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Evidence for parallel semantic memory retrieval in dual tasks

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In this dual-task study, we applied both cross-talk logic and locus-of-slack logic to test whether participants can retrieve semantic categories in Task 2 in parallel to Task 1 bottleneck processing. Whereas cross-talk logic can detect parallel memory retrieval only in conditions of categorical overlap between tasks, the locus-of-slack approach is independent of such restrictions. As was expected, using the cross-talk logic, we found clear evidence for parallel retrieval of semantic categories when there was categorical overlap between tasks (Experiment 1). Locus-of-slack-based evidence for parallel semantic retrieval was found, however, both in conditions with (Experiment 1) and in those without (Experiment 2) categorical overlap between tasks. Crucially, however, increasing the demand for resources required to switch from Task 1 to Task 2 eliminated even the locus-of-slack-based evidence for parallel memory retrieval during the psychological refractory period (Experiment 3). Together, our results suggest that parallel retrieval is not bound to conditions of categorical overlap between tasks but, instead, is contingent upon resources needed for switching between tasks (e.g., Oriet, Tombu, & Jolicœur, 2005).

In everyday life, people are confronted with situations in which they are required to access and retrieve information from memory in order to perform a given task. Not only do people access memory without intention (Bargh & Ferguson, 2000; Ferguson & Bargh, 2004; Todorov & Uleman, 2002, 2003; Uleman, 1999), but they do so in highly complex situations—for instance, when performing several tasks at once. Driving a car, for instance, requires the continuous retrieval of specific previously learned knowledge and motor skills in order to execute an appropriate action in a particular traffic situation. Simultaneously, many drivers communicate with their passengers or through their mobile phones while monitoring traffic, displays, and instruments, thus increasing the overall complexity of the activity. Thereby, each individual task seems to require more or less access to highly task-specific memory information.

The aim of the present study was to investigate whether people can access and retrieve memory information concurrently with other cognitive processes, a question that has received much interest in psychological research and has been studied with a variety of approaches. Whereas many studies have provided evidence that memory retrieval is unaffected by concurrent task performance (e.g., Baddeley, Lewis, Eldridge, & Thomson, 1984; Craik, Govoni, Naveh-Benjamin, & Anderson, 1996; Naveh-Benjamin, Craik, Perretta, & Tonev, 2000), others have yielded evidence that memory retrieval is impaired when another task is performed at the same time (e.g., Jacoby, 1991; Martin & Kelly, 1974; Moscovitch, 1992; Park, Smith, Dudley, & Lafronza, 1989). However, numerous methodological drawbacks in these studies make a clear interpretation of the findings rather difficult. For instance, many studies have reported only the percentage of correctly recalled items as a measurement of recall performance and have mostly neglected recall latency. Measuring response latency is crucial, because one can question the assumption of interference-free processing, which is based on 100% accuracy, when experimental task performance itself takes three times longer than that of the control task (Rohrer, 1996; Rohrer & Wixted, 1994). Also, in some studies, the relative timing between tasks or the performance in the concurrent task has not been reported or controlled for. Uncontrolled timing between tasks limits the interpretation of findings, because intelligent timing of interfering processes and task components, for instance, may allow evidence for interference to escape the researchers notice and, thus, stay undetected (Szameitat, Schubert, Müller, & von Cramon, 2002).

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Therefore, when one investigates whether memory retrieval may suffer in conditions of concurrent task performance, it appears to be necessary to use a methodology that (1) allows an exact characterization of task performance in terms of both the accuracy and the latency of responses and (2) provides conditions of measurable interference between the required tasks.

The Psychological Refractory Period Approach to Investigation of Parallel Memory Retrieval in Dual Tasks

In order to satisfy these methodological constraints, some researchers have used the psychological refractory period (PRP) paradigm to investigate the possibility of parallel memory retrieval in situations of concurrent task performance (e.g., Carrier & Pashler, 1995; Logan & Delheimer, 2001; Logan & Schulkind, 2000). In a PRP paradigm, participants are required to respond to two speeded tasks with stimuli presented at various stimulus onset asynchronies (SOAs). Commonly observed response time (RT) functions show that Task 2 RT (RT2) is strongly affected by varying SOA. In particular, the greater the temporal overlap between Task 1 and Task 2 (i.e., with a shorter SOA), the slower are Task 2 responses. This specific pattern of an effect of SOA on RT2 is referred to as the *PRP effect* (for reviews, see Meyer & Kieras, 1997b; Pashler, 1994).

