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“Just do it when you get a chance”: the effects of a background task on primary task performance

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Abstract Two experiments investigated multitasking performance with a new “prioritized-processing paradigm” in which participants responded only to a high-priority primary task when this task required some action, responding to a low-priority background task only when no action was required for the primary task. In both experiments, performance was worse on the primary task than on the same task performed in isolation, indicating that this attempt to give absolute priority to the primary task is not sufficient to protect it from multitasking interference. Multitasking interference was present for task-repetition trials as well as task-alternation trials, so the interference could not be completely explained as a task-switching cost. In addition, responses to the primary task were influenced by their compatibility with the responses associated with the stimulus for the background task, indicating that there was some activation of S-R associations within the background task even when this task did not require any response. The findings generalize a number of effects from the psychological refractory period and task-switching paradigms to the prioritized-processing paradigm, thereby providing hints as to the underlying mechanisms responsible for those effects. The “prioritized-processing paradigm” appears to have several desirable features for the study of multitasking interference.

Keywords Multitasking interference · Task priority · Reaction time

Recent technological advances—particularly in communication—offer greatly increased opportunities and demands for multitasking (e.g., Appelbaum, Marchionni, & Fernandez, 2008; Gleick, 1999; Rosen, 2008). It is widely recognized, however, that people’s cognitive abilities to handle multiple tasks simultaneously are severely limited. Such limitations have been extensively documented and explored through research investigating attentional capacity (e.g., Navon & Gopher, 1979, Norman & Bobrow, 1975, 1976; Wickens, 1984), bottlenecks in central decision-making processes (e.g., Pashler, 1992; Welford, 1967), mutual interference between cognitive processes involved in different tasks (e.g., Bergen, Medeiros-Ward, Wheeler, Drews, & Strayer, 2013; Chong, Mills, Dailey, Lane, Smith, & Lee, 2010; Dutta, Schweickert, Choi, & Proctor, 1995; Hazeltine, Ruthruff, & Remington, 2006; Meyer & Kieras, 1997; Navon & Miller, 1987), and the performance decrements that arise when people must switch among different tasks (e.g., Jersild, 1927; Rogers & Monsell, 1995). Although there appear to be some cases in which people can carry out multiple highly practiced continuous tasks with little interference (e.g., Peterson, 1969; Shaffer, 1975; Spelke, Hirst, & Neisser, 1976), there are good reasons to suspect that such dual-task situations allow intermittent processing of separate chunks within each task (Pashler, 1998, p. 270). Numerous studies with discrete tasks that prevent such chunking have revealed only a few exceptions to the generalization that performance worsens when multitasking is required (e.g., Brebner, 1977; Greenwald & Shulman, 1973; Schumacher et al., 2001). Moreover, multitasking limitations appear to have important implications not only in labo-

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ratory experiments but also in real-world situations (e.g., Hembrooke, & Gay, 2003)—perhaps most famously that of texting while driving (e.g., Janssen, Brumby, & Garnett, 2012; Levy & Pashler, 2008; Strayer & Drews, 2004).

In light of the cognitive limitations on multitasking, one obvious and appealing strategy for optimizing performance on an especially important task is to give it maximum priority. In theoretical terms, this could mean, for example, (a) giving it all available attentional capacity both during task execution itself and during any advance task preparation phase, (b) giving it privileged access to the central bottleneck, and (c) shielding its processes from interference generated by low-priority tasks. An extreme version of the task-emphasis strategy is to focus entirely on one task at a time, and this strategy certainly has its advocates as a way of optimizing performance (e.g., Ferriss, 2007). In the limit, focusing completely on a single task produces single-task performance *by definition*, so it is tautological to say that people suffer no multitasking interference when they do this. It is not clear, however, just what conditions are required for people to achieve single-task focus within a situation with the potential for multitasking. The experiments reported in this article investigated this issue using a new experimental task designed to put a particularly strong emphasis on a primary task within a multitasking situation. The central question was whether the strong emphasis would enable participants to achieve a single-task focus within the multitasking situation, thereby eliminating the multitasking decrement.

Our prioritized-processing paradigm is a variant of the well-known psychological refractory period (PRP) paradigm (e.g., Davis, 1962; Pashler, 1984; Telford, 1931; Welford, 1952), so it is useful to begin by reviewing that paradigm and some of its major results. We will then introduce the prioritized-processing paradigm and highlight its main features that might enable participants to escape multitasking interference.

In PRP studies, participants are presented with stimuli for two separate tasks in each trial, and they must make the responses for both tasks as rapidly as possible (e.g., Karlin & Kestenbaum, 1968). Typically, the stimuli for the two tasks (S_1 and S_2) are presented sequentially in each trial, separated by a short stimulus onset asynchrony (SOA). Either explicitly or implicitly, participants are usually encouraged to make the responses for the two tasks (R_1 and R_2) in the same order in which the stimuli are presented, thereby emphasizing the priority of the first task.

Two kinds of multitasking interference are commonly observed in PRP tasks. Most studies have focused on the so-called "PRP effect", which is the finding that second-task responses are substantially slowed when SOA is short. This effect indicates that performing the higher-priority T_1 greatly interferes with the processing required to make the lower-priority R_2. For the present purposes, though, the multitasking interference suffered by the low-priority T_2 is somewhat tangential to the question of when people can fully protect a high-priority task—here, T_1—from interference.

The other type of multitasking interference observed in PRP tasks, which is of major concern for the present investigation, is that high-priority T_1 responses are generally slower than responses in a single-task condition where the same T_1 is the only task being performed (e.g., Schumacher et al., 2001). This slowing of responses to the high-priority task shows that participants in PRP tasks do not fully protect the high-priority T_1 from interference by the low-priority T_2. Thus, giving T_1 higher priority in the standard PRP task does not protect its performance from impairment by the concurrent lower priority T_2. Evidently, the priority given to T_1 is not high enough to avoid multitasking interference.

The fact that a high-priority T_1 suffers interference from a low-priority T_2 in the PRP paradigm does not mean that a high-priority task could never be protected from multitasking interference, so it is difficult to know how widely to generalize the multitasking interference found in PRP studies. One reason is that participants may only partially prioritize T_1 over T_2 in PRP tasks. Graded manipulations of task priorities—either by instructions or by payoffs—do have clear effects on multitasking interference, so it is possible that the multitasking interference on T_1 could disappear with an even stronger emphasis on T_1 priority. This theoretical limit has not yet been reached, however, because previous studies have always found that primary tasks are still performed worse than they are in isolation (e.g., Hiscock, 1982; Janssen et al., 2012; Levy & Pashler, 2008; Navon & Gopher, 1979). A second reason is that the precise causes of T_1 interference have not yet been identified. For example, one explanation of the interference is that participants withdraw some capacity from T_1 so that they can process T_2 in parallel to some extent (e.g., Navon & Miller, 2002; Tombu & Jolicoeur, 2002)—a strategy that may help optimize performance under some conditions (Miller, Ulrich, & Rolke, 2009). Alternatively, it may be difficult to maintain optimal T_1 preparation because some preparation for T_2 must also be maintained (e.g., Gottsdanker, 1980; Pashler, 2000). A third possibility is that T_1 slowing results from an occasional strategy of holding back R_1 so that it can be emitted simultaneously with R_2 (i.e., response grouping), which is known to be a common strategy in PRP tasks (e.g., Borger, 1963; Ulrich & Miller, 2008).

