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Separating Limits on Preparation Versus Online Processing in Multitasking Paradigms: Evidence for Resource Models

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We conducted 2 multitasking experiments to examine the finding that first-task reaction times (RTs) are slower in the psychological refractory period (PRP) paradigm than in the prioritized processing (PP) paradigm. To see whether this difference between the 2 paradigms could be explained entirely by differences in first-task preparation, which would be consistent with the standard response selection bottleneck (RSB) model for multitasking interference, we compared the size of this difference for trials in which a second-task stimulus actually occurred against the size of the difference for trials without any second-task stimulus. The slowing of first-task RTs in the PRP paradigm relative to the PP paradigm was larger when the second-task stimulus appeared than when it did not, indicating that the difference cannot be explained entirely by between-paradigm differences in first-task preparation. Instead, the results suggest that the slowing of first-task RTs in the PRP paradigm relative to the PP paradigm is partly because of differences between paradigms in the online reallocation of processing capacity to tasks. Thus, the present results provide new evidence supporting resource models over the RSB model.

Keywords: multitasking, response selection bottleneck model, resource models, psychological refractory period paradigm, prioritized processing paradigm

In many everyday situations, it is quite common to do more than one activity simultaneously ("multitasking"). Although multitasking is not a new phenomenon, it has become increasingly prevalent in our technologically advanced world. For example, while walking or driving a car, people often use a navigation device and/or text or talk on a phone. It is well known, however, that performance often suffers when people perform multiple tasks at the same time (e.g., Pashler, 2000; Pashler, Johnston, & Ruthruff, 2001). Understanding the reasons for such multitasking decrements could have important implications in many real-word situations (e.g., Hembrooke & Gay, 2003; Levy & Pashler, 2008; Strayer, Drews, & Johnston, 2003). To achieve this, it is indispensable to understand the cognitive processes that are limited when performing multiple tasks. Furthermore, a precise understanding of these dual-task performance limitations provides fundamental information regarding the architecture of our cognitive systems (Pashler, 1994a).

The most widely used methodology in dual-task investigations is the psychological refractory period (PRP) paradigm (Pashler, 1984; Telford, 1931; Welford, 1952). In a classic PRP study, the stimuli of two tasks (S_1 and S_2) are presented sequentially, and participants must respond to each stimulus with a separate response (R_1 and R_2). The key independent variable is the interval between the presentations of the two stimuli, known as the stimulus onset asynchrony (SOA). One typical PRP finding is that the mean reaction time (RT) for the second task (RT_2) increases substantially as SOA decreases. This so-called PRP effect is very robust (for a review, see Pashler, 1994a, and for an exception, see Janczyk, Pfister, Wallmeier, & Kunde, 2014) and demonstrates that humans' cognitive abilities to perform two tasks simultaneously are limited, even when very simple tasks are used (Pashler & O'Brien, 1993).

One of the two most standard approaches used to explain the PRP effect is the response selection bottleneck (RSB) model (e.g., Pashler, 1994a, 1994b). This model describes the performance of each task in terms of a series of processing stages (i.e., perception, response selection, and response execution), and it assumes that the response selection stage of the second task cannot begin until the response selection stage of the first task has been finished, although the other stages (i.e., perception and response execution) can proceed in parallel. Thus, according to this model, the PRP effect is a consequence of the waiting time of the second task because of a bottleneck at the response selection stage.

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In contrast to the RSB model, a second standard approach favored by many other researchers is to suggest that dual-task decrements such as the PRP effect should be conceptualized in terms of resource models (e.g., Navon & Miller, 2002; Tombu & Jolicoeur, 2003). According to these models, limited cognitive processing capacity can be shared between two tasks so that both are processed simultaneously, with sharing possible even within the central response selection process. Naturally, though, the requirement to share processing capacity across tasks means that each task is carried out more slowly than it would be in isolation, thus accounting for dual-task slowing in general and many effects seen in the mean RTs of PRP tasks (e.g., Navon & Miller, 2002; Tombu & Jolicoeur, 2003).

The purpose of the present study was to investigate empirical differences between the PRP paradigm and an alternative multitasking paradigm—the prioritized processing (PP) paradigm (Miller & Durst, 2014, 2015). As we will explain in detail within our introduction, this investigation also helps to compare the RSB and resource models, because these models provide somewhat different explanations for the differences between these two paradigms.

Key Findings in the PRP Paradigm

Overall, studies using the PRP paradigm are often regarded as supporting the RSB model. As has been reviewed numerous times (e.g., Pashler, 1994a), three strong predictions of the RSB model seem to be confirmed within the PRP paradigm, at least to a reasonable approximation. First, the function relating RT_2 to SOA has a slope of approximately -1, as is predicted by the idea that RT_2 is increased purely by waiting for access to a bottleneck process. Second, the effects of S_2 perceptual manipulations on RT_2 are greatly decreased or eliminated at short SOAs—a pattern known as "absorption into slack"—as is directly predicted by the RSB model. Third, the effects of S_1 perceptual and response selection manipulations are found not only on RT_1 but also propagate fully to RT_2, as is also predicted by the RSB model's assumption that Task 2 must wait for access to a bottleneck process. Because these three quite specific findings are directly predicted by the RSB model, they are generally regarded as support for that model.

On the other hand, these three findings are not decisive evidence in favor of the RSB model, because resource models can also accommodate them within a framework in which resources can be flexibly shared between tasks even during central stages (Navon & Miller, 2002; Tombu & Jolicoeur, 2003).[1] First of all, these models can closely mimic the bottleneck model by allocating all capacity to one task, and it would make sense to do that when this allocation policy is more efficient than processing the two tasks in parallel (Miller, Ulrich, & Rolke, 2009). Second, even when central resources are divided between tasks, mathematically explicit formulations of resource models are capable of producing the three findings taken as support for the RSB model (for details, see Appendix A in Navon & Miller, 2002, and Case B in Tombu & Jolicoeur, 2003). Thus, resource models are compatible with the three key phenomena thought to support the RSB model, even though they do not predict the phenomena as directly as the RSB model does.

There is one phenomenon observed in the PRP paradigm that seems more consistent with resource models than with the RSB model, however. This is the phenomenon of backward compatibility effects (BCEs), which show that first-task processing can in fact be affected by second-task response characteristics (e.g., Fischer & Dreisbach, 2015; Hommel, 1998; Janczyk, Pfister, Hommel, & Kunde, 2014; Ko & Miller, 2014; Koch, 2009; Lien & Proctor, 2000, 2002; Logan & Schulkind, 2000; Miller, 2006). For example, the compatibility of R_2 with R_1 influences the first-task RT, demonstrating that second-task responses are at least partially activated in time to influence the latencies of first-task responses (Hommel, 1998). This phenomenon is quite consistent with resource models, according to which both tasks can be processed simultaneously to a certain extent (e.g., Janczyk, 2016). It is not so obviously consistent with the RSB model, however, because of that model's premise that selection of R_2 must wait until selection of R_1 is finished. Nonetheless, a number of investigators have suggested ways of extending the RSB model in order to reconcile it with BCEs (e.g., Hommel & Eglau, 2002; Schubert, Fischer, & Stelzel, 2008).

The PP Paradigm

Given the difficulties in distinguishing between the RSB and resource models based solely on the PRP paradigm, it seems reasonable to consider how well these models can account for results across a wider variety of multitasking paradigms. The PP paradigm, introduced by Miller and Durst (2014, 2015), seems especially promising in this regard because it is closely related to—yet critically different from—the PRP paradigm. The PP paradigm is similar to the PRP paradigm in that it also includes two independent task sets, each with its own S-R assignments. Like the PRP paradigm, it provides precise control over the timing between the stimuli for the two tasks and sensitive RT measures of the time at which each task is completed. The crucial difference is that the participants never make more than one response per trial in the PP paradigm, whereas they usually or always respond to both stimuli in the PRP paradigm. This task change is realized by designating one task as the high priority "primary" task (T_p, with its corresponding S_p and R_p) and the other task as the low priority "background" task (T_b, with its corresponding S_b and R_b). Specifically, the participants are instructed to respond only to S_p when this task requires a response, ignoring S_b completely in that case. A response to the background task stimulus (R_b) is required only in trials for which the primary task stimulus (S_p) requires no overt response (i.e., "no-go R_p").