Although several models have been proposed to account for the observed RT2 slowing at short SOAs (Byrne & Anderson, 2001; Logan & Gordon, 2001; Luria & Meiran, 2003; Meyer & Kieras, 1997a, 1997b; Navon & Miller, 2002; Tombu & Jolicœur, 2003), the most prominent and still most accepted model is the so-called response selection bottleneck (RSB) account, originally introduced by Welford (1952; see also Pashler, 1994, 1998). According to the RSB model, the cognitive system is able to perform noncentral processing stages in parallel without interference between the tasks (e.g., peripheral perceptual and motor processes). On the other hand, structural limitations lead to serial processing of central stages (such as response selection). Here, it is assumed that information processing in both tasks requires access to a single bottleneck process (e.g., a response selection process that is exclusively devoted to only one input at a time). Therefore, while the bottleneck stage is carrying out processing for Task 1, Task 2 has to wait for the completion of processing in Task 1 before it can be processed by the bottleneck stage. Due to this serial processing, Task 2 processing is temporarily interrupted, which leads to the idea of a bottleneck in the RSB model (McCann & Johnston, 1992; Pashler, 1994; Pashler & Johnston, 1989).

In general, the particular strength of the PRP paradigm is that it represents a strong empirical tool for studying the microstructure of dual-task performance, with respect to both response latencies and response accuracy. In addition, it allows an exact manipulation of dual-task load by precisely varying the timing (SOA) and, thus, the temporal overlap between the two tasks.

Applying the PRP paradigm in a very elaborate study, Carrier and Pashler (1995) found no evidence that Task 2 memory retrieval can go on in parallel with Task 1 bottleneck stage processing. Participants first studied a set of word pairs and then performed a PRP task with a tone discrimination as Task 1 and a cued retrieval of the word pairs as Task 2. Specifically, the visually presented word in Task 2 served as the cue for the recall of its paired associate target word, which had to be named aloud. The authors found that the effect of a manipulation of memory retrieval difficulty did not depend on the temporal overlap of the tasks. On the basis of this result, they concluded that the Task 2 memory retrieval processes were subject to typical dual-task processing limitations. In other words, memory retrieval processes could not proceed until the processing of Task 1 bottleneck stages was completed.

A serious challenge to the strict serial Task 2 retrieval of response information was provided in dual-task studies with extensive practice. In a seminal study, Schumacher et al. (2001; see also Hazeltine, Teague, & Ivry, 2002), for instance, demonstrated that after about 8 sessions of practice, dual-task costs decreased to such an amount that dual-task performance was virtually the same as performance in single tasks (see also Liepelt, 2006, for an overview). Such findings of so-called *perfect time-sharing* were extended to even more complex working memory updating operations after 24 sessions of practice (Oberauer & Kliegl, 2004) and suggest that central operations can proceed in parallel after sufficient practice (but see Anderson, Taatgen, & Byrne, 2005, and Levy & Pashler, 2001, for alternative interpretations).

Carrier and Pashler's (1995) proposal of strictly serial memory retrieval processes in dual-task situations has also been challenged by the findings of Logan and his colleagues (Logan & Delheimer, 2001; Logan & Gordon, 2001; Logan & Schulkind, 2000) in a series of studies applying *cross-talk logic* within a more typical PRP paradigm. The idea of cross-talk logic is that if the processing of the second task influences responses in the first task, there must have been some second-task processing before the first task was completed (Duncan, 1979; Hommel, 1998; Hommel & Eglau, 2002; Navon & Miller, 1987; see Lien & Proctor, 2002, for an overview). Specifically, Logan and his colleagues found that the semantic category of S2 affected the time needed to categorize S1. Thus, the memory retrieval processes required to categorize S2 must have taken place before the categorization of S1 was complete, which can be interpreted as evidence for parallel memory retrieval in dual tasks.