Levy and Pashler (2008) carried out what is arguably the strongest previous attempt to maximize the priority of one task within the PRP setting, and they found that the strongly prioritized task was not completely protected from interference. Specifically, they studied performance in a simulated driving situation, and the high-priority task was to make a braking response as quickly as possible when a visual or tactile stimulus was presented. The low-priority task required participants to discriminate between one versus two brief tones. Participants were explicitly encouraged to give the braking task maximal priority, and they were even instructed that they could ignore the tones completely when the braking response was required. Nonetheless, braking responses were still subject to interference from concurrent tones, indicating that the braking task had not been completely protected from multitasking interference despite its high priority.

Several features of Levy and Pashler (2008) design may have made it difficult for participants to maximize the braking task's priority, however. Crucially, single-task tone trials were randomly intermixed with dual-task trials, and tones were sometimes presented first in the dual-task trials. Thus, when a tone was presented, participants would initially have been uncertain whether they were experiencing a single-task tone trial—in which case they should start processing the tone immediately—or a dual-task trial—in which case they should defer tone processing until after braking had been accomplished in the interests of optimizing braking-task performance. Levy and Pashler (2008) suggested that participants sometimes started processing the leading tone within dual-task trials in order to minimize their RTs in the single-task tone trials, from which they argued that their experiment essentially addressed the question of "whether people can interrupt the performance of one [low-priority] task in favor of a driving task that is assigned high priority" (Levy & Pashler, 2008, pp. 521–522). Levy and Pashler (2008) concluded that people could not do that, and they favored an account in which the two tasks raced to take over a single-channel response selection bottleneck, with braking-task performance suffering whenever the tone task won the race. The possibility remains open, then, that primary task performance would not have suffered any interference in a paradigm giving participants no incentive to start processing the low-priority task until after processing of the high-priority task had finished.

The prioritized-processing paradigm used in the present studies was designed to create a multitasking situation in which one task would receive higher priority than is allocated to the first of two PRP tasks, even with extreme prioritization instructions like those used by Levy and Pashler (2008). The present conditions were intended to mimic those found in many applied settings, where people attempt to focus completely on a primary task, but stimuli for potentially distracting background tasks are also present. In these situations, people often attempt to squeeze in a bit of background task processing when they can do nothing on the primary task. As an example, during office hours, a professor concentrates on the primary task of meeting with students but might also attempt to make progress on the background task of writing a research article when no students were present.

Specifically, these conditions were implemented by instructing participants to make only one response in each trial. One task was designated as the primary task, and participants were instructed that they should respond to this task whenever it required a response, completely ignoring the other task in that case. The other task was designated as the background task, and participants were instructed that they should respond to this task only when the primary task required no response. Intuitively, these instructions provide even stronger emphasis on the primary task than does the PRP paradigm, because the low-priority background task is completely ignored whenever primary task processing is required. In addition, responses were required more often for the primary task than for the background task (67 % versus 22 % of trials, with 11 % no-go trials), which also tends to emphasize the primary task. Furthermore, in our experiments, the background-task stimulus was never presented before the stimulus for the primary task, so participants would never have been tempted to start processing the lower-priority task while waiting for a primary task stimulus. Our central question, then, was whether multitasking interference would be eliminated when the background task was always to be considered second and was only to be performed after determining that the primary task required no action. To assess multitasking interference, we compared the performance of the high priority task in multitasking blocks against performance of the same task in single-task blocks.

When comparing primary task multitasking performance against single-task performance, task-switching must be considered as one possible source of interference. Previous studies with interleaved tasks—as are found in our multitasking blocks but not our single-task blocks—demonstrate the existence of switching costs: responses are generally faster and more accurate when the same task is performed twice in succession (i.e., "task-repetition" trials) than when the task changes from one trial to the next (i.e., "task-alternation" trials; e.g., Rogers & Monsell, 1995). Thus, it is possible that high-priority multitasking performance could be worse than single-task performance simply because the former consist of a mixture of task-repetition and task-alternation trials whereas the latter consist exclusively of task-repetition trials.

Actually, it is still an open question whether task-switching costs will even be found in the present prioritized-processing paradigm. Previous studies demonstrating task-switching costs have used equal-priority tasks, so it is theoretically possible that a primary task—especially one to which responses are required in the majority of trials—could be protected from task-switching costs by the tendency to maintain a high level of preparation for this task. Furthermore, in the present multitasking blocks, the primary task had to be performed to some extent in every trial—even if only to decide that no response is required—so the participant may never fully disengage from this task, as can be done in task-switching paradigms (e.g., Rogers & Monsell 1995).

In any case, switching costs can be assessed within the present prioritized-processing paradigm via sequential analyses—that is, by comparing performance for task-repetition versus task-alternation trials—just as these costs are assessed in task-switching studies with equal-priority tasks. If present, such switching costs would extend the switching cost phenomenon to multitasking situations with extremely unequal task priorities, thereby demonstrating one inherent limitation on primary task performance in multitasking situations. On the other hand, if there are no switching costs associated with the primary task in the prioritized-processing paradigm, switching costs with equal-priority tasks could be inferred to be dependent on the relatively equal task priorities normally used.

If switching costs do happen to be observed in our prioritized-processing paradigm, it will also be possible to check for additional sources of multitasking interference with primary task performance. Specifically, these additional sources can be assessed by comparing performance for task-repetition trials of multitasking blocks versus single-task blocks. If the multitasking interference suffered by the primary task is completely due to switching costs, then primary task performance in task-repetition trials should be just as good as performance of the same task in single-task blocks.[1] Alternatively, if multitasking creates additional sources of interference beyond switching itself, then primary task performance in task-repetition trials should still be worse than single-task performance even when task-alternation trials are excluded.

Beyond the major question of whether primary task performance is fully protected from multitasking interference, an additional question of interest in the prioritized processing task is whether primary-task responses are affected by their compatibility with the responses assigned to concurrent background-task stimuli. Such an effect might seem unlikely both because participants would be expected to carry out the primary task before starting to process the background-task stimulus and because the background-task stimulus need not be processed at all when a primary-task response is made. Nonetheless, an exactly analogous phenomenon has been observed in numerous PRP tasks, where it is often called the "backward compatibility effect" or "BCE" (e.g., Caessens, Hommel, Reynvoet, & Van der Goten, 2004; Hommel, 1998; Hommel & Eglau 2002; Ko & Miller, 2014; Lien, Ruthruff, Hsieh, & Yu, 2007; Logan & Schulkind 2000; Miller, 2006; Watter & Logan, 2006; Thomson & Watter, 2013). Specifically, in the PRP paradigm, the BCE is finding that the time needed to make R_1 is influenced by R_1's compatibility with the upcoming R_2.[2]

The BCE suggests that response activation associated with the selection of R_2 starts before the ballistic phase of R_1 execution is reached (Hommel, 1998), and this conclusion is theoretically important because it provides evidence against response-selection bottleneck (RSB) models in which the selection of R_1 must finish completely before any processing associated with the S_2–R_2 mapping can begin. Clearly, interpretation of the BCE will be aided by finding out whether a similar pattern is present in the prioritized-processing paradigm. A finding that it is present would support the idea that the BCE arises due to automatic, stimulus-driven processing associated with S_2 rather than due to early activations produced in the process of selecting and executing R_2, since no R_2 would actually be produced following the affected primary task responses in the prioritized-processing paradigm. Conversely, a finding that no such pattern is observed in the prioritized-processing paradigm would support the idea that the BCE in PRP tasks arises from controlled processes that are only carried out when R_2 must actually be executed.

