $T_2$  error analyses, we again also excluded trials in which participant responded incorrectly to  $T_1$ .

##### Reaction Time (RT) Analyses

Figure 1E shows the mean RT for all conditions. As in the previous experiments, we conducted a  $2 \times 2$  mixed ANOVA with the within-subject factor of task ( $T_1$  vs.  $T_2$ ) and the between-subjects factor of task order (tone-arrow vs. arrow-tone) for trials with long SOA. Importantly, this ANOVA again revealed a significant main effect of task,  $F(1, 38) = 25.93$ ,  $p < .001$ ,  $\eta_p^2 = .41$ , reflecting

slower mean RTs for  $T_1$  compared to  $T_2$  (698 vs. 515 ms). There was also a significant interaction,  $F(1, 38) = 11.17$ ,  $p = .001$ ,  $\eta_p^2 = .23$ , which basically indicated faster responses to the (presumably easier) arrow task than tone task.

The mixed measures ANOVA with the factors SOA and task order for  $T_1$  revealed no significant effects (all  $ps > .137$ ). For  $T_2$ , there was a significant main effect of SOA,  $F(1, 38) = 325.97$ ,  $p < .001$ ,  $\eta_p^2 = .90$ , reflecting longer mean  $RT_2$  for short compared to long SOA (i.e., PRP effect of  $874 - 515 = 359$  ms). This effect was further modulated by task order,  $F(1, 38) = 5.55$ ,  $p = .024$ ,  $\eta_p^2 = .13$ , indicating a larger PRP effect for arrow-tone than tone-arrow task order.

##### Percentage Error (PE) Analyses

Figure 1F shows the mean PEs for the corresponding conditions. The mixed ANOVA with the factors of task and task order at SOA = 1000 ms only revealed a significant interaction,  $F(1, 38) = 6.22$ ,  $p = .017$ ,  $\eta_p^2 = .14$ , reflecting smaller PEs for the arrow task than tone task. Thus, in contrast to the previous experiments, there was no significant difference in PEs between  $T_1$  (2.0%) and  $T_2$  (2.9%),  $F(1, 38) = 2.31$ ,  $p = .137$ ,  $\eta_p^2 = .06$ .

The mixed measures ANOVA for  $T_1$  revealed that all effects were significant. The main effect of SOA,  $F(1, 38) = 39.15$ ,  $p < .001$ ,  $\eta_p^2 = .51$ , the main effect of task order,  $F(1, 38) = 10.95$ ,  $p = .002$ ,  $\eta_p^2 = .22$ , and the interaction,  $F(1, 38) = 10.96$ ,  $p = .002$ ,  $\eta_p^2 = .22$ . There difference in  $PE_1$  for short compared to long SOA was larger for tone-arrow (7.4% vs. 2.7%) than for arrow-tone task order (2.7% vs. 1.2%). For  $T_2$ , there was a significant main effects of task order,  $F(1, 38) = 9.97$ ,  $p = .003$ ,  $\eta_p^2 = .21$ , and a significant interaction,  $F(1, 38) = 6.21$ ,  $p = .017$ ,  $\eta_p^2 = .14$ . For the arrow-tone task order, there were larger  $PE_2$ s for short compared to long SOA (i.e., PRP effect of  $5.1 - 3.6 = 1.3\%$ ), whereas for the tone-arrow task order,  $PE_2$ s were slightly larger for long compared to short SOA (2.2% vs. 1.7%).

#### Discussion

As in the previous experiments, the responses were faster for  $T_2$  vs.  $T_1$  at long SOA. Moreover, error rates were descriptively slightly larger for  $T_1$  than  $T_2$ , but contrary to the previous experiments, there was no strong evidence of an overall difference in error rates between tasks. Presumably we were successful in reducing a SAT in this experiment because the use of easy tasks (i.e., compatible S-R mappings) minimized the risk of potential rehearsal effects which might have contributed to a  $T_1$  advantage in the previous experiments. In any case, the present results provide further evidence for online resource reallocation allowing  $T_2$  to use all resources at long SOA after  $T_1$  processing has finished.

### Experiment 4

In the first three experiments, we established a novel marker of multitasking interference in the PRP paradigm—that is, there is a specific processing disadvantage for  $T_1$  compared to  $T_2$  at long SOA, which cannot be explained by differences in task difficulty. This finding is in line with resource sharing models, according to which some limited resources are withheld from  $T_1$  processing to

maintain and process  $T_2$  in parallel whereas  $T_2$  processing can make use of all resources once  $T_1$  is completed. At the same time, this finding is at odds with standard versions of bottleneck models according to which  $T_1$  should be processed with 100% of resources.