For example, Logan and Schulkind (2000, Experiment 2) investigated semantic memory retrieval. Participants had to perform a size judgment task (smaller or larger than 5) or a parity judgment task (odd or even) on each of two digits presented during a trial. In different conditions, the two digits had to be processed either with the same task set in Tasks 1 and 2 (i.e., size–size or parity–parity) or with different task sets (size–parity or parity–size). In this context, a task set reflects the specific categorization that has to be performed on a particular stimulus and, thus, describes an instruction-induced set of stimulus–response (S–R) translation rules (e.g., Schuch & Koch, 2004). Logan and Schulkind tested for parallel semantic memory retrieval by examining cross-talk effects based on category match. If a category in Task 2 can be retrieved simultaneously with Task 1 processing, S1 categorization should be faster when S1 and S2 belong to the same category (category match) than when they belong to different categories (category mismatch). In particular, this means that responses should be faster, for example, when both stimuli match the category *smaller than 5* (e.g., 3 and 4) than if one requires the categorization as smaller and the other as larger than 5 (e.g., 3 and 8). This category match effect was investigated when (1) the same task set was applied in both tasks (e.g., size–size) and (2) different task sets were required for Tasks 1 and 2 (e.g., size–parity). Consider two digits smaller than 5 (e.g., 3 and 4) in a size–parity condition. Even though the second digit would have to be classified as *even* in the parity judgment task, its size representation could be automatically activated and retrieved (Brysbaert, 1995; Dehaene & Akhavein, 1995), and thus, it could influence the categorization of the first digit as smaller than 5 (category match).

The results were quite clear: Task 1 responses were faster when categories matched than when they differed, but only when the same type of stimulus categorization was required in both tasks (size–size or parity–parity). Logan and Schulkind (2000) obtained analogous category match effects for letter/digit discrimination and word/nonword decisions (Experiments 1 and 3, respectively). Thus, Logan and colleagues concluded that participants are able to retrieve the category of S2 while processing S1. However, their data suggest that this parallel operation of retrieval processes is restricted to situations of *identical stimulus categorizations*, because no category match effects were found in conditions with different task sets. Logan and Schulkind themselves concluded that "parallel retrieval appears to require that the same task set be applied to both tasks" (p. 1088).

The interpretation provided by Logan and Schulkind (2000) appears to be at odds with a large number of studies showing that magnitude information of a digit can be accessed regardless of whether this information is task relevant or not (e.g., Dehaene & Akhavein, 1995; Henik & Tzelgov, 1982). In fact, in a very recent study, Oriet, Tombu, and Jolicœur (2005) directly questioned the proposed necessity of identical task sets for parallel magnitude retrieval. These authors designed a PRP paradigm in which participants performed a tone judgment in Task 1 and a number size judgment (larger or smaller than 5) in Task 2.

Oriet et al. (2005) applied the locus-of-slack logic within a PRP paradigm, which allowed testing evidence for parallel semantic memory retrieval in Task 2 independently of any possible cross-talk with Task 1. Empirically, this was done with two manipulations. (1) The duration of Task 2 memory retrieval was manipulated using the so-called numerical distance effect. In size judgment tasks, the numerical distance effect describes the fact that RT decreases with an increasing distance between the numbers whose sizes are being compared (Dehaene, Dupoux, & Mehler, 1990; Moyer & Landauer, 1967). For example, it is faster to retrieve the category *larger than 5* for the digit 9 than to retrieve the same category for the digit 6. (2) The second manipulation concerned the temporal overlap between the two tasks (McCann & Johnston, 1992; Pashler & Johnston, 1989). According to the locus-of-slack logic, one can determine whether the retrieval of numerical size representations occurs in parallel with Task 1 bottleneck processing by looking at the interaction between the effects of numerical distance and task overlap (i.e., SOA).

If memory retrieval processes in Task 2 are subject to Task 1 bottleneck processing, Task 2 memory retrieval processes cannot operate in parallel with Task 1 processing and must, instead, wait until bottleneck processing in Task 1 is completed. In this case, the effects of numerical distance should be of the same size regardless of temporal overlap (e.g., McCann & Johnston, 1992; Miller & Reynolds, 2003; Schubert, 1999). That is, numerical distance and SOA should have additive effects on RT2.