Experiment 1

Participants in this experiment were presented with two stimuli in each trial, consisting of a white letter surrounded by a colored square. For each participant there were three possible letters—one go letter assigned to the left-index-finger response, one go letter assigned to the right-index-finger response, and one assigned to the no-go response. Likewise, there were three possible colors for the square, with one go color also assigned to each response. The nine possible stimuli (i.e., three letters × three colors) were presented equally often.

Two types of single-task blocks were tested, with participants responding only to the letters in some single-task blocks and only to the colors in others. Two types of prioritized-processing blocks were also tested. In a "letter-plus-color" condition the participants' primary task was to make a letter-task response if one was required—as it was in 2/3 of all trials, and they responded to the color background task only in the 2/9 of trials in which

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[1] This prediction depends on previous studies suggesting that task switching costs are generally confined to the first trial after the switch (e.g., Kiesel et al., 2010; Monsell, Sumner, & Waters, 2003; Pashler, 2000; Rogers & Monsell, 1995).

[2] Analogous effects are also sometimes observed in task-switching paradigm, as is considered further in the General Discussion.

the no-go letter was presented together with one of the go colors. Conversely, in a "color-plus-letter" condition participants responded to the square's color if that color required a response (2/3 of trials), and they responded to a go letter only when the square appeared in the no-go color (2/9 of trials).

As was discussed in the Introduction, the central question was whether participants would be able to make primary task responses just as rapidly in the prioritized-processing blocks as in the single-task blocks. If so, this would demonstrate that the primary task had been fully protected from multitasking interference, and thereby indicate that relegating a low-priority task to the present background status was sufficient to block its interference with a primary task. Alternatively, if primary task responses are slower in the prioritized-processing blocks than in the single-task blocks, the conclusion would be that the background task produced some interference despite its very low priority. As was discussed in the Introduction, secondary issues involve the questions of (a) to what extent task-switching might be responsible for any observed multitasking interference, and (b) whether stimuli associated with background tasks would nonetheless produce backward compatibility effects.

Method

Participants

Participants were 32 students (26 female) at the University of Otago, Dunedin, whose ages ranged from 18 to 29 years ($M = 19.8$). Mean handedness score was $M = 79.7$ as measured by the Edinburgh Handedness Inventory (Oldfield 1971), and 30 were right-handed. Each student attended a single experimental session lasting approximately 40 min.

Apparatus and stimuli

Stimuli were presented and responses and RTs recorded by an IBM-PC compatible computer under the control of the MATLAB program using the Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997; Kleiner, Brainard, & Pelli, 2007). All stimuli were bright figures appearing on an otherwise black computer monitor. Letters were presented in white at fixation in a 28-point font that subtended approximately 0.7° of visual angle from the viewing distance of 60 cm. Outline squares, also centered at fixation, were constructed from lines that were approximately 2.5° in length and 0.2° in thickness. Responses were key presses with the left and right index fingers on the "Z" and "/?" keys of a standard computer keyboard.

Procedure

For each participant, three consonants were selected randomly for use as stimulus letters, with one each assigned to the left hand, right hand, and no-go responses. The stimulus colors red, green, and blue were also assigned randomly to these three responses. All stimulus–response assignments remained fixed throughout testing for each participant.

Each participant was tested in 12 blocks of trials, including three blocks in each of the four task conditions: letter single task, color single task, letter-plus-color, and color-plus-letter. Each block began with an instructional screen describing the assignment of the possible letters and colors to responses for the upcoming task. Of the 12 blocks, the first two were always the two single tasks, with the letter and color tasks in random order, and third and fourth were always the two prioritized tasks letter-plus-color and color-plus-letter, also in random order. Then, each of these four tasks was tested for a second time in blocks 5–8 with task order randomized, and each task was tested for a third time in blocks 9–12. Each block included 63 trials, with seven presentations of each of the nine possible stimulus displays (i.e., three possible letters × 3 possible square colors). After all blocks were completed, participants filled out the Edinburgh Handedness Inventory and were debriefed.

Each trial began with the onset of the central fixation cross for 500 ms. The stimulus letter and square were presented immediately at the offset of this fixation cross, and these remained on the screen until the participant responded or for a maximum of 2 s. After each response, feedback was displayed for 1 s to indicate that the response was correct or for 3 s to indicate that the response was an error. Participants were instructed to respond as quickly and accurately as possible in each trial in accordance with the task being performed for the current block.

Results and discussion

The first four blocks were considered to be practice and were omitted from the final analysis, which thus included two blocks for each task. In addition, 0.8 % of trials with RTs exceeding 2 s were excluded as slow outliers. Excluding no-go trials, the basic performance results were summarized by computing the mean correct reaction time (RT) and the percentage of correct responses (PC) for each participant as a function of the task emphasis (single, primary task, background task) and the relevant dimension (letter, color) on which the response was based, and the averages of these values across participants are shown in Figure 1.[3]

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[3] Responses were correctly withheld in 97.1 % of no-go trials, and this percentage did not vary significantly across tasks ($p > 0.3$), so the no-go trials were excluded from consideration in order to have parallel analyses for RT and PC.

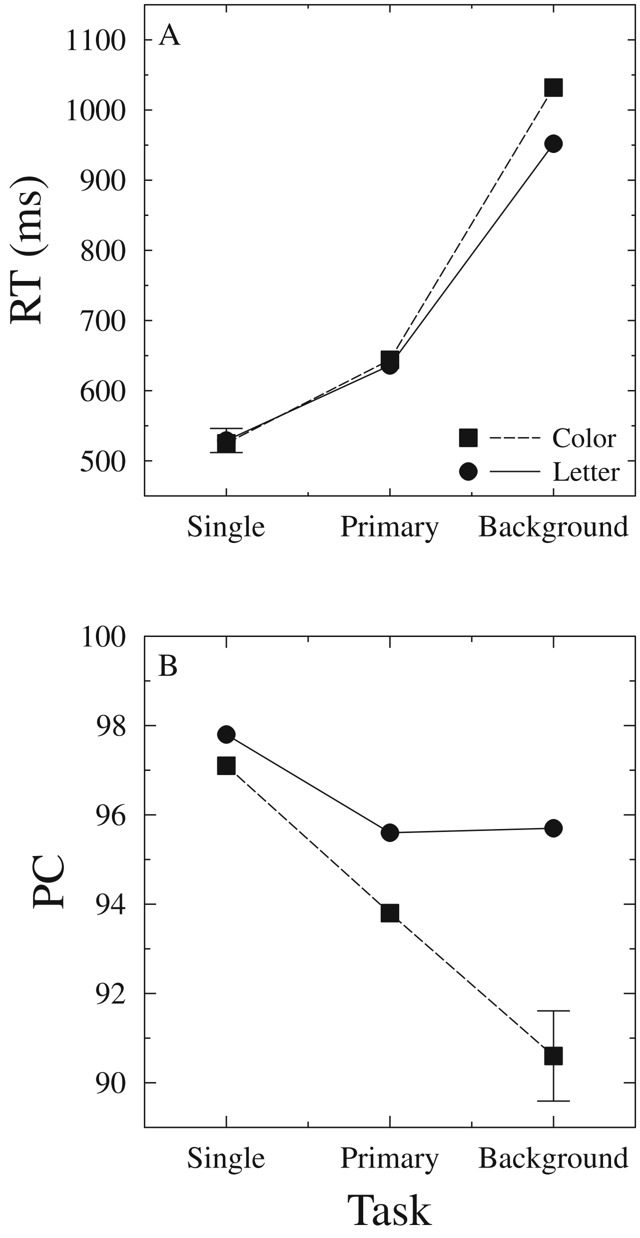

Fig. 1 Mean reaction time (RT, A) and percentage correct (PC, B) in Experiment 1 as a function of task emphasis (single, primary task, background task) and relevant dimension (letter, color). *Error bars* indicate one standard error computed from the pooled error terms of the two main effects and the interaction