To reconcile this finding with the fundamental assumption of a central bottleneck, it seems necessary to postulate additional assumptions. As mentioned in the introduction, some researchers have emphasized that differences in task preparation could account for certain changes in  $T_1$  performance that are not otherwise explained by bottleneck models (De Jong, 1995; Gottsdanker, 1979). For example, an assumption of differential task preparation allows bottleneck models to accommodate the finding that responses are typically slower in  $T_1$  than in the equivalent single-task condition (Pashler, 1994). One may speculate that the present  $T_2$  performance advantage could be caused solely by reactive (i.e., online) changes in preparatory processes without assuming any sharing or reallocation of limited processing resources (i.e., resources that are required for actual task processing). Accordingly, even though participants only process one task at a time (i.e., with 100% of processing resources), they could be slower in retrieving the  $T_1$ -specific than  $T_2$ -specific S-R mappings from working memory at long SOA, because they initially prepared both  $T_1$  and  $T_2$  mappings (and potentially also the switch between these tasks) and after completing  $T_1$  they can fully load up preparation for  $T_2$  (for a similar suggestion, see Maquestiaux et al., 2020). In other words, participants may keep S-R mappings for both tasks active during  $T_1$  processing, but afterward only the ones for  $T_2$ . Thus, this account assumes pretrial sharing of limited resources for preparatory processes and that full preparation is devoted to  $T_2$  after  $T_1$  processing has been completed.

In order to see whether this account in terms of differential preparation—as opposed to sharing of limited processing resources—can explain the between-task difference at long SOA we conducted another experiment in which we isolated the effects of preparation from potential limited-capacity parallel processing. In half of the blocks (i.e., PRP blocks), participants were tested in the same PRP paradigm as in the previous experiment and hence we expected to replicate the finding that mean  $RT_2$  would be less than  $RT_1$  at long SOA. In the other half of blocks (i.e., task-switching blocks), only the stimulus of  $T_1$  or  $T_2$  was randomly presented in each trial and hence participants were required to process  $T_1$  without the presence of  $S_2$  in half of the trials. The critical focus was the comparison of  $T_1$  performance in PRP blocks (at short SOAs) with  $T_1$  performance in switch trials of the task-switching blocks, because for this comparison resource-sharing accounts could make a different prediction than preparation-extended bottleneck accounts.

If only preparation-related processes play a role in slowing  $RT_{1,PRP}$  in PRP blocks, then these RTs should be actually smaller than  $RT_{1,TS}$  in task-switching blocks. Recall that participants have to be prepared for both  $T_1$  and  $T_2$  in both PRP and task-switching trials, but they know in advance of each PRP trial that they always have to perform  $T_1$  first, whereas they are required to randomly switch between tasks in task-switching blocks. Given the greater predictability of  $T_1$  in PRP trials, there should be greater preparation for  $T_1$  in those trials than in task-switching trials, and hence a smaller mean  $RT_{1,PRP}$ . For the  $RT_{1,TS}$  in task-switching, we even considered whether a trial was a repetition or switch trial. We reasoned that the comparison with switch trials is most relevant because

$RT_1$  in PRP is essentially also a switch trial (i.e., participants always performed  $T_2$  as the previous response). Because participants cannot anticipate whether a switch is required in task-switching blocks, however,  $RT_{1,TS}$  in switch trials is particularly impaired due to switching-related preparatory processes taking place after stimulus onset. Thus, even if participants prepare both tasks in advance of a trial in both PRP and task-switching blocks, a preparation-based account would predict that  $RT_{1,PRP}$  should be smaller than  $RT_{1,TS}$ . On the other hand, if  $S_2$  withdraws limited processing resources from  $T_1$  processing in PRP blocks, as is allowed by resource sharing but not bottleneck-based accounts, then, there would be an additional slowing of  $T_1$  processing in PRP blocks due to the presence of  $S_2$ , compared with  $T_1$  processing in task switching blocks when  $S_2$  is absent. In this case,  $RT_{1,PRP}$  might be similar to or even larger than  $RT_{1,TS}$  in task-switching blocks. Naturally, any slowing of  $RT_{1,PRP}$  due to  $S_2$  onset in PRP blocks would be greatest when SOA was short, so we focused on trials with short SOA in PRP for which the contribution of parallel processing should be greatest.

In sum, one question relates again to the comparison of  $RT_1$  vs.  $RT_2$ . If participants can quickly reallocate freed-up resources after they have finished limited processing of  $T_1$ ,  $RT_2$  should be less than  $RT_1$  at long SOA. Another question relates to the comparison of  $RT_{1,PRP}$  at short SOA in the PRP blocks versus the corresponding mean  $RT_{1,TS}$  of this task in switch-trials of task-switching blocks.  $RT_{1,PRP}$  has a predictability advantage in preparation but a potential resource-sharing disadvantage because  $S_2$  is present. Conversely,  $RT_{1,TS}$  has an unpredictability disadvantage in preparation but a potential resource-sharing advantage because  $S_2$  is not present. Thus, the comparison of  $RT_{1,PRP}$  versus  $RT_{1,TS}$  essentially assesses whether the preparation effect is larger than the resource sharing effect.