In contrast, if Task 2 memory retrieval processes do not require access to the central bottleneck, these retrieval processes will not have to wait until bottleneck processing in Task 1 is completed but can proceed in parallel with it. In that case, the effect of numerical distance will decrease with a short SOA between Task 1 and Task 2. With a very short SOA, in fact, numerical distance may have no effect at all on RT2. In this case, differential processing of digits with near versus far distance may be absorbed in the slack—that is, concealed by the waiting time before Task 2 can access the bottleneck. At a long SOA in which no bottleneck is typically present, however, the full numerical distance effect should be revealed because there is no waiting time to conceal it (Hein & Schubert, 2004; Lien & Proctor, 2000; McCann & Johnston, 1992; Pashler, 1984; Pashler & Johnston, 1989). Thus, an underadditive interaction between the effect of numerical distance and SOA on RT2 would constitute evidence that Task 2 memory retrieval occurred in parallel with Task 1 central processing.

This is in fact what Oriet et al. (2005) found in their study. The authors reported an underadditive interaction between numerical distance and SOA, which is an important result for at least two reasons: First, in line with Logan and Schulkind (2000), these findings add further evidence for the possibility of parallel memory retrieval in PRP situations, thus contradicting Carrier and Pashler (1995). Second, these results clearly suggest that parallel retrieval of number size information does not depend on the application of identical task sets, as had been suggested by Logan and Schulkind.

On the basis of their evidence of parallel retrieval in conditions of nonidentical task sets, Oriet et al. (2005) provided a completely different account of why Logan and Schulkind (2000) were not able to demonstrate parallel memory retrieval in these conditions. In particular, they suggested that the magnitude information of a digit may be retrieved in parallel but, importantly, that the process of comparing this size information with the decision criterion (i.e., 5) requires central resources. At the same time, switching between the parity task and the size task (as in Experiment 2 of Logan & Schulkind's study) might require a resource-demanding process that "heavily taxes a limited pool of central resources needed to carry out the comparison of the presented digit and the standard" (p. 914). Therefore, they argued that parallel retrieval of a digit's magnitude information should be possible in conditions in which the switch between Task 1 and Task 2 requires little or even no resources (in the most extreme case, in conditions with identical task sets), leaving sufficient resources for the number comparison process. Similarly, using highly *dissimilar tasks*, such as tone discrimination and number judgment in their study, also reduces the level of central resources needed by the task switch, which may also have made it easier to show parallel memory retrieval.

In sum, Oriet et al. (2005) proposed that the demand of resources needed for switching between task sets, and not the implementation of identical task sets, determines whether retrieval processes in Task 2 can operate in parallel or not.

The Present Study

The aim of the present study was to further elucidate potential reasons for the different interpretations of Logan and Schulkind (2000) and Oriet et al. (2005). Although the analysis of Oriet et al. appears reasonable, it leaves open the possibility that factors other than resource demands of the switching process between tasks may account for the lack of parallel memory retrieval in the conditions with two different tasks in Logan and Schulkind's study.

It is conceivable, for instance, that the differences in results may be at least partially due to the different sort of memory activation addressed in each study. Whereas Oriet et al. (2005) investigated both the effect of numerical distance, which includes a strong memory activation component, and the effects of number comparison, Logan and Schulkind (2000) focused solely on the number comparison process.

Another quite important reason for the discrepant results may actually stem more from the difference in diagnostics used to detect parallel retrieval, rather than from the resources demanded by task switching, contrary to the suggestion of Oriet et al. (2005). Note that Logan and Schulkind's (2000) results are based completely on the application of cross-talk logic, whereas Oriet et al. made use of locus-of-slack logic in determining the possibility of parallel retrieval in Task 2. These two different diagnostics could, in principle, give different results even within a single study if they are differentially sensitive to parallel retrieval, as will be discussed next.