Miller and Durst (2015) showed that several phenomena demonstrated in the PRP paradigm can also be observed in the PP paradigm. For example, background task RT also decreases markedly as SOA increases, and the effects of S_b perceptual manipulations on RT_b also appear to be absorbed into slack at short SOAs. Overall, their results clearly indicate that the primary task no-go decision ties up the central mechanisms needed for background task response selection in a manner quite similar to that seen in the PRP paradigm.

As can be seen from Figure 1, the RSB model can easily be adapted to describe the PP paradigm in terms of a sequence of stages quite similar to those used to explain the PRP paradigm. Within the PP paradigm, the primary Task T_p is quite analogous to

[1] Note that the division of resources is realized by an additional parameter (i.e., sharing proportion) in these models, which makes these models inherently more flexible than the RSB model.

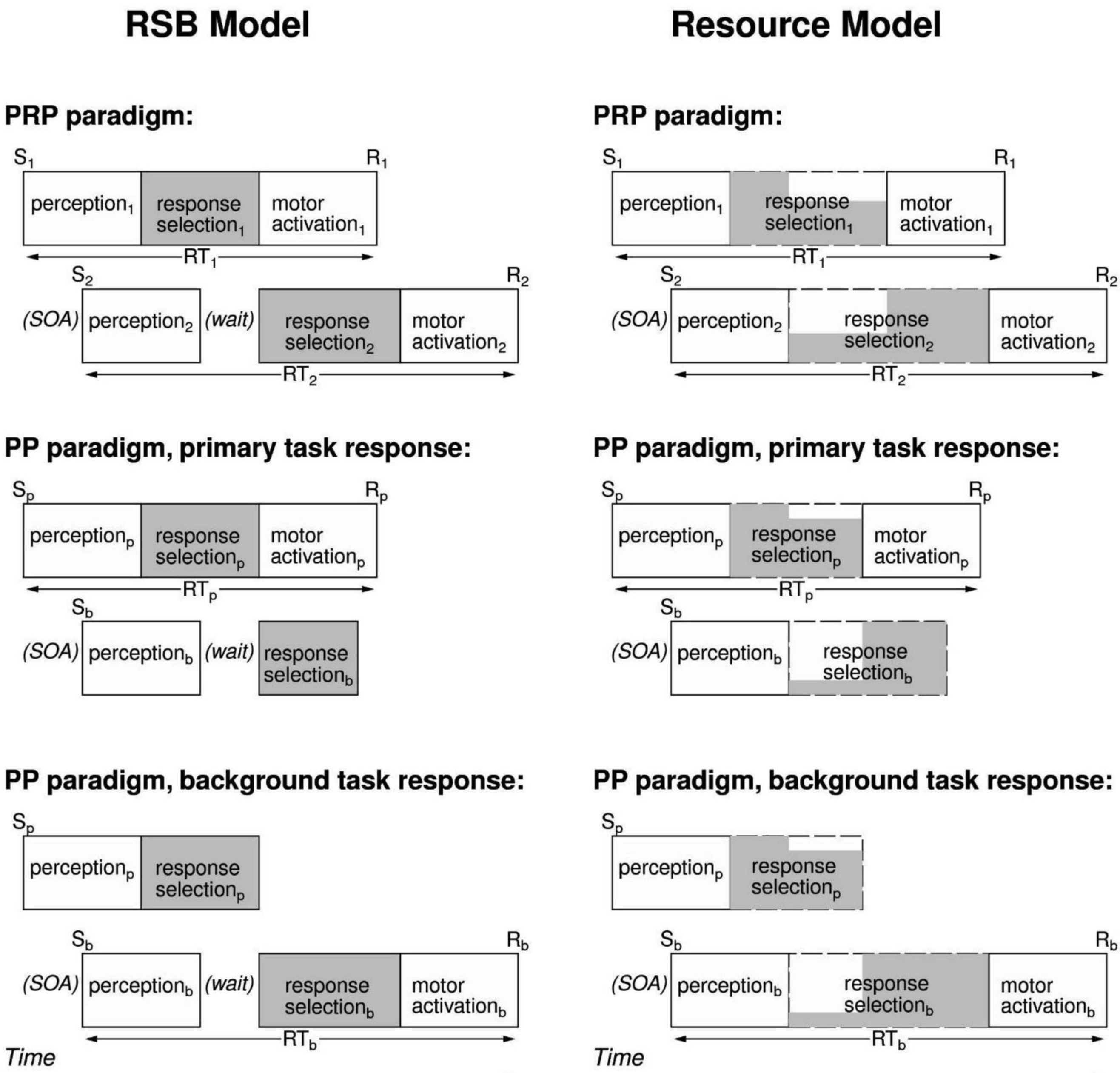

Figure 1. Depictions of the processing sequences in the psychological refractory period (PRP) and prioritized processing (PP) paradigms that are predicted by response selection bottleneck (RSB) and resource models. The two tasks in the PRP paradigm are denoted 1 and 2, whereas the two tasks in the PP paradigm are denoted primary (p) and background (b). In each task, the first stage represents precentral perceptual processes, the second stage represents central response selection processes, and the third stage represents postcentral motor execution processes. Within the PP paradigm, the processing sequence depends on whether the trial requires a response in the primary task or in the background task. The RSB model postulates a bottleneck at the central stage, whereas the resource model assumes that central processes of the two tasks can be processed simultaneously because resources are flexibly shared between tasks. This figure illustrates the idea that more processing resources are allocated to Task 2 in the PRP paradigm than to the background task in the PP paradigm. (After Miller & Durst, 2015, Figure 1, and Case B in Tombu & Jolioeur, 2003, Figure 6.)

the PRP paradigm's T_1, so it is convenient to refer to both of these as the "first" tasks. Similarly, the background Task T_b is analogous to the PRP paradigm's T_2, and we will refer to these as the "second" tasks in the two paradigms. As shown in Figure 1, the RSB model suggests that first-task responses (i.e., R_1 and R_p) would be executed following perceptual, response selection, and response execution stages whenever the first-task stimulus required an overt response (e.g., left or right key press). Whereas in the PRP paradigm a response would always also be selected and executed for T_2, no response would necessarily have to be selected for T_b in the PP paradigm following an actual R_p. BCEs are present in the PP paradigm for these trials (Miller & Durst, 2014), however, suggesting that some background task response selection does take place even though it is not necessary. Background task response selection is definitely required in the PP paradigm when the first-task stimulus T_p requires withholding the execution of R_p (no-go first-task responses), just as it is required for the second-Tasks T_2 in the PRP paradigm. According to the RSB model, in these trials the selection of T_b would have to wait until the no-go response of T_p had been selected, assuming that no-go responses are also selected (e.g., Bertelson & Tisseyre, 1969; Logan, Van Zandt, Verbruggen, & Wagenmakers, 2014), just as T_2 response selection must wait for T_1 response selection in the PRP paradigm. Thus, despite the fundamental difference between the paradigms regarding the number of responses in the same trial (i.e., never more than one response in the PP), the RSB model predicts very similar processing sequences and thus very similar patterns of RTs for the two paradigms.

Resource models can also be adapted to the PP paradigm, of course, as is illustrated in Figure 1. According to these models, the primary and secondary tasks could in principle be processed simultaneously, even in the central response selection stage, although the secondary task would presumably be allocated less processing capacity in the PP paradigm, where it is often ignored, than in the PRP paradigm, where it is always relevant.

Between-Paradigm Differences in First-Task Responses: Limits on Preparation or Differences in Online Processing?

To examine the empirical similarity of the PRP and PP paradigms, Miller and Durst (2015) compared the paradigms with respect to the three classic PRP phenomena predicted by the RSB model. In particular, their studies showed that the paradigms yield similar results with respect to (a) the PRP effect of SOA on RT_2, (b) the absorption of S_2/S_b perceptual effects into slack, and (c) effect propagation. These aspects of their results supported the idea that the RSB model could also be extended to the new PP paradigm. On the other hand, evidence of BCEs was also found in the PP paradigm (Miller & Durst, 2014, 2015), providing evidence for parallel response selection analogous to that found in the PRP paradigm.