## Method

### Participants

We again tested 40 people online, but data of 4 participants was excluded due to error rates larger than 30% in task switching and/or PRP blocks. Note that this resulted in unequal group sizes (i.e., 17 participants for arrow-tone order and 19 participants for tone-arrow order).<sup>4</sup> They ranged in age from 18 to 33 years ( $M = 22.1$ ), 30 were right-handed and 27 female.

### Apparatus, Stimuli, and Procedure

Task requirements (PRP, task-switching) were held constant within a block and alternated across blocks. Instruction in advance of each block described the specific task requirements. Each participant was tested in 1 practice PRP and 1 practice task-switching block with 32 trials followed by 6 experimental (i.e., 3 PRP and 3 task-switching) blocks of 64 randomly ordered trials per block. Half of the participants were tested with a PRP block for the first block, whereas the other half of participants started with a task-switching block. Furthermore, as in the previous experiment, for half of the participants the arrow task was  $T_1$  and the tone task  $T_2$  in the PRP paradigm whereas this mapping was reversed for the other half of participants. The stimuli and procedure in PRP blocks

<sup>4</sup> Preregistration is available via the Open Science Framework at <https://osf.io/6pebr>.



were identical to the ones from the previous experiment. The trial procedure in task-switching blocks was similar to PRP blocks and the only difference was that only one stimulus (i.e., arrow or tone) was presented in each trial and hence only a response to this stimulus was required. After a response had been made in a task-switching trial (or the maximum time of 4s had elapsed), feedback was displayed, and the next trial started. Each task-switching block included 16 presentations of the two possible arrows and two possible tones that were presented in a random order.

**Results**

The practice blocks were excluded from any analyses. Trials with too fast (<100 ms, PRP: .9%, task-switching: .01%) responses were excluded from any analyses. We additionally excluded trials in which participants responded too slowly (>2 s) to either T<sub>1</sub> or T<sub>2</sub> (PRP: 1.4%, task-switching: .1%). For RT analyses, we additionally excluded trials in which any response error was made (PRP: 4.4%, task-switching: 5.4%). For T<sub>2</sub> error analyses in PRP blocks, we again also excluded trials in which participant responded incorrectly to T<sub>1</sub>.

**Reaction time (RT) Analyses in PRP Blocks**

Figure 1G shows the mean RT for all conditions. We again first conducted a 2 × 2 mixed ANOVA with the within-subject factor of task (T<sub>1</sub> vs. T<sub>2</sub>) and the between-subjects factor of task order (tone-arrow vs. arrow-tone) for trials with long SOA. This ANOVA again revealed a significant main effect of task,  $F(1, 34) = 39.99, p < .001, \eta_p^2 = .54$ , reflecting slower mean RTs for T<sub>1</sub> compared to T<sub>2</sub> (517 vs. 697 ms). There was no significant interaction,  $F(1, 34) = 2.97, p = .094, \eta_p^2 = .08$ . Descriptively, the RT advantage for T<sub>2</sub> was larger when the arrow instead of tone task was T<sub>2</sub>.

The mixed measures ANOVA with the factors SOA and task order for T<sub>1</sub> revealed no significant effects (all  $ps > .509$ ). For T<sub>2</sub>, this ANOVA yielded a significant main effect of SOA,  $F(1, 34) = 389.58, p < .001, \eta_p^2 = .92$ , reflecting longer mean RT<sub>2</sub> for short compared to long SOA (i.e., PRP effect of 890 – 517 = 373 ms). There was no significant effect of task,  $F(1, 34) = 3.90, p = .056, \eta_p^2 = .10$ . Descriptively, there were again faster responses when the arrow task than tone task was T<sub>1</sub> (664 vs. 747 ms).

**Percentage Error (PE) Analyses in PRP Blocks**

Figure 1H also shows the mean PEs for the corresponding conditions. The mixed ANOVA with the factors of task and task order at SOA = 1000 ms revealed a significant main effect of task,  $F(1, 34) = 6.74, p = .017, \eta_p^2 = .17$ . Contrary to the RT pattern, but generally in line with the previous three experiments, this main effect indicated smaller PEs for T<sub>1</sub> compared to T<sub>2</sub> (1.1% vs. 2.0%). There was no significant interaction between task and task order,  $F(1, 34) = 3.89, p = .057, \eta_p^2 = .10$ . Descriptively, PEs were generally smaller for the tone task than for the letter task.