In Logan and Schulkind's (2000) study, evidence for parallel memory retrieval depended solely on the demonstration of cross-talk effects; that is, effects of Task 2 characteristics had to influence Task 1 responses. In the different-task conditions (e.g., parity in Task 1 and size judgment in Task 2) in which cross-talk effects were not obtained, however, one could argue that Task 2 memory retrieval processes did occur in parallel with Task 1 but simply did not influence RT1. In other words, S2 may have been able to activate its required task-relevant category in parallel, yet no evidence for that would be seen in RT1 because Task 1 responses required a different categorization (e.g., size vs. parity; see also Jolicœur, Tombu, Oriet, & Stevanovski, 2002). To illustrate this possibility in more detail, suppose that S1 had to be categorized as odd or even (parity task), whereas S2 had to be categorized as large or small (size task). Then, a given S2 might lead to the automatic and parallel retrieval of the relevant size category (e.g., *large*), yet this might have no effect on the central *odd*/*even* decision required by Task 1, because there is no natural association of the activated *large*/*small* category with either of the possible Task 1 responses. In short, the problem with the cross-talk approach is that the category information retrieved for one task may have no effect on another task that uses different categories. Thus, one could argue that the failure of Logan and Schulkind to find evidence for parallel memory retrieval in nonidentical dual-task situations might have been due to the mere application of the cross-talk logic, which may not be sufficient to detect evidence of parallel processing when task sets are different. Note that this assumption is not based on task-specific resource requirements for switching, as was suggested by Oriet et al. (2005), but, instead, is based exclusively on methodological constraints of the cross-talk logic that they applied.

In contrast, Oriet et al. (2005) avoided these methodological constraints by applying the locus-of-slack logic. They investigated the possibility of parallel memory retrieval in Task 2 independently of Task 1 characteristics and, thus, were able to demonstrate effects of parallel retrieval (underadditivity). However, this evidence of parallel retrieval for nonidentical task sets is quite specific to the condition in which the two tasks in the paradigm are highly dissimilar. Oriet et al. explicitly stated that switching between easy (e.g., highly dissimilar) tasks may be accomplished with very little requirements for central resources, which is in accordance with task-switching studies using univalent stimuli with univalent responses (e.g., Allport & Wylie, 2000).

In short, we believe there is still some doubt about why Logan and Schulkind (2000) found no evidence for parallel memory retrieval in conditions with different task sets.

If the mere application of the cross-talk logic is responsible for this result, the evidence for parallel retrieval as found with the locus-of-slack logic, as in Oriet et al.'s (2005) study, should be independent of the amount of resources required for switching from Task 1 to Task 2. In other words, in that case, evidence for parallel retrieval should *not* depend on the similarity or dissimilarity of the two tasks. Note that Oriet et al. operationalized the resource demand for the switch via the degree of similarity between tasks. Consequently, increasing resource demands for switching between tasks should have no effects on the underadditive result pattern found by Oriet et al.

On the other hand, if specific resource requirements for switching between tasks were responsible for missing parallel memory retrieval for nonidentical tasks in Logan and Schulkind's (2000) study, the underadditive result pattern found for highly dissimilar tasks (Oriet et al., 2005) should change when there is an increase in the resource demands for switching between tasks; in that case, additivity between SOA and a Task 2 manipulation should be found.

Three experiments were conducted in order to distinguish between these two possibilities. The first experiment tested whether the results of Logan and Schulkind (2000, Experiment 2) could be replicated implementing *both* the cross-talk logic and the locus-of-slack logic. Since the tasks sets are identical in this experiment and, thus, switching requirements are minimal, both methods should indicate parallel memory retrieval in Task 2 processing. Experiment 2 was designed to investigate whether the underadditive results of Oriet et al. (2005) can also be found in conditions of different but more similar tasks (assumed to require more resources for switching), as compared with the tasks used by Oriet et al. Instead of using an auditory–visual task combination, we implemented a visual–visual task setting. Finally, Experiment 3 provided the direct and conclusive test by investigating the possibility of parallel memory retrieval in the context of the locus-of-slack approach when different but highly similar tasks, such as parity and size judgment, were implemented, as in Logan and Schulkind's study.

EXPERIMENT 1

In Experiment 1, we adopted the design of Logan and Schulkind (2000), in which participants performed a speeded size judgment (larger or smaller than 5) on each of two numbers presented one above the other on the screen. Responses to the upper digit were given with the right hand (Task 1), and responses to the lower digit were given with the left hand (Task 2). In Task 2, numerical distance to 5 was *near* (digits 4 and 6) or *far* (digits 2 and 8). In order to avoid any influence of Task 1 stimuli on Task 2 numerical distance effects, the numerical distance of S1 was kept constant; that is, only the digits 3 and 7 were used in Task 1.

Experiment 1 was designed to extend the findings of Logan and Schulkind's (2000) study. Since we included only conditions of identical stimulus categorization demands in both tasks (size judgment), we expected to demonstrate evidence for parallel semantic memory retrieval. This evidence should include cross-talk-based category match effects, replicating the findings of Logan and Schulkind. Furthermore, it should also include the finding of an underadditive interaction between the effects of numerical distance and SOA, reinforcing their conclusions with the locus-of-slack logic.