Overall analyses and multitasking interference

A repeated-measures ANOVA on RT with the two factors shown in Fig. 1 revealed a significant main effect of the relevant dimension, $F(1, 31) = 7.44$, $p < 0.025$, $\eta_p^2 = 0.193$ with faster responses to letters than colors. There was also a highly significant effect of task emphasis, $F(2, 62) = 537.41$, $p < 0.001$, $\eta_p^2 = 0.945$.[4] As can be seen in Fig. 1, responses were fastest for the single-task blocks, somewhat slower for the primary task in the prioritized-processing blocks, and slowest for the background task in these blocks, with all pairwise comparisons statistically reliable ($p < 0.01$). The analysis also revealed a significant interaction between dimension and task, $F(2, 62) = 14.43$, $p < 0.001$, $\eta_p^2 = 0.318$, with the difference between the color and letter dimensions emerging almost exclusively in the background task. The explanation for this asymmetry between the letter and color tasks is not clear; fortunately, it is tangential to our main concerns.

A parallel ANOVA on the PCs revealed corresponding effects of stimulus dimension, $F(1, 31) = 18.27$, $p < 0.001$, $\eta_p^2 = 0.371$, and task emphasis, $F(2, 62) = 14.54$, $p < 0.001$, $\eta_p^2 = 0.319$, with significant pairwise comparisons between the single task and the primary task or background task conditions. This analysis also revealed a significant interaction, $F(2, 62) = 7.10$, $p < 0.005$, $\eta_p^2 = 0.186$, with the difference between the color and letter tasks again most pronounced for the background task.

More detailed examination of the critical RT difference between the single-task and primary-task conditions showed that this difference grew across the RT distribution, as is most common with RT effects (e.g., Schwarz & Miller, 2012). Specifically, there was only a 31-ms difference between conditions for the fastest one-third of responses, a 93-ms difference for the middle one-third, and a 236-ms difference for the slowest one-third. A difference in these mean RTs was observed in the same direction for every participant, and it tended to be larger for participants who were slower overall, producing a Pearson correlation of $r = 0.68$ ($p < 0.001$) between a participant's mean RT and effect size. As was discussed by Miller and Ulrich (2013), however, this positive correlation is open to numerous interpretations in terms of the durations of specific mental processes contributing to the RT. Similar patterns of larger effects for slower responses and participants were also observed in comparisons of the primary and background tasks, as well as in analogous comparisons using the data of Experiment 2.[5]

Sequential analyses

To assess the contribution of task-switching costs to the performance decrement for primary tasks as compared with

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[4] For repeated measures factors with two or more degrees of freedom, all reported p values have been adjusted for possible violations of the sphericity assumption using the method described by Huynh (1978). Pairwise comparisons were performed using the Newman–Keuls method.

[5] We thank Hal Pashler for suggesting these analyses.

single tasks, further analyses were carried out in which trials were classified according to the nature of the previous trial. We included only go responses in trial N that followed go responses in trial $N-1$. In the single-task blocks, these trials were necessarily task repetitions. In the prioritized-processing blocks, these trials could be either task repetitions or alternations, depending on whether the response in trial $N-1$ was determined by the same or opposite task (i.e., primary task versus background task).

Figure 2 summarizes the results of the sequential analysis, and these were examined statistically with two separate ANOVAs. One ANOVA included the four conditions within the prioritized-processing blocks, and this analysis showed a strong advantage for task repetitions as compared with task alternations for both RT, $F(1,31) = 266.10$, $p < 0.001$, $\eta_p^2 = 0.896$, and PC, $F(1,31) = 37.99$, $p < 0.001$, $\eta_p^2 = 0.551$. The RT advantage was especially large for background tasks, $F(1,31) = 25.29$, $p < 0.001$, $\eta_p^2 = 0.449$, but the PC advantage was especially large for primary tasks, $F(1,31) = 5.70$, $p < 0.025$, $\eta_p^2 = 0.155$, and we have no explanation for this discrepancy.

A second ANOVA compared performance just in the single-task and primary-task repetition conditions. Crucially, the primary task was impaired relative to the single-task control even when only task repetitions were considered. This difference was statistically reliable for both RT, $F(1,31) = 95.86$, $p < 0.001$, $\eta_p^2 = 0.756$, and PC, $F(1,31) = 4.71$, $p < 0.05$, $\eta_p^2 = 0.132$. Thus, although task switching costs clearly contribute to the performance decrement observed with the primary tasks, they do not completely explain it.

Backward compatibility effect

The significant performance decrement of the primary tasks relative to the corresponding single tasks suggests that participants were not completely successful in excluding the background task from processing while they were working on the primary task and that the primary task suffered as a result. Further evidence for that conclusion comes from an analysis of primary task RT and PC as a function of the response compatibility of the background-task stimulus. Specifically, the background-task stimulus could be (a) associated with the same response required for the primary task ("compatible"), (b) associated with the opposite response from that required for the primary task ("incompatible"), or (c) associated with the no-go response ("no-go"). As can be seen in Fig. 3, primary task responses were affected by the type of background-task stimulus both for RT, $F(2,62) = 9.62$, $p < 0.001$, $\eta_p^2 = 0.237$, and for PC, $F(2,62) = 43.23$, $p < 0.001$, $\eta_p^2 = 0.582$. All pairwise comparisons were significant ($p < 0.05$) for RT; for PC, pairwise comparisons only indicated that accuracy was lower with an incompatible background-task stimulus than with a compatible or no-go stimulus ($p < 0.01$), but the latter two conditions did not differ significantly from each other ($p > 0.1$). Neither the main effect of relevant dimension nor its interaction with background-task stimulus type was significant for RT, but both were significant for PC ($p < 0.05$).