The mixed measures ANOVA for T<sub>1</sub> revealed that all effects were significant. The main effect of SOA,  $F(1, 34) = 37.97, p < .001, \eta_p^2 = .53$ , the main effect of task order,  $F(1, 34) = 6.26, p = .017, \eta_p^2 = .16$ , and the interaction,  $F(1, 34) = 4.81, p = .035, \eta_p^2 = .12$ . The difference in PE<sub>1</sub> for short compared to long SOA was larger for tone-arrow (5.2% vs. 1.4%) than for arrow-tone task

order (2.6% vs. .9%). For T<sub>2</sub>, there was significant main effects of task order,  $F(1, 34) = 14.13, p = .001, \eta_p^2 = .29$ , and a significant interaction,  $F(1, 34) = 8.22, p = .007, \eta_p^2 = .19$ . For the arrow-tone task order, there were larger PE<sub>2s</sub> for short compared to long SOA (3.8% vs. 2.4%), whereas for the tone-arrow task order, PE<sub>2s</sub> were larger for long compared to short SOA (1.6% vs. .6%).

**Comparison of RT<sub>1</sub> in PRP Blocks With RT<sub>1</sub> in Task Switching Blocks**

To begin with, we computed the corresponding mean RT<sub>1,TS</sub> in task-switching blocks separately for switch and repetition trials while also considering the between-subjects factor of task (tone vs. arrow). Thus, RT<sub>1,TS</sub> in task-switching blocks refers to the same task (i.e., arrow or tone) that was T<sub>1</sub> in PRP blocks. Table 1 shows the corresponding means separately for conditions in PRP vs. Task switching blocks. We then compared the mean RT<sub>1</sub> in PRP blocks (i.e., RT<sub>1,PRP</sub>) at short SOA with the corresponding mean RT<sub>1</sub> of switch trials in task-switching blocks (i.e., RT<sub>1,TS</sub>). To do so, we conducted a 2 × 2 mixed ANOVA with the within-subject factor of block requirements (PRP vs. task-switching) and the between-subjects factor of task (tone vs. arrow) on these mean RTs. This ANOVA only revealed a significant interaction,  $F(1, 34) = 57.31, p < .001, \eta_p^2 = .63$  (all other  $ps > .108$ ). As can be seen in Table 1, arrow responses were slower in PRP blocks than in task-switching blocks whereas the reverse was true for tone responses (with both pairwise comparisons significant,  $ps < .003$ ). We then compared RT<sub>1,PRP</sub> at short SOA with the corresponding mean RT<sub>1,TS</sub> of repetition trials. The 2 × 2 mixed ANOVA revealed a significant main effect of block requirements,  $F(1, 34) = 78.82, p < .001, \eta_p^2 = .70$ , and a significant interaction,  $F(1, 34) = 36.87, p < .001, \eta_p^2 = .52$ . Responses were generally slower in the PRP than in task-switching blocks (in average 706 vs. 593 ms, respectively); this difference was more pronounced for arrow- than tone-task responses, but it was significant for both tasks (with  $ps < .018$ ). We then computed the 2 × 2 mixed ANOVA while considering only RT<sub>1,PRP</sub> at long SOA in PRP blocks and RT<sub>1,TS</sub> of switch trials in task-switching blocks. This ANOVA only revealed a significant interaction,  $F(1, 34) = 15.16, p < .001, \eta_p^2 = .31$ , indicating slower arrow-task responses in PRP than task-switching blocks and a reversed

**Table 1**  
*M Reaction Time and M Percentage Error in PRP (RT<sub>1,PRP</sub> and PE<sub>1,PRP</sub> at Short and Long SOAs) and Task-Switching Blocks (RT<sub>1,TS</sub> and PE<sub>1,TS</sub> in Switch and Repetition Trials) for the Task (i.e., Arrow or Tone) That Was T<sub>1</sub> in PRP Blocks of Experiment 4*

Task	RT <sub>1,PRP</sub>		RT <sub>1,TS</sub>	
	short SOA	long SOA	switch	repeat
Arrow	729 (31)	703 (54)	588 (22)	533 (16)
Tone	686 (30)	693 (53)	766 (42)	645 (30)
Task	PE <sub>1,PRP</sub>		PE <sub>1,TS</sub>	
	short SOA	long SOA	switch	repeat
Arrow	2.6 (0.6)	0.9 (0.3)	5.5 (0.9)	2.8 (0.5)
Tone	5.2 (0.8)	1.4 (0.4)	7.9 (1.5)	4.8 (1.1)

*Note.* Standard error of the means in parentheses. SOA = stimulus onset asynchrony.

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pattern for tone-task responses (with both pairwise comparisons significant,  $p_s < .026$ ). Finally, we computed the  $2 \times 2$  mixed ANOVA while considering only  $RT_{1,PRP}$  at long SOA in PRP blocks and  $RT_{1,TS}$  of repetition trials in task-switching blocks. This ANOVA revealed a significant main effect of block requirements,  $F(1, 34) = 14.56$ ,  $p < .001$ ,  $\eta_p^2 = .30$ , and a significant interaction,  $F(1, 34) = 4.78$ ,  $p = .036$ ,  $\eta_p^2 = .12$ . Responses were generally slower in the PRP than in task-switching blocks (in average 698 vs. 593 ms, respectively), but this difference was more pronounced and only significant in the arrow task not the tone task ( $p = .003$  and  $p = .129$ , respectively).