Method

Participants. Thirty-six students (19 female, mean age = 22.2 years) at the University of Otago took part in the experiment. All had normal or corrected-to-normal vision. The participants attended a single experimental session lasting about 1.25 h and received NZ $12 as payment.

Apparatus and Stimuli. The experiment was conducted in a darkened, sound-attenuating booth. The stimuli were displayed on a 17-in. color monitor that was connected to a Pentium I PC. Task 1 stimuli were the digits 3 and 7, and Task 2 stimuli were the digits 2, 4, 6, and 8. They were presented in the computer's standard text font in white against the black background of the computer screen. Each digit was approximately 12 × 5 mm in size. The positions of the digits were indicated by a fixation field, which consisted of four horizontal dashes (each 4 mm), two 10 mm above and two 10 mm below the screen center (extending 36 mm horizontally). The stimuli for Task 1 (S1) appeared 10 mm above the screen center between the upper two dashes. Similarly, the stimuli for Task 2 (S2) were presented in the center location between the lower two dashes. Responses to the upper stimulus (Task 1) were made with the index and middle fingers of the right hand pressing the "." and "/" keys of the standard computer keyboard. Correspondingly, the participants had to press the "Z" or "X" key with their left index and middle fingers when responding to the bottom stimulus (Task 2).

Procedure. The participants were told that they would be presented with two digits, one above and one below the fixation cross as indicated by the dashes. They were instructed to respond as quickly and as accurately as possible first to the upper digit and second to the lower digit. Task 1 priority was emphasized. The stimulus-to-response mapping was counterbalanced between participants and can be described as SLSL, SLLS, LSSL, and LSLS, respectively (here, S refers to the response *smaller than 5* and L to *larger than 5*). The left-to-right orderings in these mappings refer to the left middle, left index, right index, and right middle fingers, respectively.

Each trial began with the presentation of the fixation display for 500 msec, after which S1 (the digit 3 or 7) was displayed between the upper dashes. Following an SOA of 0, 100, 300, or 900 msec, S2 was presented between the lower dashes. S1 was displayed for 1,000 msec plus the time of the SOA, and S2 was displayed for 1,000 msec. Both stimuli were replaced by a blank screen for 3,500 msec after which the feedback "correct" was displayed for 500 msec when both responses were performed accurately. In case of a wrong response in either task or in case of a missing response, the feedback "error" was provided. Following the feedback, there was a random delay of 1–1,000 msec before the fixation field indicated the beginning of the next trial.

The experiment consisted of six blocks, each containing 96 experimental trials, for a total of 576 trials per participant. The trials were equally divided among 32 conditions defined by two S1s (small vs. large), two S2s (small vs. large), two distances of S2 to 5 (far vs. near), and four SOAs (0, 100, 300, or 900 msec from S1 to S2). Each block included 3 trials from each condition, and the order of experimental trials was randomized separately for each block.

Results

One participant was replaced due to an unusually high error rate (>24%). The first block of trials served as practice and was not included in the analyses. Furthermore, all the trials with incorrect responses in either task (4.0%) and all the trials on which RTs did not fit into the acceptable range of 200–2,000 msec for RT1 and 200–2,300 msec for RT2 (0.44%) were excluded prior to statistical analyses. Overall average values of RT1 and RT2 as a function of condition are presented in Figure 1.

Separate repeated measures ANOVAs including the factors of S1 (3 vs. 7), S2 (small vs. large), numerical distance (near vs. far), and SOA (0, 100, 300, or 900 msec) and the between-subjects factor of S–R mapping (SLSL, SLLS, LSSL, or LSLS) were conducted on RT1 and RT2. Note that in these analyses, the interaction between the S1 and the S2 factors can be used to assess cross-talk effects, because this interaction represents the effect of the category match between the two stimuli (e.g., both digits are smaller than 5) on RT1 and RT2. For all repeated measures ANOVAs, we report the Greenhouse–Geisser adjusted p values.