Somewhat surprisingly, the results of Miller and Durst (2015) also yielded a few notable empirical differences between the PRP and PP paradigms. Most strikingly, the mean RT_p of the PP paradigm was more than 250 ms less than the mean RT_1 of the PRP paradigm. This remarkable difference is not immediately explained by the RSB models for the two paradigms shown in Figure 1, and it would seem to require some elaborations of the RSB model, as will be considered in detail later. On the other hand, resource models seem to explain the finding quite naturally. The first task would have higher priority in the PP paradigm, where it is often the only task being performed, than in the PRP paradigm, where both tasks are always performed. Because of its higher priority, the first task would receive a larger share of the processing capacity in the PP paradigm than in the PRP paradigm, leading to its faster responses. Thus, we take the advantage of RT_p over RT_1 as a further piece of evidence, in addition to BCEs, that seems more favorable to resource models than to the RSB model.

In the hopes of shedding further light on the distinction between the RSB and resource models, the present study was designed to investigate further the reasons for the difference between the mean RT_1 of the PRP paradigm and the mean RT_p of the PP paradigm. At an empirical level, we investigated two kinds of mechanisms that might be responsible for the advantage for the first task in RT_p relative to RT_1. As is elaborated next, these two types of mechanisms would seem to be differentially compatible with the RSB and resource models.

One possible account of the advantage for RT_p relative to RT_1 is that it results from differential preparation arising before the onset of the first or primary task stimulus. Specifically, there could be a higher degree of preparation for T_p in the PP paradigm than for T_1 in the PRP paradigm. This might be the case, for example, because participants usually only have to perform T_p in the PP paradigm, whereas they always have to perform both tasks in the PRP paradigm (Miller & Durst, 2015). If the degree of preparation is sensitive to relative task frequency, then preparation would be greater for T_p than for T_1, and this might explain the faster first-task responses in the PP paradigm.

At a theoretical level, the idea that preparation differences could account for the RT_p advantage is entirely consistent with both resource and PRP models. Within resource models, preparation would simply involve the pretrial division of processing capacity between the two potential tasks. If the PP primary task received a larger share of the available processing capacity than did the PRP T_1, perhaps because of higher task frequency as just discussed, then RT_p would be less than RT_1.

More important, a preparation-based explanation for the RT_p advantage is also consistent with the RSB model. There is strong evidence that advance preparation has an important influence on performance in PRP tasks (e.g., Bausenhart, Rolke, Hackley, & Ulrich, 2006; De Jong, 1995; De Jong & Sweet, 1994; Koch & Prinz, 2005; Leonhard, 2011), and the idea of task preparation has already been used within the RSB model. Specifically, Pashler (1994a) noted that preparation for a given task would be greater in a single-task condition than in the T_1 of the PRP paradigm, because in the single-task condition it is only necessary to be prepared for one instead of two tasks. Pashler (1994a) used this preparation difference to explain the fact that responses to the first task are generally slowed in the PRP paradigm in comparison to a single-task condition. Analogous reasoning suggests that preparation for the first task would be greater in the PP paradigm than in the PRP paradigm, because in the PP paradigm it is *usually* only necessary to be prepared for the first task. Conversely, R_b is only selected in some trials of the PP paradigm (i.e., no-go R_p), whereas R_2 is selected in every trial of the PRP paradigm. Thus, more preparation should be devoted to the S_2-R_2 mapping in the PRP paradigm than to the S_b-R_b mapping in the PP paradigm. Given that previous studies have indicated a limited capacity for preparatory processes (e.g., Gottsdanker, 1980; Maslovat et al., 2013), the greater preparation of the S_2-R_2 mapping in the PRP paradigm provides a further reason to expect that preparation for the S_1-R_1 mapping would be reduced relative to preparation of the S_p-R_p mapping in the PP paradigm. Similarly, coordination- and switching-related preparatory processes might withdraw preparation from the first task to a greater extent in the PRP paradigm than in the PP paradigm. For example, participants must be prepared for switching to the second task after responding to the first task in the PRP paradigm. The importance of task preparation in task-switching is well-known (e.g., Lien, Ruthruff, Remington, & Johnston, 2005; Luria & Meiran, 2003; for a review, see Kiesel et al., 2010).

Aside from pretrial preparation differences, a second possible account of the advantage for RT_p relative to RT_1, which is not mutually exclusive with the account in terms of differential preparation, is that the RT_p advantage arises at least partly because of first-task processing differences arising *after* the onsets of the second stimuli (i.e., S_2 or S_b). Within resource models, for example, it seems natural to assume that more capacity is allocated to processing of S_2 in the PRP paradigm than to S_b in the PP paradigm, because S_2 always requires a response but S_b does not. If more capacity is allocated to S_2 than to S_b, then there would be correspondingly less capacity for T_1 than for T_p—and thus RT_1 would be longer than RT_p. Of course, such an account of the RT_p advantage would be highly problematic for the RSB model, since that model explicitly denies the idea of graded capacity allocation that is at the heart of this account of the advantage for RT_p. According to the RSB model, first-task processing should not be affected by the presentation of the second stimulus. Perceptual processing of S_2 goes on in parallel with T_1 central processing but does not interfere with it, and central processing of S_2 waits until the first task is finished with the RSB. Thus, the RSB model seems incompatible with the idea that the RT_p advantage arises partly because of reallocation of processing capacity after S_2 onset, rather than being entirely because of differential preparation.

In summary, to compare the RSB and resource models, it seems useful to get further information about the cause of the advantage of RT_p over RT_1. If this advantage arises entirely from differential preparation before the onset of the first stimulus, then it would be fully compatible with both RSB and resource models. Alternatively, if the advantage arises at least partly because of differences in online processing arising after the onset of the second stimulus, then the advantage would be very hard to explain with the RSB model, according to which T_2 processing has to wait until T_1 processing has finished with the bottleneck.

Logic of the Present Experiments

To assess the contribution of online second-task processing to first-task RT, we used a very simple approach in this study. Specifically, the second-task stimulus was omitted in some trials, which we assumed would totally eliminate online processing of S_2/S_b. If part of the advantage for RT_p over RT_1 is because of this online processing, as is allowed by resource models but not by the RSB model, then the advantage should be reduced when the second-task stimulus is omitted (see the Appendix for details concerning the predictions of the two types of models). Obviously, in these trials no second-task response was ever required in either the PRP or PP paradigm, because there was no stimulus indicating what second response to make. On the other hand, if the RT_p advantage is entirely because of preparation-related differences between the two paradigms, as would be allowed by both resource models and the RSB model, then this advantage should not be reduced by omission of the second-task stimulus. Note that we did not directly or specifically manipulate preparation per se in these experiments. Instead, we attribute to "preparation" any RT_p versus RT_1 differences that are present in trials without a second stimulus.

To see whether some of the advantage for RT_p over RT_1 arises after S_2 onset, we included as a control condition trials in which a second-task stimulus was presented but also required no response in either task (i.e., a no-go stimulus for S_2/S_b). These trials are equivalent to the trials without any S_2 in that they require an R_1 but no R_2, thus eliminating any contribution of motor interference to the RT_p versus RT_1 comparison. Importantly, for these trials, some second-task processing was required because a second-task stimulus was presented, so online differences in second-task processing could contribute to the advantage for RT_p over RT_1. Thus, to the extent that the difference between RT_p and RT_1 arises because of between-paradigm processing differences arising after second-stimulus onset, this difference should be larger when the second-task stimulus is actually presented than when it is not.