### Comparison of $PE_1$ in PRP Blocks With $PE_1$ in Task Switching Blocks

Finally, we compared the mean  $PE_1$  in PRP and task-switching blocks in an analogous manner as for the corresponding  $RT_1$  comparison. First, we computed a  $2 \times 2$  mixed ANOVA with the factors of block requirements and task while only considering  $PE_{1,PRP}$  at short SOA in PRP blocks and  $PE_{1,TS}$  of switch trials in task-switching blocks. This ANOVA only revealed a significant main effect of block requirements,  $F(1, 34) = 12.98$ ,  $p = .001$ ,  $\eta_p^2 = .28$  (all other  $p_s > .058$ ), indicating larger PEs in task-switching than PRP blocks (3.9% vs. 6.8%). Second, we computed a  $2 \times 2$  mixed ANOVA with the factors of block requirements and task while only considering  $PE_{1,PRP}$  at short SOA in PRP blocks and  $PE_{1,TS}$  of repetition trials in task-switching blocks. This ANOVA only revealed a significant main effect of task,  $F(1, 34) = 5.18$ ,  $p = .029$ ,  $\eta_p^2 = .13$  (all other  $p_s > .618$ ), indicating larger PEs for tone than arrow responses (2.7% vs. 5.0%). Third, we computed a  $2 \times 2$  mixed ANOVA with the factors of block requirements and task while only considering  $PE_{1,PRP}$  at long SOA in PRP blocks and  $PE_{1,TS}$  of switch trials in task-switching blocks. This ANOVA only revealed a significant main effect of block requirements,  $F(1, 34) = 36.60$ ,  $p < .001$ ,  $\eta_p^2 = .52$  (all other  $p_s > .145$ ), indicating larger PEs in task-switching than PRP blocks (1.1% vs. 6.8%). Fourth, we computed a  $2 \times 2$  mixed ANOVA with the factors of block requirements and task while only considering  $PE_{1,PRP}$  at long SOA in PRP blocks and  $PE_{1,TS}$  of repetition trials in task-switching blocks. This ANOVA only revealed a significant main effect of block requirements,  $F(1, 34) = 16.45$ ,  $p < .001$ ,  $\eta_p^2 = .33$  (all other  $p_s > .083$ ), indicating larger PEs in task-switching than PRP blocks (1.1% vs. 3.9%).

### Further Examination of SATs

As discussed already, the consistent advantage for  $RT_2$  over  $RT_1$  is especially problematic for bottleneck models if it cannot be explained by an SAT, as is suggested by the findings noted earlier that the critical  $T_2$  advantage at long SOA was present in this and in the previous experiments for several overall efficiency scores combining RT and accuracy into a single measure. As an additional check on the relation between this error rate difference and the  $RT_2$  advantage, we carried out one further analysis examining the  $RT_2$  advantage separately for participants who were more accurate in  $T_2$  versus participants who were more accurate in  $T_1$ . Collapsing across the PRP tasks in all experiments, participants who showed a  $T_2$  accuracy advantage ( $N = 53$ ) also showed a significant  $RT_2$  advantage ( $RT_1 = 739$  ms,  $RT_2 = 507$  ms,  $p < .001$ ,  $\eta_p^2 = .56$ ), demonstrating that the  $T_2$  performance advantage is not

simply an SAT. In comparison, for participants who showed a  $T_1$  accuracy advantage ( $N = 101$ ), there was also a significant  $RT_2$  advantage ( $RT_1 = 623$  ms,  $RT_2 = 526$  ms,  $p < .001$ ,  $\eta_p^2 = .39$ ), but the  $RT_2$  advantage for this group was actually significantly smaller than the one for the group who showed a  $T_2$  accuracy advantage ( $p < .001$ ,  $\eta_p^2 = .13$ ). Thus, the overall pattern of  $T_1/T_2$  differences in RTs and error rates for these two groups provides further evidence against the idea that the  $RT_2$  advantage emerges from an SAT.