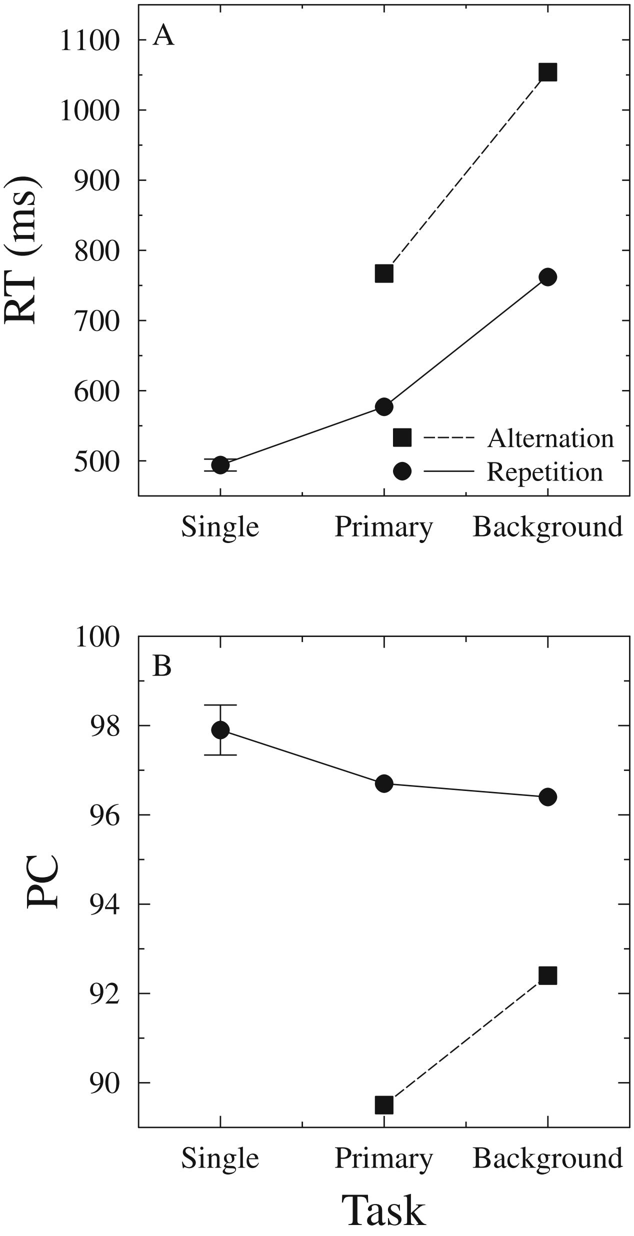

Fig. 2 Mean reaction time (RT, A) and percentage correct (PC, B) in Experiment 1 as a function of task emphasis (single, primary task, background task) and of whether the task was a repetition or alternation relative to the preceding trial. *Error bars* indicate one standard error computed from the error terms for the comparison of the single task and primary task repetition conditions

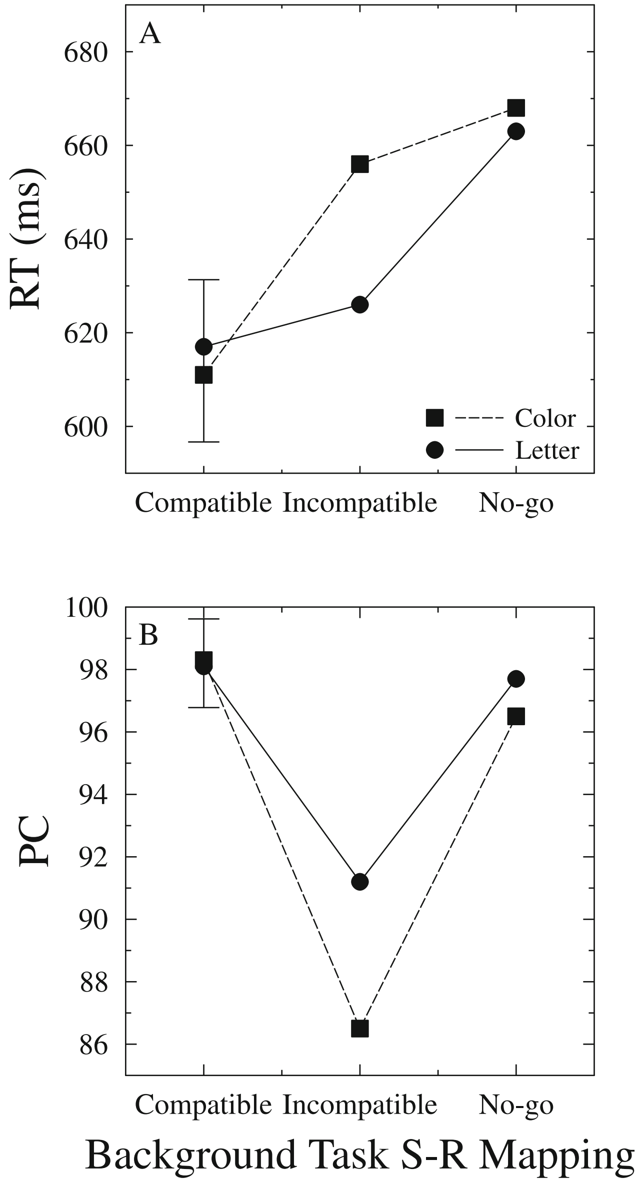

Fig. 3 Mean reaction time (RT, A) and percentage correct (PC, B) for primary task responses as a function of the response associated with the background-task stimulus (compatible, incompatible, no-go) and relevant dimension (letter, color) in Experiment 1. *Error bars* indicate one standard error computed from the pooled error terms of the two main effects and the interaction

A final analysis checked whether multitasking interference would be eliminated when controlling for both backward compatibility effect and sequential effects at the same time. Mean primary task RTs from the prioritized-processing block were computed using only task-repetition trials in which the current trial's background-task stimulus was response-compatible, and the corresponding mean single-task RTs were computed using exactly the same two-stimulus sequences that were included in the primary task means. In this comparison, primary-task response were on average 77 ms slower than single-task responses, $F(1, 31) = 66.09$, $p < 0.001$, $\eta_p^2 = 0.68$, indicating that multitasking interference does remain even when controlling for both of these factors. The 0.9 % effect in PC was not statistically reliable, however, $F(1, 31) = 2.60$, $p > 0.1$, $\eta_p^2 = 0.08$.

Discussion

The main finding of this experiment is that performance in the primary task suffered multitasking interference relative to the single-task block despite the strong emphasis given to it in this paradigm. This interference was evident in both RT and PC, and it was present even when considering only prioritized-processing paradigm trials that were task repetitions, that had response-compatible background-task stimuli, or both. Thus, it is clear that participants in the present prioritized-processing paradigm were not able to achieve a complete single-task focus. Experiment 2 will explore the effects of further task modifications designed to promote such focus.

A subsidiary finding of Experiment 1 is that an analog of the BCE can be observed in the prioritized-processing paradigm, with primary-task responses influenced by the response compatibility of the accompanying background-task stimulus. This finding reinforces the idea that participants are unable to achieve a complete single-task focus in this situation, because responses associated with the low-priority background task must have been processed to some degree in order to influence the primary-task responses. As will be considered further in the General Discussion, this finding also has implications for the interpretation of the BCE commonly found in the PRP paradigm.

Experiment 2

Since multitasking interference was not eliminated in Experiment 1, this experiment added two procedural changes to create an even stronger emphasis on the primary task. First, the same primary task was used in all prioritized-processing blocks. Specifically, the letter task was always the primary task when multitasking, although participants still performed both the letter task and the color task in single-task block to ensure that they were familiar with each of these tasks. It was anticipated that a consistent emphasis on a fixed primary task across the full experimental session might further enhance the priority of that task. Second, the primary task and background task were performed with separate hands (i.e., right and left, respectively). Previous results suggest more independence of tasks that use different response sets rather than a common one (e.g., Meiran, 2000), so it seemed possible that response set segregation would also enhance the maintenance of differential task priorities.

Method

Except as noted otherwise, the apparatus and procedure for Experiment 2 were the same as those used in Experiment 1.

Participants

Participants were 56 students (42 female) from the same pool tested in Experiment 1, and none had been tested in the previous experiment. Their ages ranged from 18 to 42 years ($M = 19.8$), 48 were right-handed, and mean handedness score was $M = 56.4$.

Procedure

Responses to letters were presses of the "." and "/" keys of a standard computer keyboard with the right index and middle fingers, and responses to colors were presses of the "X" and "Z" keys with the left index and middle fingers. Each participant was tested in 12 blocks of trials, including three blocks in each of the two single-task conditions (i.e., letter and color) and six blocks in the letter-plus-color prioritized-processing paradigm.

The first four blocks were again considered practice, starting with the two single task blocks in random order and then including two blocks in the letter-plus-color priority task. There were then two more sets of four blocks in random order, with each set consisting of one letter single-task block, one color single-task block, and two blocks of the letter-plus-color prioritized-processing paradigm.