Overall, then, we compared the performance of the first task (i.e., T_1 and T_p) with and without a second-task stimulus (i.e., no-go S_2 vs. no S_2). To the extent that online differences contribute to the advantage for RT_p, there should be an interaction: the advantage for RT_p over RT_1 should be larger in the trials with a no-go second-task stimulus than in the trials with no second-task stimulus at all. Note that this comparison of the RT_p advantage for no-go versus no-stimulus second-task trials is fully equated with respect to the first-task stimuli and responses and the second-task responses, differing only in the presence/absence of the second-task stimulus. If the interaction is observed, it will indicate that the RT_p advantage over RT_1 is not determined entirely by differential preparation happening in advance of a trial and that first-task responses are at least partially affected by second-task processing, which would seem to challenge a strict RSB model but would be compatible with resource models. Viewed from the opposite perspective, if preparation differences before the onset of a trial entirely explain the difference between RT_1 and RT_p, then the RT_p/RT_1 difference should be the same for no-go and no second-task stimuli (i.e., no interaction).

Experiment 1

The basic tasks used in this experiment were modeled after those used by Miller and Durst (2014, 2015). In each trial, the first-task stimulus was one of three possible letters presented at fixation. These letters were assigned to left index finger, right index finger, and no-go first-task responses. The second-task stimulus was a colored square surrounding the letter, with one color each assigned to left middle finger, right middle finger, and no-go second-task responses. As described in the introduction, the square was omitted completely in some trials to eliminate second-task processing in those trials. Different participants were tested in the PRP and PP paradigms to ensure that there was no contamination of performance in one paradigm by prior experience with the other paradigm.

Method

Participants. Fifty students (37 women) in psychology at the University of Otago, New Zealand, participated in the experiment in partial fulfilment of course requirements. They ranged in age from 18 to 33 years ($M = 20.1$) and 42 were right-handed. Mean handedness score was $M = 52.9$ as measured by the Edinburgh Handedness Inventory (Oldfield, 1971). Each participant was tested in a single experimental session lasting 35–45 min.

Apparatus and stimuli. Participants were tested individually in a dimly illuminated room. Stimulus presentation and recording of responses were controlled by an IBM-PC compatible computer using MATLAB with the Psychophysics Toolbox extension (Brainard, 1997; Pelli, 1997). All visual stimuli were presented as light figures on the black background of a computer monitor, which was viewed from a distance of approximately 60 cm. A centrally positioned white plus sign (+) served as fixation point. Letters were displayed in white at fixation in a 28-point font that subtended approximately 0.7°. Outline squares were also centered at fixation and constructed from lines that were approximately 1.6° in length and 0.2° in thickness. Responses were key presses with the left and right index and middle fingers on the “Z”, “X”, “.”, and “/?” keys of a standard computer keyboard. The index fingers were always used for letter-task responses (i.e., Task 1 or primary task) and the middle fingers for color-task responses (i.e., Task 2 or background task).

Procedure. Half of the participants were tested in the PRP paradigm, whereas the other half were tested in the PP paradigm. For each participant, three consonants were randomly selected for use as stimulus letters, with one each assigned to the left index finger, right index finger, and no-go responses. Similarly, red, green, and blue stimulus squares were assigned randomly to the left middle finger, right middle finger, and no-go responses. Participants were also informed that in some trials no square would appear, which would also require no response; we refer to this condition as the “no-square” condition. Each participant was tested in seven blocks of 84 randomly ordered trials per block (588 trials in total). Specifically, each block included seven presentations of each of the 12 possible stimulus displays defined by the combination of the three possible letters (left, right, no-go) with the four possible squares (left color, right color, no-go color, no-square).

At the beginning of each trial, the fixation cross appeared on the screen for 500 ms. The letter stimulus and square (if any) were displayed simultaneously at the offset of the fixation cross. For trial types with only one required key press, the stimuli remained on the screen until the participant responded, up to a maximum of 2 s. For trial types with two required key presses (which were only possible in the PRP paradigm), the stimuli remained on the screen after the first response for a maximum of another 2 s. After all required responses had been made in a trial, feedback was displayed for 1 s to indicate correct response(s) or for 3 s to indicate that an error had been made.

The experiment started with an instructional screen describing the assignment of the two possible go-letters and go-colors, with instructions not to respond if some other letter or color appeared. Furthermore, participants were instructed to respond as quickly and accurately as possible and to keep their eyes focused on the fixation cross before the stimuli appeared. The remaining instructions differed according to the paradigm.

For the PRP paradigm, participants were instructed to respond first to the letter if either the left or right go letter was shown and to withhold that response if some other letter was shown. After responding to the letter, participants were asked to respond to the color of the square if one of the go-colors was shown and to withhold that response if another color or no square was shown.

For the PP paradigm, participants were instructed to respond first to the letter. If neither of the corresponding go letters was shown, they were instructed to respond to the color of the square and to withhold the response if neither of the go-colors was shown (including the no-square condition).

Results

The first block of trials for each participant was excluded as practice. In addition, trials without any responses (i.e., catch trials) were excluded from any analyses. Trials in which any response error was made were excluded from RT analyses (9.7% in the PP and 9.9% in the PRP paradigm), and no trials were excluded as RT outliers based on lower and upper RT cutoffs of 200 ms and 2 s, respectively.

Letter task: RT_p, RT_1, PC_p, and PC_1. Figure 2 shows the mean letter-task RTs for the interaction of primary interest: no-go square versus no-square second-task stimulus, separately for each paradigm. As is evident in the figure, the mean RT_p advantage was larger when a no-go square was presented ($814 – 676 = 138$ ms) than when no square was presented ($708 – 631 = 77$ ms).

These means were analyzed with an analysis of variance (ANOVA), including the within-subject factor of square presence (i.e., no-go vs. no-square) and the between-subjects factor of paradigm (i.e., PRP vs. PP). This ANOVA revealed a main effect of paradigm, $F(1, 48) = 10.89$, $p = .002$, $\eta_p^2 = .19$. The mean letter-task RTs were 107 ms slower in the PRP paradigm (761 ms) than in the PP paradigm (654 ms). The main effect of square presence was also significant, $F(1, 48) = 127.60$, $p < .001$, $\eta_p^2 = .73$. Letter-task RTs were 75 ms faster with no-square (670 ms) than with the no-go square (745 ms). Most important, the analysis

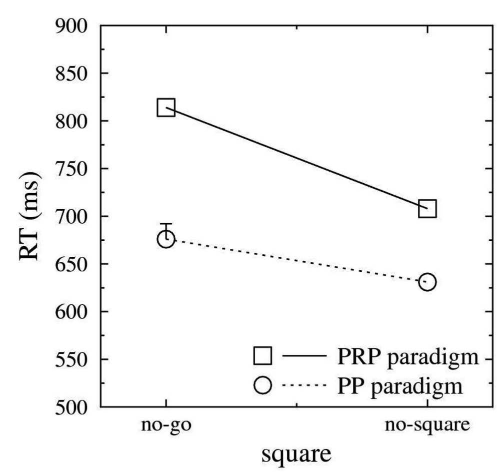

Figure 2. Mean correct reaction time (RT) for the letter task in Experiment 1 as a function of square (no-go, no-square) and paradigm (psychological refractory period [PRP] and prioritized processing [PP]). The error bar indicates 1 *SE* based on the pooled error term of the two main effects and the interaction.

also revealed a significant interaction between paradigm and square presence, $F(1, 48) = 20.61$, $p < .001$, $\eta_p^2 = .30$, as shown in Figure 2. To assess the difference between the paradigms when there was no square to be processed, an additional ANOVA was carried out in which only trials with no-square were included. Thus, this ANOVA of letter-task RTs included only the factor paradigm, and this analysis still showed an advantage of 77 ms for the PP paradigm over the PRP paradigm, $F(1, 48) = 6.50$, $p = .014$, $\eta_p^2 = .12$. The difference between the paradigms was also significant when there was a no-go square to be processed, $F(1, 48) = 14.64$, $p < .001$, $\eta_p^2 = .23$.

A secondary ANOVA of letter-task RTs in trials with left and right go square stimuli was also conducted to check for an effect of backward compatibility. Trials were classified as compatible if the square was assigned to the response made with the same hand as that required by the letter (e.g., left index finger and left middle finger) and as incompatible if the square was assigned to the response made with the opposite hand (left index finger and right middle finger). The ANOVA thus included the within-subject factor of compatibility and the between-subjects factor of paradigm (i.e., PRP vs. PP). For this analysis, 24.3% of the two-response trials were excluded from the analysis of PRP paradigm results (i.e., RT_1) on the basis of response grouping, as indicated by an IRI of 100 ms or less.