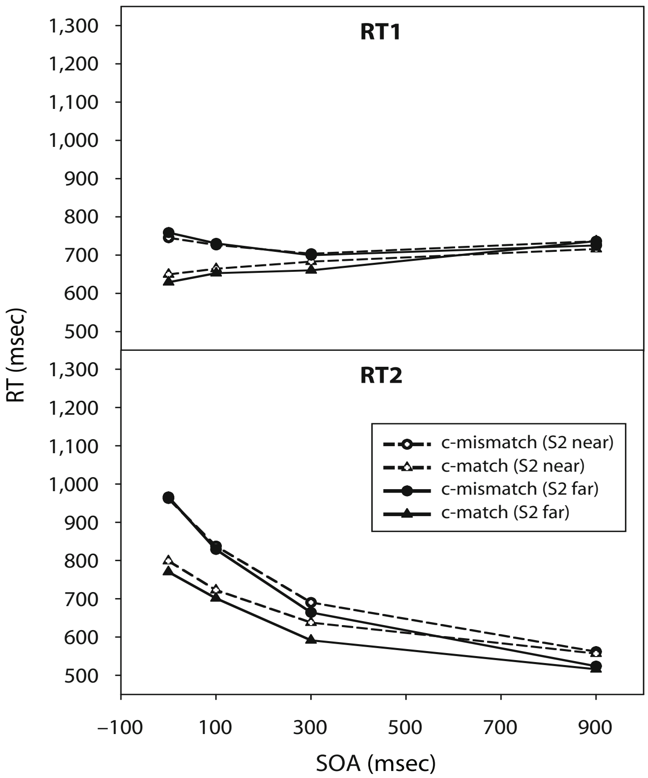

Figure 1. Response times (RTs) for Task 1 and Task 2 in Experiment 1 depending on stimulus onset asynchrony (SOA), numerical distance of the Task 2 stimulus (S2) to 5 (near vs. far), and category match between S1 and S2 (c-match vs. c-mismatch).

Trials were considered for analyses only if responses were correct in both tasks. In other words, an error in either Task 1 or Task 2 reflected a failure of correct dual-task performance. Therefore, accuracy data were identical for Task 1 and Task 2 and were thus analyzed in a single ANOVA irrespective of task (see also Logan & Schulkind, 2000).

Task 1 performance. RT1 was not affected by SOA [$F(3,96) = 1.45$, $MS_e = 190{,}721.21$, $p = .240$]. It was, however, affected by category match, as indicated by the significant interaction between S1 and S2 on RT1 [$F(3,32) = 89.73$, $MS_e = 9{,}393.11$, $p < .001$]. Specifically, RT1 was smaller when S1 and S2 were both smaller than 5 or both larger than 5 (674 msec) than when one stimulus was smaller than 5 and the other was larger than 5 (728 msec). This result is a replication of the category match effect reported by Logan and Schulkind (2000). Furthermore, this category match effect was more pronounced at a short SOA than at a long SOA, as shown by the three-way interaction between S1, S2, and SOA [$F(3,96) = 37.06$, $MS_e = 5{,}062.81$, $p < .001$]. Numerical distance in Task 2 affected neither RT1 [$F(1,32) = 1.45$, $MS_e = 2{,}006.06$, $p = .158$] nor the category match effect on RT1, as shown by a nonsignificant three-way interaction between S1, S2, and numerical distance [$F(1,32) = 2.08$, $MS_e = 2{,}806.44$, $p = .159$]. However, a significant four-way interaction between S1, S2, numerical distance, and SOA [$F(3,96) = 3.96$, $MS_e = 4{,}667.21$, $p < .05$] suggested that the pattern of category match effects across SOAs depended on numerical distance. It is plausible that any Task 2 influence on Task 1 performance should be more detectable at short than at long SOAs, so to examine this four-way interaction in more detail, we conducted a separate ANOVA including only the three shorter SOAs. This ANOVA revealed a clear influence of numerical distance on the size of the category match in RT1 [$F(1,32) = 8.22$, $MS_e = 3{,}266.09$, $p < .01$]. Specifically, the effect of category match was larger when the Task 2 numerical distance was far (82 msec) than when it was near (59 msec). Thus, more extreme category members produced larger category match effects. A further ANOVA showed that this pattern was absent (even slightly reversed) at the longest SOA, however [$F(1,32) = 3.10$, $MS_e = 5{,}538.79$, $p = .088$; see also Figure 1].