Results and discussion

Means across participants of the correct RTs and percentages of correct responses are shown in Fig. 4, with 0.4 % of trials having been excluded as slow outliers (i.e., RT > 2 s). Preliminary overall ANOVAs were conducted on both RT and PC with factors of task (single versus prioritized-processing) and dimension (letter versus color). These showed that both main effects and the interaction were highly significant ($p < 0.001$), but these results are not directly interpretable because of the confounding of dimension and priority in the letter-plus-color prioritized-processing blocks.

Multitasking interference

The central question motivating this experiment was whether the primary letter task would escape multitasking interference, and the answer is that it clearly did not. In analyses including only responses to the letter task, the difference between the single and primary tasks was highly significant for both RT, $F(1, 55) = 122.19$, $p < 0.001$, $\eta_p^2 = 0.690$, and PC, $F(1, 55) = 5.80$, $p < 0.025$, $\eta_p^2 = 0.095$.[6]

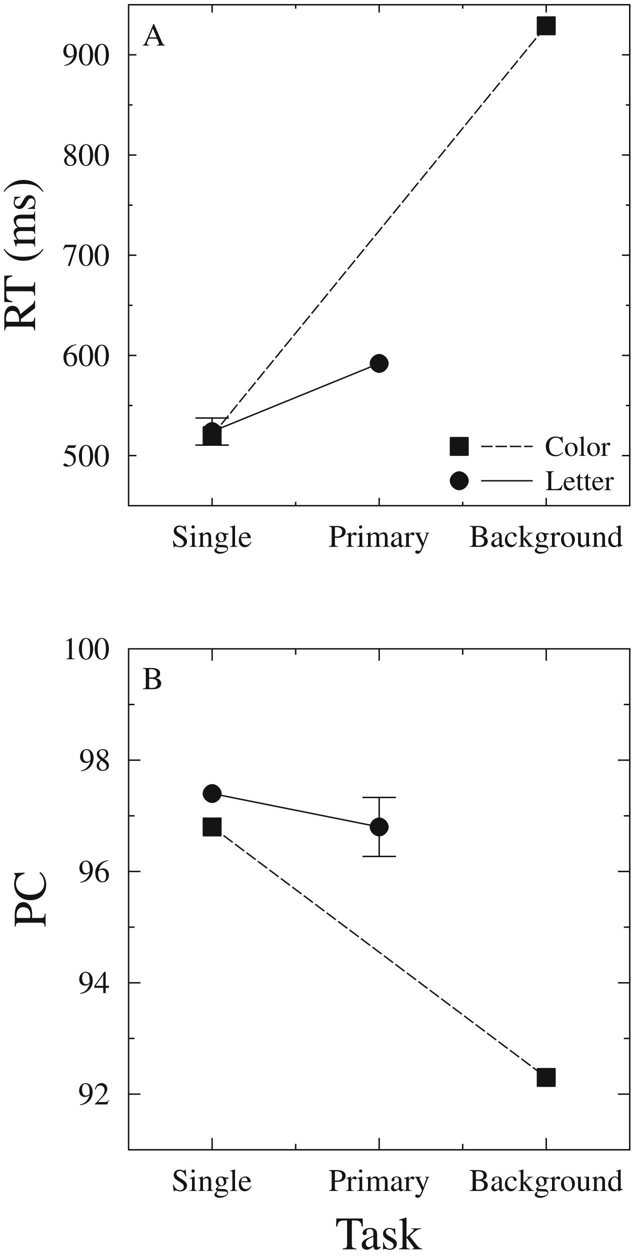

Fig. 4 Mean reaction time (RT, A) and percentage correct (PC, B) in Experiment 2 as a function of task emphasis (single, primary task, background task) and relevant dimension (letter, color). *Error bars* indicate one standard error computed from the pooled error terms of the two main effects and the interaction

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[6] Similar results were also obtained in a separate analysis limited to right-handed participants, which would arguably further increase the already-high priority associated with the letter task.

Sequential analyses

Sequential analyses parallel to those used in Experiment 1 were conducted, and the results are summarized in Fig. 5. Prioritized processing blocks again showed strong advantages for task repetitions over task alternations in both RT, $F(1, 55) = 335.33$, $p < 0.001$, $\eta_p^2 = 0.859$, and PC, $F(1, 55) = 29.89$, $p < 0.001$, $\eta_p^2 = 0.352$. The RT advantage was larger for the background color task than for the primary letter task, $F(1, 55) = 123.79$, $p < 0.001$, $\eta_p^2 = 0.692$, and the PC advantage was not reliably different between the two tasks ($p > 0.2$). Most importantly, performance in the primary task was still impaired relative to single tasks even when only task repetitions were considered. This effect was highly reliable for RT, $F(1, 55) = 88.33$, $p < 0.001$, $\eta_p^2 = 0.616$, though not for PC ($p > 0.1$). The overall conclusion is again that task switching costs are not sufficient to account for all of the performance decrements observed with primary tasks relative to single tasks.

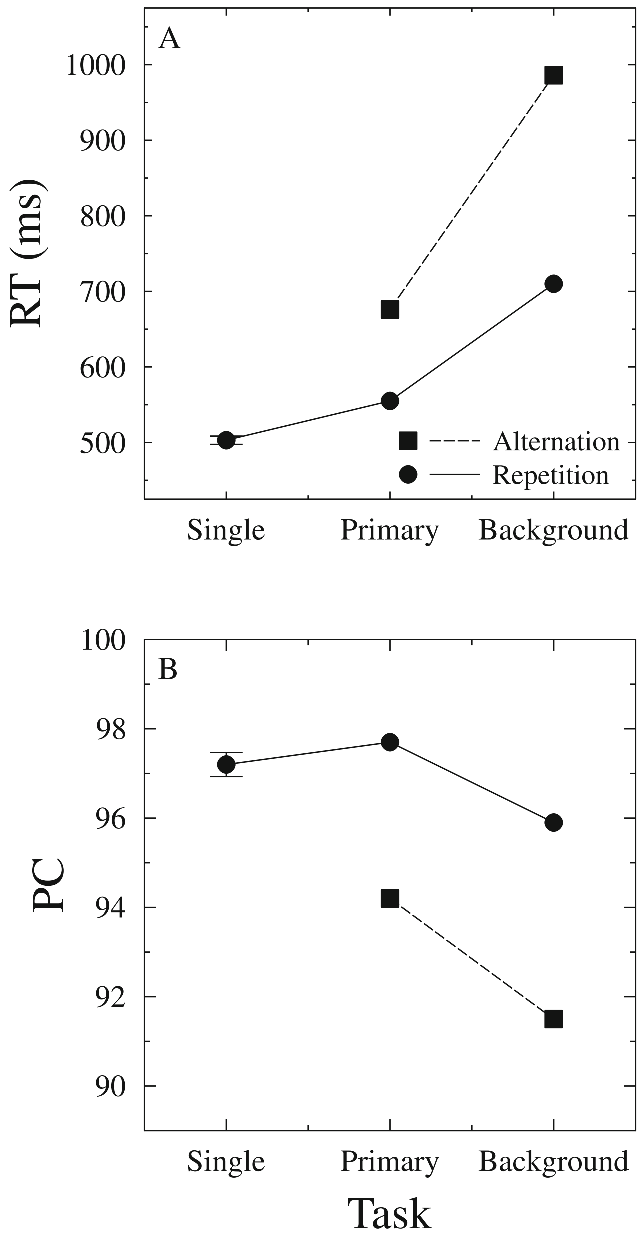

Fig. 5 Mean reaction time (RT, A) and percentage correct (PC, B) in Experiment 2 as a function of task emphasis (single, primary task, background task) and of whether the task was a repetition or alternation relative to the preceding trial. *Error bars* indicate one standard error computed from the error terms for the comparison of the single-task and primary task repetition conditions

Backward compatibility effect

As in Experiment 1, the conclusion that the background task was not completely ignored is again reinforced by effects of the S-R mapping of the background-task stimulus, as shown in Fig. 6. Specifically, primary task responses were slower and more accurate when the background-task stimulus was assigned to the no-go response than when it was assigned to either of the go responses, leading to significant S_2–R_2 mapping effects in both RT, $F(2, 110) = 12.30$, $p < 0.001$, $\eta_p^2 = 0.183$, and PC, $F(2, 110) = 7.31$, $p < 0.005$, $\eta_p^2 = 0.117$. Because responses to the two tasks were made with different hands, a background-task stimulus could only require responses with a finger that was homologous or nonhomologous to the finger used for the primary task—rather than compatible versus incompatible fingers as was possible in Experiment 1—and the results displayed in Fig. 6 show that the distinction between homologous and nonhomologous fingers had little or no influence on the results.