This ANOVA again revealed a significant main effect of paradigm, $F(1, 48) = 73.09$, $p < .001$, $\eta_p^2 = .60$. Letter-task RTs were 313 ms slower in the PRP paradigm (991 ms) than in the PP paradigm (678 ms). There was also a significant main effect of compatibility, $F(1, 48) = 39.56$, $p < .001$, $\eta_p^2 = .45$. Letter-task RTs were 63 ms faster with compatible (803 ms) than with incompatible (866 ms) R_2. The analysis also revealed a significant interaction between paradigm and compatibility, $F(1, 48) = 26.64$, $p < .001$, $\eta_p^2 = .36$. As was also reported by Miller and Durst (2015), the BCE was greater in the PRP paradigm (1,049 – 934 = 115 ms) than in the PP paradigm (684 – 672 = 12 ms). Separate ANOVAs for each paradigm revealed that the BCE was significant in the PRP paradigm ($p < .001$) but not in the PP paradigm ($p = .132$).

Overall, letter-task responses of trials with an overt R_p and R_1 were 95.7% correct (96.2% in the PP and 95.2% in the PRP paradigm). ANOVAs parallel to those conducted on the RTs were also conducted on the letter-task PCs. The ANOVA including the within-subject factor square (i.e., no-go, no-square) and the between-subjects factor paradigm revealed no significant effects (all ps $> .158$). The ANOVA including the factors compatibility and paradigm also yielded no significant effects (all ps $> .053$). The descriptive pattern for letter-task PCs was consistent with the one found for letter-task RTs—that is, whenever accuracy differed much across conditions, participants were less accurate in the slower conditions—which rules out a speed–accuracy trade-off as an explanation of the RT differences.

Color task: RT_b, RT_2, PC_b, and PC_2. When comparing color task RTs across the PRP and PP paradigms, we restricted the analysis to trials with no-go R_p and R_1 to compare the paradigms using only trials with the same S-R sequences. An ANOVA with the between-subjects factor of paradigm (i.e., PRP vs. PP) was performed on the color-task RTs. This ANOVA revealed no significant difference between the PP (1,057 ms) and PRP (976 ms) paradigm ($p = .064$).

On average, color-task responses of trials with no-go R_p and R_1 were 90.7% correct. A parallel ANOVA on the PC's yielded also no significant main effect of paradigm ($p = .110$).

Discussion

The primary finding of this experiment is that the advantage for RT_p over RT_1 is larger when a second-task stimulus is presented than when it is not. This suggests that the advantage is determined partly by online processes that are put into motion by S_2/S_b onset. Some advantage is still present when no second-task stimulus is presented, however, so these online processes do not seem to be entirely responsible for the RT_p advantage. As will be considered further in the General Discussion, the influence of the second-task stimulus on the RT_p suggests that the second-task stimulus receives more processing in PRP than in PP, and that this extra second-task processing produces a correspondingly larger interference in first-task RT. This implication is reinforced by the fact that BCEs were much stronger in the PRP paradigm than in the PP paradigm. These findings raise some difficulties for standard RSB model, as will be considered further in the General Discussion, because they imply some overlap in the processing of the two tasks rather than the strict task queueing required by a bottleneck.

Experiment 2

An important limitation of Experiment 1 is that the first- and second-task stimuli were always presented simultaneously (i.e., SOA = 0). This is rather atypical, particularly within the PRP paradigm, and it could have encouraged participants to process the two tasks simultaneously to a greater extent than is normally seen in this paradigm. Thus, the purpose of Experiment 2 was to check whether the findings would still be obtained when the stimuli were presented sequentially. Specifically, SOAs of 100 ms and 300 ms were used.

Method

A fresh sample of 40 students (25 women) from the same pool participated in the experiment. Their ages ranged from 17 to 29 years ($M = 67.9$). Mean handedness score was $M = 67.9$ and 38 were right-handed.

The apparatus, stimuli, procedure, and instructions were the same as in Experiment 1 except as otherwise described. The paradigm (i.e., PRP vs. PP) was again varied between subjects, with 20 participants for each paradigm. An SOA manipulation of the no-square condition was not logically possible, but the no-square condition was nonetheless treated symmetrically to the other square conditions to balance the trial combination possibilities. There were again seven blocks, but this time each block included 72 trials (514 trials in total), with three tests of each of the 12 possible stimuli types (i.e., left/right/no-go letter × left/right/no-go/no-square color) at each of the two possible SOAs (i.e., 100 and 300 ms). The first stimulus (i.e., letter) was displayed immediately at the offset of the fixation cross and the second stimulus was added to the display at the end of that trial's SOA. Both stimuli remained on the screen until the participant responded or for a maximum of 2 s. The stimuli remained on the screen for a maximum of another 2 s if another response was required. RT was measured from the onset of the stimulus to which each response was made.

Results

We followed the same data preparation procedure as in Experiment 1. We excluded 7.7% error trials in the PRP paradigm and 7.4% error trials in the PP paradigm from RT analyses. In the RT analyses of the PRP paradigm, 0.41% of trials with RT_1 greater than 2 s were excluded as slow outliers. In the RT analyses of the PP paradigm, 0.02% of trials with RT_p less than 200 ms were excluded as anticipations, and 0.18% of trials with RT_p (0.08% of trials with RT_b) greater than 2 s were excluded as slow outliers.

Letter task: RT_p, RT_1, PC_p, and PC_1. First, we examined the effect of the appearance of a no-go square in comparison to the no-square condition, while taking SOA into account. For this purpose, we distinguished conditions with a no-go square at short SOA (i.e., no-go-100), a no-go square at long SOA (i.e., no-go-300), and no-square. Figure 3 shows the mean letter RTs for these three conditions plotted separately for each paradigm.

To evaluate these letter-task RTs, we conducted an overall ANOVA including the within-subject factor of square (i.e., no-go-100, no-go-300, no-square) and the between-subjects factor of paradigm (i.e., PRP vs. PP). This ANOVA revealed a significant main effect of paradigm, $F(1, 38) = 24.54$, $p < .001$, $\eta_p^2 = .39$. As can be seen from Figure 3, letter-task RTs were 185 ms faster in the PP paradigm (637 ms) than in the PRP paradigm (822 ms). The main effect of square was also significant, $F(1, 38) = 29.25$, $p < .001$, $\eta_p^2 = .44$. Most important, the ANOVA yielded a significant interaction between the two factors, $F(2, 76) = 14.26$, $p < .001$, $\eta_p^2 = .27$. To investigate this interaction in a manner parallel to Experiment 1, separate square presence × paradigm ANOVAs were carried out for the two different SOAs. In the ANOVA comparing no-go-100 and no-square, the interaction of square with paradigm was marginally significant, $F(1, 38) = 3.04$, $p = .089$, $\eta_p^2 = .07$. In the ANOVA comparing no-go-300 and no-square, the interaction of square with paradigm was highly significant, $F(1, 38) = 26.48$, $p < .001$, $\eta_p^2 = .41$.[2] In the ANOVA comparing no-go-100 and no-go-300, the interaction of square with paradigm was also significant, $F(1, 38) = 14.75$, $p < .001$, $\eta_p^2 = .28$.[3]

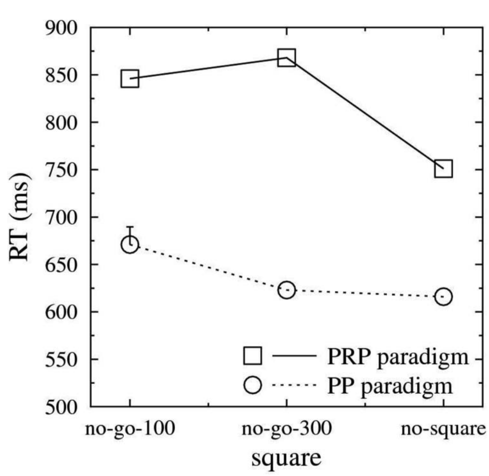

Figure 3. Mean correct reaction time (RT) for the letter task in Experiment 2 as a function of square (no-go-100, no-go-300, no-square) and paradigm (psychological refractory period [PRP] and prioritized processing [PP]). The error bar indicates 1 *SE* based on the pooled error term of the two main effects and the interaction.