## Discussion

In line with the previous three experiments, RTs were substantially larger for  $T_1$  than  $T_2$  at long SOA in the PRP blocks. Critically, the  $RT_2$  advantage at long SOA cannot be simply explained by preparation-extended bottleneck accounts according to which people can prepare better for  $T_2$  than  $T_1$  after  $T_1$  processing has been completed. If only differential preparation plays a role,  $RT_{1,PRP}$  in PRP blocks should always have been smaller than  $RT_{1,TS}$  in task-switching blocks, because the greater predictability of  $T_1$  in PRP blocks allows better preparation. Contrary to this account,  $RT_{1,PRP}$  in the presence of  $S_2$  was generally larger than  $RT_{1,TS}$  in repetition trials, and this  $RT_{1,PRP}$  disadvantage was observed even when comparing arrow task responses with  $RT_{1,TS}$  in switch trials.<sup>5</sup>

This suggests that  $S_2$  taps into the same limited resources needed to process  $T_1$  in PRP blocks and that this resource-sharing disadvantage for  $T_1$  can be strong enough to overwhelm its predictability advantage in preparation under some circumstances—that is, when  $T_1$  is the arrow task and  $T_2$  is the tone task. In retrospect, it also seems quite plausible that the tone  $S_2$  would produce especially strong interference with  $T_1$  processing, since participants must grab this tone and hold it in short term memory so that it will be available for later  $T_2$  processing. Thus,  $S_2$  might only withdraw sufficient limited processing resources from  $T_1$  to overcome a predictability advantage when this stimulus is associated with a more difficult—more resource-consuming—task. Furthermore, it should be noted that the amount of  $T_1$  slowing due to resource-sharing is relatively small compared to the amount of slowing observed on  $T_2$ . This indicates that resource-sharing is quite lopsided in favor of  $T_1$ , which is not surprising given the strong focus on  $T_1$  inherent in the PRP paradigm. Of course, any ratio of resource sharing between tasks other than 100%/0% is incompatible with standard versions of bottleneck models. Overall, then, the findings of Experiment 4 provide further support for the idea that resource-sharing can occur at least under some circumstances in the PRP paradigm.

## General Discussion

In the present study, we compared mean  $RT_1$  with mean  $RT_2$  in a PRP paradigm constrained—by counterbalancing task order—to

<sup>5</sup> Note that a similar pattern of results was observed when considering the three combined measures of speed and accuracy mentioned in the Discussion of Experiment 1, suggesting that  $RT_{1,PRP}$  was truly larger than  $RT_{1,TS}$  even when controlling for the SAT. Furthermore, as mentioned in the Results section of Experiment 1, the pattern of results in this experiment also held when excluding trials with short IRIs which could be contaminated by response grouping (cf. Miller & Tang, 2021).

have equally difficult first and second tasks. Across four experiments, we demonstrated a novel marker of multitasking interference in the PRP paradigm by showing that  $T_2$  responses at long SOAs were consistently faster than  $T_1$  responses. This between-task difference suggests that fewer resources are available for the processing of  $T_1$  than  $T_2$ , contrary to bottleneck accounts in which all resources are allocated to  $T_1$  processing until it is complete. Instead, the  $T_2$  advantage fits better with resource-based accounts in which a fixed total set of resources can be proactively and reactively divided between the two tasks based on the processing requirements. More precisely, it seems that most of the resources (e.g., 90%) were proactively allocated to  $T_1$ , but that some (remaining) resources (e.g., 10%) were allocated to maintain and process  $T_2$ . Within such models, a  $T_2$  advantage would be found at long SOAs if  $T_1$  were processed with less than 100% of the resources because a fraction of the resources were allocated to the upcoming  $T_2$ . Obviously,  $T_2$  performance was strongly impaired at short SOA, because in that situation  $T_2$  processing would be delayed by waiting for resources to be freed up at the termination of  $T_1$ . Importantly, however, the fact that  $T_2$  responses were faster than  $T_1$  responses at long SOA suggests that in this situation 100% of resources were devoted to  $T_2$ , presumably because resources were reallocated to this task after  $T_1$  finished.

In general, the finding that resource allocation effects can explain performance in the present PRP paradigm fits well with growing evidence indicating that an interplay of cognitive control and resource sharing also influences performance in other multitasking environments (Boag, Strickland, Heathcote, et al., 2019; Boag, Strickland, Loft, et al., 2019; Miller & Tang, 2021; Mittelstädt et al., 2022; Palada et al., 2019). Clearly, the question of what constitutes cognitive resources could be further elucidated, but for now it seems quite reasonable to assume that working memory can be seen as a limited resource (Huynh Cong & Kerzel, 2021, 2022; Janczyk, 2017; Musslick & Cohen, 2021; Redick et al., 2016). Specifically, both maintaining preparation for task processing and task processing itself require limited working memory resources (see also Belletier et al., 2021; Huynh Cong & Kerzel, 2021; Cowan, 2008). In this context, one might argue that models allowing resource-sharing are inherently more flexible than the standard bottleneck model. As mentioned in the introduction, however, the bottleneck model was often extended by a number of ancillary assumptions to account for certain empirical findings in the PRP paradigm while maintaining its fundamental assumption that a central bottleneck impairs multitask performance. For example, previous findings indicating parallel processing in terms of BCEs could simply indicate that some automatic  $T_2$  response activation operates while  $T_1$  occupies the bottleneck (e.g., Hommel, 1998; Janczyk et al., 2018; Schubert et al., 2008; Thomson et al., 2015). Furthermore, it has been shown that preparatory processes in retrieving S-R mappings need to be considered when interpreting PRP performance against the predictions of bottleneck models (De Jong, 1995; Gottsdanker, 1979; Mittelstädt & Miller, 2017). However, it is not clear how the present  $T_2$  performance advantage at long SOA could be reconciled with extended bottleneck accounts, whereas resource-sharing accounts offer a natural explanation for the present findings. Specifically, the most straightforward interpretation seems to be that resources were withheld from  $T_1$  for  $T_2$  processing and full resources were reactively allocated to  $T_2$  once  $T_1$  processing was finished.