Again, we also checked whether multitasking interference would be eliminated in an analysis controlling for both backward compatibility effects and sequential effects. Mean primary task RTs were computed using only task-repetition trials in which the current trial's background-task stimulus was associated with either of the two go responses (i.e., excluding any no-go background-task stimulus), and the corresponding mean single-task RTs were computed using the same stimulus sequences. In this comparison, primary-task responses were on average 45 ms slower than single-task responses, $F(1, 55) = 69.934$, $p < 0.001$, $\eta_p^2 = 0.560$, but the analogous 0.1 % difference in PC did not approach significance, $F(1, 55) = 0.055$, $p > 0.5$, $\eta_p^2 = 0.001$.

Discussion

Despite two procedural modifications designed to increase the emphasis on the primary letter task, the major results of this experiment were quite similar to those of Experiment 1. First, the slower and less accurate letter-task responses in prioritized-processing blocks relative to single-task blocks

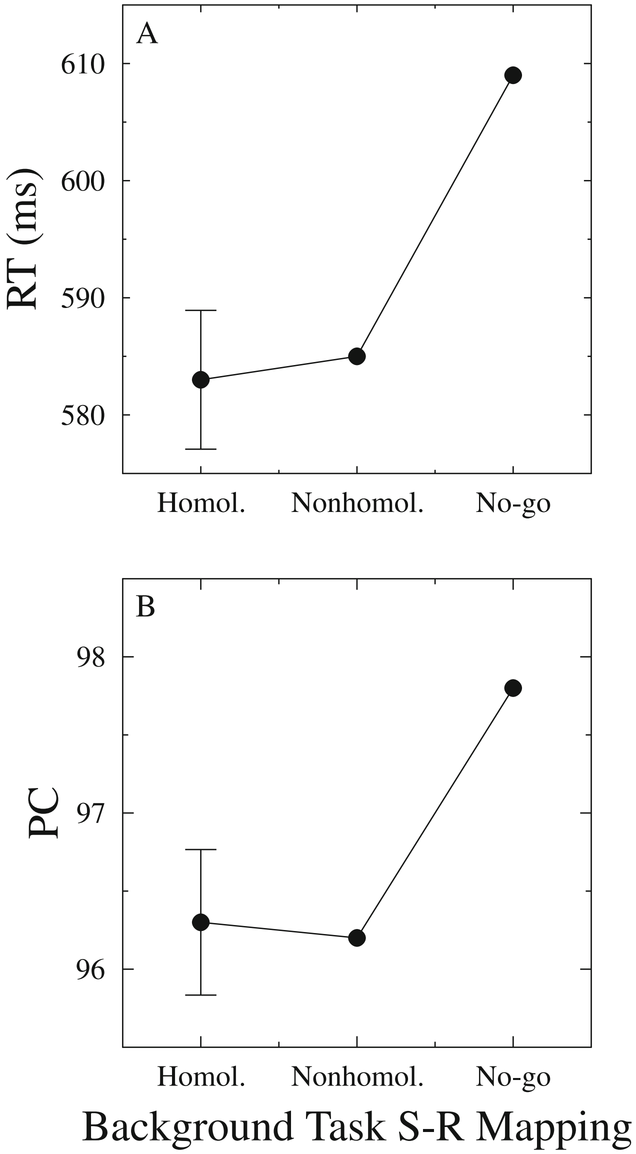

Fig. 6 Mean reaction time (RT, A) and percentage correct (PC, B) for responses to the letter primary task as a function of the response associated with the color background-task stimulus (homologous, nonhomologous, no-go) in Experiment 2. *Error bars* indicate one standard error computed from the error term of the main effect

again showed clear multitasking interference. For RT, this interference was present even in task-repetition trials, showing that it is not fully attributable to task-switching costs. Second, the presence of a BCE in the prioritized-processing blocks provides a further indication that participants were unable to focus completely on the primary task in these blocks.

General discussion

The present experiments introduced a prioritized-processing paradigm having elements in common with—but also distinct from—the PRP and task-switching paradigms. As in both of those earlier paradigms, the prioritized-processing paradigm requires participants to maintain readiness for two different tasks, both of which must be performed within each block of trials. As in the traditional PRP paradigm, the prioritized-processing paradigm involves presentation of stimuli for both tasks in each trial. The instructions determine the order in which these stimuli must be processed, and these instructions remain fixed within each block. The main difference between the PRP and prioritized-processing paradigms is that the latter involves only one response per trial. In this respect, the prioritized-processing paradigm is similar to the task-switching paradigm, and it is possible to distinguish between task-repetition and task-alternation trials because participants must respond to each of the two tasks in some trials within a block. In contrast to the task-switching paradigm, however, relative task priorities within the prioritized-processing paradigm do not change from trial to trial but instead are held constant. Finally, because two stimuli are presented in each trial, the prioritized-processing paradigm allows the possibility that the response to the primary task could be affected by its compatibility with the response associated with the background-task stimulus, analogous to the BCE observed in the PRP paradigm and to response-compatibility effects observed in the task-switching paradigm.

Given the commonalities and differences of the prioritized-processing paradigm relative to the PRP and task-switching paradigms, it is not surprising that the results obtained with this paradigm have implications not only for our central question about the possibility of eliminating multitasking interference but also for several secondary issues commonly investigated within these other paradigm (e.g., sources of task-switching costs, the mechanisms underlying BCEs). The implications of the present results concerning each of these issues are examined in the next three sections.

Multitasking interference

Multitasking interference similar to that documented in previous comparisons of single- versus multiple-task performance is also quite prominent in the prioritized-processing paradigm. Such interference effects are considerably larger on background tasks than on primary tasks (Figs. 1 and 4), amounting to several hundred ms in the former tasks. Of course, interference was expected to be much larger for the background task than for the primary task, because the paradigm was designed to maximize the priority of the latter.

The main goal of the present studies was to determine whether multitasking interference would be eliminated by designating the primary task as the *only* task to be performed when it required a response. This is an experimental analog of real-world situations in which people attempt to (a) concentrate fully on a primary task when it requires some action, but also (b) work on a low-priority background task when the primary task requires no action. In principle, such a strategy could protect the primary task from multitasking interference and yet allow some work to be accomplished on the background task. The empirical question, however, is whether this strategy really does enable such an effectively single-task focus on the primary task in practice.

The present results clearly indicate that the strong emphasis on the primary task in the present prioritized-processing paradigm is not sufficient to protect that task from multitasking interference. Evidently, even when the primary task is the only task that needs to be performed in a multitasking trial (i.e., the background task is de-emphasized so much that it does not require any response if the primary task does), the mere possibility of having to perform the background task is sufficient to worsen primary task performance in comparison with a single-task control. These results therefore extend previous findings of stubborn multitasking interference to a paradigm in which one task has such strong emphasis that it can always be processed first and it is the only task to be performed when it requires a response.