As in Experiment 1, a further analysis checked for the letter-task RTs for BCEs. This analysis involved trials with two responses in the PRP paradigm, so 24.63% of trials were excluded from the analysis of the PRP paradigm results on the basis of response grouping, as indicated by an IRI of 100 ms or less. The ANOVA included the within-subject factors of SOA (i.e., 100 vs. 300) and compatibility (i.e., compatible vs. incompatible), as well as the between-subjects factor of paradigm (i.e., PRP vs. PP). This ANOVA again revealed a significant main effect of paradigm with shorter RTs in the PP paradigm (654 ms) than in the PRP paradigm (921 ms), $F(1, 38) = 30.87$, $p < .001$, $\eta_p^2 = .45$. The main effect of SOA was also significant, $F(1, 38) = 9.78$, $p = .003$, $\eta_p^2 = .21$. Letter task responses were faster at long SOA (766 ms) than at short SOA (809 ms). A significant main effect of compatibility yielded faster responses for letter-task RTs with compatible (760 ms) than with incompatible R_2 (815 ms), $F(1, 38) = 23.15$, $p < .001$, $\eta_p^2 = .38$. In addition, the interaction between paradigm and compatibility was significant, $F(1, 38) = 19.11$, $p < .001$, $\eta_p^2 = .34$. BCEs were again much stronger in the PRP paradigm (973 – 869 = 104 ms) than in the PP paradigm (657 – 652 = 5 ms). Separate ANOVAs for each paradigm revealed that the BCE was significant in the PRP paradigm ($p < .001$) but not in the PP paradigm ($p = .574$).

Overall, letter-task responses of trials with an overt R_p and R_1 were 95.5% correct (95.7% in the PP and 95.2% in the PRP paradigm), and analyses of PC were conducted parallel to those of RT. An ANOVA including the within-subject factor square (i.e., no-go-100, no-go-300, no-square) and the between-subjects factor paradigm revealed no significant effects (all *p*s > .621). An ANOVA including the within-subject factors SOA and compatibility, as well as the between-subjects factor of paradigm, revealed a significant main effect of SOA, $F(1, 38) = 9.04$, $p = .005$, $\eta_p^2 = .19$. Responses were more accurate at the long SOA (94.8%) than at the short SOA (92.5%). The interaction between compatibility and SOA was also significant, $F(1, 38) = 6.24$, $p = .017$, $\eta_p^2 = .14$. Separate ANOVAs for each SOA revealed that accuracy was higher with compatible (93.6%) than with incompatible R_2 (91.3%) at short SOA ($p = .014$), but not at long SOA ($p = .496$).

Color task: RT_b, RT_2, PC_b and PC_2. An ANOVA with the within-subject factor SOA (i.e., 100 ms vs. 300 ms) and the between-subjects factor paradigm (i.e., PRP vs. PP) was performed on the color-task RTs. Figure 4 shows the mean RTs for the two SOAs plotted separately for each paradigm.

[2] Note that these two ANOVAs are statistically dependent because they both involve the no-square condition as comparison.

[3] Separate ANOVAs for each paradigm revealed a significant main effect of square in the PRP paradigm, $F(2, 38) = 22.34$, $p < .001$, $\eta_p^2 = .54$, and in the PP paradigm, $F(2, 38) = 19.60$, $p < .001$, $\eta_p^2 = .51$. Pairwise comparisons (Bonferroni-adjusted *p* values) indicated that letter-task RTs in the PRP paradigm were shorter with no-square (751 ms) than with no-go-100 (846 ms) or no-go-300 (868 ms), *p*s < .001, but the latter two conditions did not differ significantly from each other ($p = .562$). Letter-task RTs in the PP paradigm were longer with no-go-100 (671 ms) than with no-go-300 (623 ms) or no-square (616 ms), *p*s < .001, but the latter two conditions did not differ significantly from each other ($p > .999$).

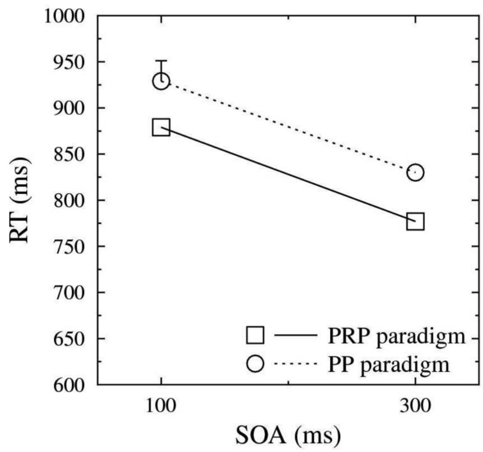

Figure 4. Mean correct reaction time (RT) for the color-task in Experiment 2 as a function of stimulus onset asynchrony (SOA) and paradigm (psychological refractory period [PRP] and prioritized processing [PP]). The error bar indicates 1 *SE* based on the pooled error term of the two main effects and the interaction.

This ANOVA revealed a significant main effect of SOA, $F(1, 38) = 78.28$, $p < .001$, $\eta_p^2 = .67$. Responses were faster at the long SOA (803 ms) than at the short SOA (904 ms), as is typical in PRP paradigms. Furthermore, the decrease of color-task RTs with increasing SOA was similar in the PRP (−0.51 slope) and PP (−0.50 slope) paradigms, as can be seen in Figure 4 and is indicated by the nonsignificant interaction ($p = .927$).

On average, color-task responses of trials with no-go R_p and R_1 were 93.0% correct. A parallel ANOVA on the PC's revealed that accuracy was higher in the PRP paradigm (95.1%) than in the PP paradigm (90.8%), $F(1, 38) = 7.16$, $p = .011$, $\eta_p^2 = .16$.[4]

Discussion

The results of this experiment replicate Experiment 1's finding that RT_1 is more strongly reduced by the omission of a second stimulus than is RT_p. In particular, Experiment 2 generalizes this finding to paradigms with SOAs between the stimuli of the two tasks, as is typical especially in the PRP paradigm. These results thus provide further support for the idea that part of the RT_p advantage stems from online processing adjustments that take place after the second-task stimulus appears.

General Discussion

The main findings of these two experiments are that (a) first-task RT is longer when a second-task stimulus is presented than when it is not and that (b) this effect is larger for the PRP paradigm than for the PP paradigm. Specifically, the onset of the second-task stimulus prolongs first-task processing to a greater degree in the PRP paradigm than in the PP paradigm. Thus, we conclude that the RT_p advantage over RT_1 is not entirely because of between-paradigm differences in processes that take place before first-stimulus onset, which we have collectively designated as preparatory processes. Instead, the interaction suggests that some of the RT_p advantage arises because of changes in first-task processing that take place online—that is, after the onset of the second-task stimulus. As was elaborated in the introduction, these results have implications for the debate concerning RSB and resource models.

Implications for Bottleneck Models

In general, effects of the presence of a second task on first-task processes in a PRP paradigm are not directly predicted by the RSB model (e.g., Strobach, Schütz, & Schubert, 2015). A number of theorists, however, have previously proposed that such models must incorporate a contribution for task preparation in addition to the bottleneck assumption (e.g., Pashler, 1994a). Indeed, a preparation-based explanation provides a plausible account of first-task slowing in multitasking situations (i.e., first-task responses are slowed in the PRP paradigm in comparison to a single-task condition). The present study provides further evidence for the importance of preparatory effects on first-task performance by showing that RT_p is faster than RT_1 even without a second-task stimulus. This difference cannot be attributed to differential influences of second-task processing in the two paradigms, since there is no second-task stimulus to be processed. Instead, differential first-task preparation in the two paradigms seems the most likely explanation of the difference. Thus, our findings extend previous demonstrations of the importance of preparation by focusing explicitly on first-task performance in two similar dual-task settings (i.e., the PRP and PP paradigms) and by explicitly excluding any impact of second-task stimulus processing on the first-task slowing. As outlined in the introduction, there are a number of reasons why preparation might be more focused on the first task in the PP paradigm than in the PRP paradigm.