Of course, the present study does not imply that all aspects of concurrent multitasking interference can be explained solely by the sharing of limited central resources between two tasks—including some findings observed in the present study. In particular, we consistently found larger overall error rates at long SOA for  $T_2$  than  $T_1$  across all experiments, and this finding is easily reconciled with both bottleneck and resource-sharing accounts. Specifically, because there is a greater emphasis on  $T_1$  in the PRP paradigm (e.g., Gottsdanker, 1980; Pashler, 1994), many participants may have devoted more preparation time to rehearsing the S-R mapping for  $T_1$  than for  $T_2$ , and this could have produced the overall  $T_1$  accuracy advantage. Interestingly, this SAT was smaller in experiments 3 and 4, which used a task with more natural associations, which suggests that the difficulty of retrieving task rules and/or rehearsing tasks in working memory may also play a role. In line with these speculations, other studies have found that dual-task processing also depends on task structure (e.g., ideomotor and stimulus-response compatibility, cf. Halvorson, Ebner, & Hazeltine, 2013; Lien et al., 2003, 2005; Maquestiaux et al., 2020), as well as on the cognitive control processes that coordinate the instructed task order (e.g., Kübler et al., 2022a, 2022b; Luria & Meiran, 2003; Steinhauser et al., 2021). Furthermore, motor-level interference might also be involved because there is evidence that initiating a  $T_1$  response prevents initiating a  $T_2$  response in close succession (Keele, 1973; Klapp et al., 2019; Ulrich et al., 2006). Thus, it might also be illuminating to extend the current approach of comparing  $T_1$  with  $T_2$  to dual-task paradigms with different response modalities (e.g., vocal and manual responses; cf. Hoffmann et al., 2019). Considering that motor-level interference for  $T_2$  should be smaller when using different instead of similar response modalities, this might even further increase the  $T_2$  advantage that is predicted by resource-sharing accounts. Finally, it is also important to bear in mind that resource-sharing accounts can generally allow strategic serial processing and in many different situations (and experimental settings) this may indeed be the preferred processing mode to optimize behavior (e.g., Miller et al., 2009). Nevertheless, we argue that the development of more sophisticated multitasking accounts should start from the premise that our cognitive system is also capable of sharing resources between different tasks—and also make use of it as in the present study—presumably to promote flexible behavior (e.g., Dreisbach & Fröber, 2019; Goschke, 2000; Musslick & Cohen, 2021).

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## Appendix

### Additional Analyses of Experiments 1–4

In this appendix, we report the results of a  $2 \times 2 \times 2$  mixed measures ANOVA on both RT and percentage error (PE) with the within-subject factors task and SOA and the between-subjects factor of task order for each experiment. Note that for experiment 4, this analysis refers to the data of the PRP blocks.

#### Experiment 1

For RTs, the  $2 \times 2 \times 2$  mixed measures ANOVA revealed a significant main effect of SOA,  $F(1, 36) = 711.66, p < .001, \eta_p^2 = .95$ , reflecting on average faster responses at long compared to short SOA (565 vs. 856 ms). Furthermore, there was a significant main effect of task,  $F(1, 36) = 25.99, p < .001, \eta_p^2 = .42$ , reflecting faster responses for T<sub>1</sub> compared to T<sub>2</sub> (686 vs. 734 ms). There was also a significant two-way interaction between task and task order,  $F(1, 36) = 6.50, p = .015, \eta_p^2 = .15$ . Finally, the two-way interaction between task and SOA was also significant,  $F(1, 36) = 400.86, p < .001, \eta_p^2 = .92$ . Not surprisingly, the difference between short and long SOA was smaller for T<sub>1</sub> (752 vs. 620 ms) compared to the one for T<sub>2</sub> (959 vs. 510 ms).

For PEs, the ANOVA only revealed that all main effects were significant: The main effect of task indicated smaller PEs for T<sub>1</sub> compared to T<sub>2</sub> (3.7% vs. 6.0%),  $F(1, 36) = 31.74, p < .001, \eta_p^2 = .47$ , the main effect of SOA indicated larger PEs at short compared to long SOA (6.1% vs. 3.7%),  $F(1, 36) = 38.56, p < .001, \eta_p^2 = .52$  and the main effect of task order indicated larger PEs for participants with task order letter-color compared to participants with task order color-letter (5.9% vs. 3.8%),  $F(1, 36) = 5.89, p = .020, \eta_p^2 = .14$ .