In addition to extending previous findings of multitasking interference to the prioritized-processing paradigm, the present results also provide further clues about the causes of this interference. Because only one response was required per trial, for example, certain types of response-based interference considered in the PRP paradigm can clearly be ruled out as causes of the multitasking interference observed in this paradigm (e.g., response grouping: Ulrich & Miller, 2008; structural motor limitations: Bratzke et al., 2008). For the same reason, competition for a bottleneck process also seems to be an unlikely cause. Instead, the most plausible accounts of this multitasking interference involve differences in task preparation, capacity limitations, or both. Although participants should maintain a high level of preparation for the primary task during the prioritized-processing blocks, they might also rehearse the S-R mapping for the background task occasionally, whereas they would rehearse *only* the primary task during single-task blocks. Thus, preparation for the primary task might be somewhat greater in the single-task block. Similarly, since participants must respond to the background task in some trials, they might shift a little processing capacity from the primary-task stimulus to the background-task stimulus during the prioritized-processing blocks, whereas they would process *only* the primary-task stimulus during single-task blocks.

Given the present results, a profitable avenue for further research is to investigate what further modifications of the prioritized-processing paradigm would be necessary to eliminate multitasking interference. It would be both theoretically illuminating and practically useful to know what conditions are required for people to achieve a pure single-task focus within a situation having the potential for multitasking. Possible manipulations to increase the focus on the primary task would include (a) increasing the frequency of responding to the primary task rather than the background task, (b) omitting the background-task stimulus entirely on some trials, and (c) delaying the onset of the background-task stimulus, and the influence of these manipulations on multitasking interference could help illuminate its causes. A finding that interference is eliminated when no background-task stimulus is presented, for example, would strongly support capacity-limitation explanations of the interference over accounts based on differential task preparation. Ultimately, though, it could turn out that virtually *any* possibility of multitasking causes some interference, possibly because there is some cognitive “overhead” associated with the maintenance of multiple task sets (cf. Pashler, 2000). In that case, in deciding between single- and multitasking approaches to real-world task performance, the possible benefits of increased multitasking opportunities would always have to be weighed against the inherent cost to primary task performance. Similar reductions in primary-task performance are also observed when people attempt to carry out background prospective memory tasks (e.g., Einstein & McDaniel, 2005) or to handle brief interruptions generated by a background task (e.g., Altmann, Trafton, & Hambrick, 2014).

Task-switching costs

In the prioritized-processing blocks of both of the present experiments, task-switching costs were evident for both the primary and background task (i.e., faster responses in task-repetition trials than in task-alternation trials). The costs observed for the primary task are of particular importance in the present context, because they suggest that participants failed to re-establish maximal preparation for the primary task immediately after making a response in the background task. This finding supports the idea that some task-related preparatory processes are automatic and obligatory consequences of actual task performance, which could explain why performing the background task leads to a nonoptimal preparatory state for primary task processing. Essentially the same idea has also been suggested within various two-stage models of task switching (Kiesel et al., 2010), where it explains the presence of so-called “residual” switch costs that are observed despite ample time to prepare for an upcoming task alternation. Empirically, the present results extend the case for this idea by showing that executing a background task produces switch costs for a primary task even when participants should attempt to maintain optimal preparation for that primary task in every trial.

Backward compatibility effects

In both of the present experiments, responses to the primary task were influenced by the identity of the response associated with the background-task stimulus, despite the fact that there was no need to process the background-task stimulus in these trials. In Experiment 1, primary task responses were faster when the background-task stimulus was associated with the same response key ("compatible") rather than the opposite one ("incompatible"), and they were slowest of all when that stimulus was associated with the no-go response. Non-overlapping response sets (i.e., different response hands) were used in Experiment 2, so no direct comparison of compatible versus incompatible response keys was possible, but primary task responses were still demonstrably slower when the background-task stimulus was associated with the no-go response. Thus, effects of the background-task stimulus-response mapping in both experiments indicate that the background-task response was activated to some degree even though its execution was not actually required.

The present backward compatibility effects extend those observed in PRP paradigms by showing that such effects must arise at least partly from automatic, stimulus-driven processing associated with the background task stimulus, because they were observed in trials without any actual background-task response (see also Hommel & Eglau, 2002). It seems likely that the automatic activation of the background-task response from the background-task stimulus took place in parallel with the primary task response selection, so this finding provides further evidence against RSB models in which response selection can only be driven by one S-R mapping rule at a time. Furthermore, since no background-task response was made, the present backward compatibility effect cannot be explained by the interleaving of response selection operations for the two tasks (Lien et al., 2007), by occasional reversals of task order within the processing bottleneck (Leonhard, Ruiz Fernández, Ulrich, & Miller, 2011), or by the motor interference known to play a role in the PRP paradigm (e.g., Ruiz Fernández, & Ulrich, 2010). Instead, these effects are most consistent with the idea that two separate response-activation processes can work simultaneously, even if only one response is actually selected (e.g., Hommel, 1998; Hommel & Eglau, 2002).

Analogous response-compatibility effects have also been observed in task-switching paradigms, with the response to the current task being influenced by the compatibility of the response that would have been made on the current trial's to-be-ignored task (e.g., Rogers & Monsell, 1995). Like the prioritized-processing paradigm, the task-switching paradigm involves a single response in each trial, but the two paradigms differ in that the primary task varies across trials in task switching. Response compatibility effects in task switching are generally confined to task-alternation trials and seem to indicate that the previous trial's "competing task set is not entirely disabled" (Rogers & Monsell, 1995, p. 216). Similarly, the present backward compatibility effects show that the background task set is also partially enabled, as would be expected since it must sometimes be performed.

Possible future studies with the prioritized-processing paradigm

The prioritized-processing paradigm has distinctive features—relative to PRP and task-switching paradigms—that may be advantageous in studies of multitasking interference, and in future research it would seem fruitful to investigate this paradigm even beyond looking at what further modifications are needed to attain single-task focus and thereby avoid multitasking interference. For example, relative to the task-switching paradigm, the major advantage of the prioritized-processing paradigm is that considerable processing must be carried out for both tasks before responding to the background task, leading to much clearer multitasking costs for this task.

The most important features of the prioritized-processing paradigm emerge from its comparison with the PRP paradigm, however. The key difference between these two paradigms is that there is only one response per trial in the former, which eliminates complications involving response grouping and structural limitations in response execution. Because of that, the prioritized-processing paradigm will often provide a simpler method for studying the cognitive limitations arising during multitasking. Furthermore, it could be expected on theoretical grounds that the RSB models of RT_2 developed within the PRP paradigm would apply equally well to background-task responses in the prioritized-processing paradigm, because background-task and PRP T_2 responses should depend on exactly the same sequence of mental processes: primary task or T_1 perception and decision plus background task or T_2 perception, decision, and response. It will therefore be illuminating to investigate the extent to which background-task responses are simply delayed by waiting for a response-selection bottleneck to finish with the primary task, allowing generalization of RSB models to this paradigm. To the extent that the RSB model can be generalized to the prioritized-processing paradigm, various experimental approaches developed from RSB models (e.g., "locus of slack", Pashler & Johnston, 1989; "effect propagation", Schubert, Fischer, & Stelzel, 2008) could also be used with the prioritized-processing paradigm, avoiding the complications that arise when two motor responses must be made in the same trial.

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