More important than providing further evidence of the importance of task preparation, however, the present results establish that the effect of second-task stimulus onset on first-task RT differs between the PP and PRP paradigms. These between-paradigm differences in first-task RT resulting from the onset of a second-task stimulus are especially important because they seem very difficult to reconcile with the RSB model, even if this model is elaborated to include preparation effects. During first-task processing, the model says that the second-task stimulus is only processed by unlimited capacity perceptual processes, and it is then held to await access to the bottleneck. Such unlimited capacity second-task processing would not be expected to slow first-task responses relative to trials in which no second-task stimulus was presented. Although some distracting effect of the second-stimulus onset could be postulated to explain the first-task slowing, the RSB model would still need further modification to explain why RT_1 and RT_p are differentially sensitive to second-task stimulus onset. Obviously, the second stimulus is more relevant in the PRP paradigm, where it always requires a response, than in the PP paradigm, where it less often requires a response. It is not clear why this would matter, however, if the first task had sole access to the bottleneck, as assumed by the RSB model.

To reconcile RSB models with the presence of a larger effect of the second-task stimulus on first-task RT in the PRP paradigm than in the PP paradigm, it seems necessary to postulate a source of noncentral interference that is stronger in the PRP paradigm than in the PP

[4] We also conducted parallel ANOVAs on the PC's of color-task responses for Experiment 1 and 2 while also considering trials as error when subjects responded to a no-go letter. These ANOVAs revealed no significant effects in Experiment 1 ($p = .380$) and Experiment 2 (all $ps > .064$).

paradigm. Because the number of potential responses is the fundamental between-paradigm difference, this extra source of interference could arise at a motor level. Consistent with that idea, several studies have provided evidence for motor-level processing limitations in PRP tasks (e.g., Bratzke, Rolke, & Ulrich, 2009; Bratzke et al., 2008; Ulrich et al., 2006). Thus, extra motor-level interference caused by second-stimulus onset could explain the greater slowing in the PRP paradigm associated with the appearance of the second-task stimulus. For example, the onset of the second-task stimulus might produce inhibitory effects on first-task motor processing. Unfortunately, this explanation is at odds with the RSB model's fundamental assumption that a central bottleneck is responsible for all between-task interference that arises after stimulus onsets (i.e., excluding preparation effects).

To reconcile the RSB model with the presence of backward compatibility effects (BCEs), some authors have also argued that parallel response activation might occur after the perceptual stage and before the serial response selection stage takes place (e.g., Hommel, 1998). As far as we can see, however, this extended RSB model does not provide an account for the present finding of a larger S_2 effect on first-task RT in the PRP paradigm than in the PP paradigm. Neither the no-go S_2's nor the absent S_2's involved in this comparison should have caused any response activation in either paradigm, so the first-task RT difference between the two paradigms cannot logically have arisen from such activation.

Implications for Resource Models

Contrary to the RSB model, it seems most natural to explain the interaction of paradigm and second-stimulus presence by suggesting that the second stimulus draws more resources away from first-task processing in the PRP paradigm than in the PP paradigm. In contrast to the RSB model, resource-based models of multitasking interference allow parallel processing of two tasks at a central stage (e.g., Navon & Miller, 2002; Tombu & Jolicoeur, 2003), and these models can easily explain the present results. First, the observed preparation differences are entirely consistent with these models. It is plausible to assume that capacity is preallocated before the onset of a trial based on anticipated processing requirements. Before the trial starts, for example, participants allocate 20% (80%) of their capacity to the second task (first task) in the PRP paradigm, whereas they only allocate 10% (90%) of their capacity to the corresponding tasks in the PP paradigm. The different divisions of processing capacity in advance of a trial would result in different first-task processing speeds even without the presentation of a second-task stimulus.

In addition, resource models provide a plausible explanation of why the presence of a second-task stimulus slows first-task processing more in the PRP paradigm than in the PP paradigm. According to these models, second-stimulus onset would cause some of the available processing resources to be withdrawn from first-task processing and reallocated to second-task processing. Importantly, though, it is plausible that more capacity would be reallocated to process the second-task stimulus in the PRP paradigm than in the PP paradigm, resulting in the interactive effect, because the second task is more important in the PRP paradigm than in the PP paradigm. Extending the previous example, when the second stimulus appears, participants might reallocate 40% of their capacity to the second task in the PRP paradigm but only reallocate 20% of their capacity to the second task in the PP paradigm. Taken together, the assumptions of differential pretrial allocation of processing capacity and differential online capacity reallocation in the two paradigms would explain the RT_p advantage, its dependence on the presence of the second-task stimulus, and the change in this dependence across paradigms. For this explanation to be correct, of course, there must be some control over the change of capacity allocation after second-stimulus onset, but the idea of flexible online capacity allocation is part of most resource models (e.g., Tombu & Jolicoeur, 2002). Note that flexible allocation of resources also predicts that first-task responses should be slower when SOA is short than when SOA is long, because the first task would receive more processing with full resources (i.e., before reallocation) with the long SOA. This pattern was observed in the two paradigms of Experiment 2 whenever S_2 indicated a left or right response, although only in the PP paradigm and not in the PRP paradigm when S_2 indicated a no-go response.

It is interesting to note that the RT_p advantage (i.e., interaction of S_2 Presence/Absence × Paradigm) in the second experiment was larger at SOA = 300 ms than at SOA = 100 ms. This finding is difficult to explain not only with bottleneck models but also with resource models. According to resource models, the overlap between central stages should decrease with increasing SOA so that less resources are withdrawn from first-task processing. Consequently, the RT_p advantage should be smaller rather than larger at the longer SOA. At present, we have no explanation for this result in terms of either bottleneck or resource models, and this is an issue that should be investigated in further studies.

Implications for Backward Compatibility Effects

Although it was not the main focus of our experiments, we note that resource models also seem more capable than bottleneck models of explaining the stronger BCEs in the PRP paradigm relative to the PP paradigm. In fact, BCEs were even only descriptively present in the PP paradigm—not reliably so—which suggests that participants were quite successful in shielding first-task processing from between-task interference in the present PP paradigm, although not in previous PP studies (e.g., Miller & Durst, 2014). We speculate that the consistent assignment of the background task stimuli to a less dominant finger (i.e., middle finger) might produce less interference compared with, for example, using the same finger for both tasks (e.g., Miller & Durst, 2014). This difference in S-R assignments might also help to explain why Miller and Durst (2014) observed slower primary task RTs with a no-go S_2 than with a choice S_2, whereas the opposite was observed in the present studies.

In general, the finding that first-task responses may be affected by the response associated with the second-task stimulus has often been regarded problematic for the RSB model (e.g., Hommel, 1998). Even if additional assumptions are added to the RSB model to reconcile it with BCEs (Hommel & Eglau, 2002), further additional assumptions would be required to explain why BCEs are stronger in the PRP paradigm than in the PP paradigm. In contrast, the idea that first-task processing could be influenced by parallel second-task processing is predicted by the core assumptions of resource models. In addition, resource models are compatible with the finding of stronger BCEs in the PRP than in the PP paradigm, based on the idea of greater allocation of capacity to the second task in the PRP paradigm, as explained earlier. Thus, the dependence of the present BCEs on the paradigm is quite consistent with the idea that the advantage for RT_p over RT_1 arises after the onsets of the second stimuli because of more second-task processing in the PRP paradigm relative to the PP paradigm. Moreover, the finding that the BCE on RT_1 did not vary as a function of SOA as has been demonstrated in other dual-task studies (e.g., Janczyk, 2016) suggests that the range of SOAs was not sufficiently wide to demonstrate this interaction in the present studies.