#### Experiment 2

For RTs, the  $2 \times 2 \times 2$  mixed measures ANOVA revealed a significant main effect of SOA,  $F(1, 38) = 425.98, p < .001, \eta_p^2 = .92$ , reflecting in average faster responses at long compared to short SOA (787 vs. 580 ms). Furthermore, there was a significant main effect of task,  $F(1, 38) = 37.44, p < .001, \eta_p^2 = .50$ , reflecting faster responses for T<sub>1</sub> compared to T<sub>2</sub> (645 vs. 722 ms). There was also a significant two-way interaction between task and SOA,  $F(1, 38) = 405.57, p < .001, \eta_p^2 = .91$ . The difference between short and long SOA was again smaller for T<sub>1</sub> (659 vs. 619 ms) compared to the one for T<sub>2</sub> (872 vs. 493 ms). Finally, there was a significant interaction between task and task order,  $F(1, 38) = 7.18, p = .01, \eta_p^2 = .16$ .

For PEs, the ANOVA revealed significant main effects of task and SOA: The main effect of task indicated smaller PEs for T<sub>1</sub> compared to T<sub>2</sub> (2.1% vs 3.3%),  $F(1, 38) = 12.29, p = .001, \eta_p^2 = .24$ . The main effect of SOA indicated smaller PEs for long than short SOA (2.0% vs. 3.4%),  $F(1, 38) = 18.40, p < .001, \eta_p^2 = .33$ . Furthermore, there was a significant interaction between task and task order,  $F(1, 38) = 22.10, p < .001, \eta_p^2 = .37$ .

#### Experiment 3

For RT, the  $2 \times 2 \times 2$  mixed measures ANOVA revealed a significant main effect of SOA,  $F(1, 38) = 53.15, p < .001, \eta_p^2 = .58$ , reflecting in average faster responses at long compared to short SOA (768 vs. 607 ms). Furthermore, there was a significant two-way interaction between task and SOA,  $F(1, 38) = 158.67, p < .001, \eta_p^2 = .81$ , indicating that the difference between short and long SOA was smaller for T<sub>1</sub> (662 vs. 698 ms) compared to the one for T<sub>2</sub> (874 vs. 515 ms). The two-way interaction between task order and task was also significant,  $F(1, 38) = 11.75, p < .001, \eta_p^2 = .24$ . This interaction reflected a general processing advantage for the arrow task. Finally, there was a significant three-way interaction between all factors,  $F(1, 38) = 7.56, p = .01, \eta_p^2 = .17$ .

For PEs, the ANOVA revealed a significant main effect of SOA indicating smaller PEs for long vs. short SOA (2.5% vs. 4.2%),  $F(1, 38) = 45.21, p < .001, \eta_p^2 = .54$ . Furthermore, there was a significant two-way interaction between SOA and task,  $F(1, 38) = 11.95, p < .001, \eta_p^2 = .24$ . The difference between short and long SOA was larger for T<sub>1</sub> (5.1% vs. 2.0%) compared to the one for T<sub>2</sub> (3.4% vs. 2.9%). The two-way interaction between task and task order was also significant,  $F(1, 38) = 29.02, p < .001, \eta_p^2 = .43$ . and this interaction was further modulated by SOA,  $F(1, 38) = 13.00, p < .001, \eta_p^2 = .25$ .

#### Experiment 4

For RT, the  $2 \times 2 \times 2$  mixed measures ANOVA revealed a significant main effect of SOA,  $F(1, 34) = 115.40, p < .001, \eta_p^2 = .77$ , reflecting in average faster responses at long compared to short SOA (798 vs. 607 ms). Furthermore, there was a significant two-way interaction between task and SOA,  $F(1, 34) = 167.46, p < .001, \eta_p^2 = .83$ , indicating that the difference between short and long SOA was smaller for T<sub>1</sub> (729 vs. 703 ms) compared to the one for T<sub>2</sub> (921 vs. 574 ms).

For PEs, the ANOVA revealed a significant main effect of SOA indicating smaller PEs for long vs. short SOA (1.6% vs. 3.1%),  $F(1, 34) = 19.27, p < .001, \eta_p^2 = .36$ . Furthermore, there was a significant two-way interaction between SOA and task,  $F(1, 34) = 22.09, p < .001, \eta_p^2 = .39$ . The difference between short and long SOA was larger for T<sub>1</sub> (2.6% vs. .9%) compared to the one for T<sub>2</sub> (3.8% vs. 2.3%). The two-way interaction between task and task order was also significant,  $F(1, 34) = 26.64, p < .001, \eta_p^2 = .44$ . and this interaction was further modulated by SOA,  $F(1, 34) = 15.71, p < .001, \eta_p^2 = .32$ .

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