Implications for Alternative Models of Multitasking

Although we have presented the current experiments within the context of bottleneck and resource models for multitasking limitations, the findings might also be considered within the context of several more detailed alternative models that have been proposed within the multitasking literature. For example, there are the Executive Process/Interactive Control (EPIC) model (Meyer & Kieras, 1997a, 1997b), the Executive Control of the Theory of Visual Attention (ECTVA) model (Logan & Gordon, 2001), the Threaded Cognition model (Salvucci & Taatgen, 2008), and Outcome Conflict models (Navon, 1984). Although these models differ from each other in many important respects, all of them have in common with resource models the assumptions that (a) parallel central processing of multiple tasks is possible under at least some circumstances, and (b) between-task interference can change online as a function of the instantaneous processing requirements of each task. Given that each of these models is flexible enough to accommodate the different processing requirements within the PRP versus PP paradigms, all of the models appear to be compatible with the finding that S_2 onset causes different amounts of interference in the two paradigms. It may be worth investigating whether these different models make differential predictions concerning the effects of other manipulations within the PRP versus PP paradigms.

Conclusion

In the present study, we separated the contributions of preparation and online processing to dual-task decrements by comparing first-task performance in the PRP and the PP paradigms with and without a second-task stimulus. The results of two experiments suggest that both task preparation in advance of a trial and processing differences after the onset of a second stimulus contribute to those dual-task decrements in first-task response times. The processing differences that arise after second-stimulus onset seem particularly difficult to reconcile with a bottleneck model, whereas resource models provide a natural explanation of them. Thus, we suggest that these results provide new evidence in favor resource-based accounts of dual-task decrements over bottleneck accounts.

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(*Appendix follows*)

Appendix

Predictions of Response Selection Bottleneck (RSB) and Resource Models

In this appendix, we present a more formal analysis of the predictions made by bottleneck and resource models concerning the relative effects on reaction time $(RT)_1$ versus RT_p of our main experimental manipulation of presenting versus omitting S_2. In particular, these analyses will show that (a) the RSB model predicts the same RT_1-RT_p difference whether S_2 is presented or not, whereas (b) resource models predict a larger RT_1-RT_p difference when S_2 is presented than when it is not, given the plausible assumption that participants allocate a smaller proportion of the limited-capacity processing resources to the second task in the PP paradigm—where it often requires no response—than in the PRP paradigm, where it requires a response in each trial. Thus, evidence that the size of the RT_1-RT_p difference increases when S_2 is presented would pose difficulties for the RSB model but would be compatible with resource models.

Predictions of the Bottleneck Model

According to the RSB model, the first-task RTs for the two paradigms may be written as:

$$RT_1 = A_{1,prp} + B_{1,prp} + C_{1,prp}$$
$$RT_p = A_{1,pp} + B_{1,pp} + C_{1,pp}$$

where A, B, and C indicate the durations of the perceptual, response selection, and motor stages, respectively, of each task (1 or 2) in each paradigm (PP or PRP). The durations of the first-task stages could differ across paradigms (e.g., $B_{1,prp} \neq B_{1,pp}$) if the preparation for Task 1 differed between the two paradigms, and this would cause RT_1 and RT_p to differ. Critically, however, these same equations would apply whether S_2 was presented or not, because second task processing has no effect on first task RT. Thus, bottleneck models predict that the $RT_1 - RT_p$ difference would be the same regardless of S_2 presentation, as is illustrated for a numerical example in Table A1. For this example, as is needed to explain the existence of the $RT_1 - RT_p$ difference, we assumed that Task 1 is better prepared in the PP paradigm than in the PRP paradigm because of the extra Task 1 emphasis in PP, with the extra preparation affecting only the time needed for Stage B.

Predictions of Resource Models

Resource models make the same RT_1 predictions as bottleneck models for trials in which S_2 is absent, because in these trials Task 1 is processed centrally with full resources for as long as needed:

$$RT_1 = A_{1,prp} + B_{1,prp} + C_{1,prp}$$
$$RT_p = A_{1,pp} + B_{1,pp} + C_{1,pp}$$

Table A1
Predicted Reaction Time $(RT)_1$ and RT_p Values and Their Difference for the Response Selection Bottleneck (RSB) and Resource Models as a Function of Whether the Second-Task Stimulus (S2) Is Present or Absent

Condition	RT_1 (ms)	RT_p (ms)	$RT_1 - RT_p$ (ms)
	RSB model		
S_2 present	700	600	100
S_2 absent	700	600	100
	Resource model		
S_2 present	786	618	168
S_2 absent	700	600	100

Note. Both model's predictions were computed with parameter values of stimulus onset asynchrony (SOA) = 100, $A_{1,Prp} = A_{1,Pp} = 200$ ms, $B_{1,prp} = 300$ ms, $B_{1,pp} = 200$ ms, and $C_{1,prp} = C_{1,pp} = 200$ ms. For the Resource model, the parameters of $SP_{1pp} = .85$ and $SP_{1prp} = .7$ were used.

In contrast, when S_2 is presented, central processing of the second task can proceed in parallel with central processing of the first task, and first-task central processing is slowed by a reduction in resources during this phase of parallel processing.[5] According to one formalization of this idea illustrated in Figure 1 (e.g., Navon & Miller, 2002; Tombu & Jolicoeur, 2003),

$$RT_1 = A_1 + (SOA + A_2 - A_1) + [B_1 - (SOA + A_2 - A_1)]/SP_1 + C_1,$$

where $0 < SP_1 < 1$ is Task 1's "sharing proportion"—that is, the proportion of resources allocated to Task 1 during the phase of parallel central processing. In particular, as is illustrated in Figure 1, Task 1 central processing proceeds with full resources from Time A_1 to time $SOA + A_2$, thereby accomplishing $SOA + A_2 - A_1$ units of first-task response selection during that time. Starting at time $SOA + A_2$, Task 1 has only a proportion SP_1 of the total resources. As a result, Task 1 central processing slows down, and the time $[B_1 - (SOA + A_2 - A_1)]/SP_1$ is needed to complete the remaining Task 1 response selection processing. In this case the total time for Task 1 response selection is $SOA + A_2 - A_1 + [B_1 - (SOA + A_2 - A_1)]/SP_1$, which is greater than B_1 if $SP_1 < 1$.

[5] For simplicity, we consider only the situation in which Task 1 initially has 100% of the resources in the central stage, and in which resources are shared with Task 2 when that task is also ready for central processing, which happens at time $SOA + A_2$.

(*Appendix continues*)

As was the case for the bottleneck model, this model must be applied separately to the PRP and PP paradigms, since the stage durations may depend on the paradigm:

$$RT_{1,prp} = A_{1,prp} + (SOA + A_{2,prp} - A_{1,prp}) + [B_{1,prp} - (SOA + A_{2,prp} - A_{1,prp})]/SP_{1,prp} + C_{1,prp}$$

$$RT_{1,pp} = A_{1,pp} + (SOA + A_{2,pp} - A_{1,pp}) + [B_{1,pp} - (SOA + A_{2,pp} - A_{1,pp})]/SP_{1,pp} + C_{1,pp}$$

It is also reasonable to assume that the proportion of resources devoted to Task 1 (i.e., SP_1) differs between the two paradigms. Specifically, more processing resources would be withdrawn from first-task processing and allocated to second-task processing in the PRP paradigm—where a Task 2 response is required in every trial—than in the PP paradigm—where Task 2 is ignored on many trials. This implies that $SP_{1,prp} < SP_{1,pp}$.

Under these assumptions, resource models predict that the $RT_1 - RT_p$ difference would be larger when S_2 is presented than when it is not, as is illustrated for a numerical example in Table A1.[6]

[6] The models also make predictions concerning second task RTs, but these are not examined in detail because our main experimental comparisons involve trials with no second-task responses. In order to demonstrate, however, that the models make the same predictions for second task RTs, we used the same parameters as in Table A1 and simply assumed that a no-go response had to be selected in the first task and the second-task required a response. We incorporated preparation differences for Task 2 analogous to our Task 1 assumption (i.e., $B_{2,prp} = 200$ ms, $B_{2,pp} = 300$ ms) and used the same Task 1 parameters for the other Task 2 stages (i.e., $A_{2,prp} = A_{2,pp} = 200$ ms and $C_{2,prp} = C_{2,pp} = 200$ ms). Under these assumptions, both RSB and resource models predict $RT_2 = RT_b = 800$ ms.

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