Further results of the main ANOVA are main effects on RT1 for S1, with faster responses when S1 was large (684 msec) than when it was small (719 msec) [$F(1,32) = 11.66$, $MS_e = 30{,}930.62$, $p < .01$]. The factor S2 also affected responses in Task 1 in a reversed manner: RT1 was slightly faster when S2 was smaller than 5 (694 msec) than when S2 was larger than 5 (709 msec) [$F(1,32) = 10.62$, $MS_e = 5{,}535.76$, $p < .01$]. These main effects might have been caused by associations of numerical size with the vertical positions of the stimuli, since S1 was always presented above S2. Specifically, there could have been a spatial congruency effect if larger and smaller numbers are inherently associated with upper and lower locations, respectively (S1–large and S2–small). Critically, however, the fact that S2 size influenced RT1 provides a clear additional sign that information about S2 was retrieved in parallel with Task 1 processing. Further significant results included an interaction between S1 and SOA on RT1 [$F(3,96) = 4.05$, $MS_e = 3{,}044.30$, $p < .05$], expressing the fact that the finding of slower responses to a small than to a large S1 was most pronounced for the longest SOA (52, 25, 28, and 37 msec for a 900-, 300-, 100-, and 0-msec SOA, respectively). The response assignment factor did not show a main effect ($F < 1$), nor did it interact with any other factors.

Task 2 performance. As is evident in Figure 1, RT2 was strongly affected by the temporal overlap between Tasks 1 and 2 [$F(3,96) = 459.43$, $MS_e = 23{,}532.27$, $p < .001$], as is commonly observed in the PRP literature. Faster responses were also found when numerical distance was far (695 msec) than when it was near (721 msec) [$F(1,32) = 50.41$, $MS_e = 3{,}765.62$, $p < .001$]. Most important for the present research aims, numerical distance in Task 2 interacted underadditively with SOA [$F(3,96) = 4.52$, $MS_e = 3{,}175.25$, $p < .01$]. In fact, the size of the numerical distance effect decreased monotonically with increases in the temporal overlap between Task 1 and Task 2 (i.e., effects of 40, 36, 15, and 13 msec for SOAs of 900, 300, 100, and 0 msec, respectively). Further analyses showed that the effect of numerical distance was not significant at the shortest SOA [$t(36) = 1.43$, $p = .162$]. There was also an interaction of numerical distance with the between-subjects factor of response mapping [$F(1,3) =$

6.89, $MS_e = 3{,}765.62$, $p < .01$]. We observed numerical distance effects of 54, 14, 20, and 15 msec for the response groups SLSL, SLLS, LSSL, and LSLS, respectively. The critical underadditive interaction of numerical distance and SOA did not differ across response mappings, however ($F < 1$).

As in Task 1, a category match effect was also observed in RT2 [$F(1,32) = 212.28$, $MS_e = 11{,}710.51$, $p < .001$].[1] Responses were faster when S1 and S2 were both smaller than 5 or both larger than 5 (662 msec), as compared with the case of different size categories in the two tasks (754 msec). Again, this category match effect depended strongly on SOA [$F(3,96) = 99.85$, $MS_e = 4{,}397.80$, $p < .001$]. Furthermore, this effect was also influenced by numerical distance in Task 2 [$F(1,32) = 6.98$, $MS_e = 2{,}928.53$, $p < .05$]. As in Task 1, the category match effects were larger when the digit was far from 5 (101 msec) than when it was near to 5 (84 msec). In addition, we found a main effect of the factor S1 on RT2 [$F(1,32) = 6.50$, $MS_e = 19{,}103.30$, $p < .05$]. The pattern of this effect in Task 2 is in accordance with the one observed in Task 1; that is, RT2 is smaller when S1 is the digit 7 (698 msec) than to when S1 is the digit 3 (719 msec), which seems to reflect the aforementioned spatial congruency relation due to the vertically arranged stimulus presentation. No other main effects or interactions reached statistical significance.

Error analysis. Percentages of error are presented in Table 1. These percentages were analyzed with the same factorial ANOVA structure as that used for the RT data analyses. More errors were committed when numerical distance was near (4.7%) than when it was far (3.3%) [$F(1,32) = 12.87$, $MS_e = 40.34$, $p < .01$]. This difference in the percentage of errors was especially pronounced at longer SOAs, as indicated by the significant interaction between numerical distance and SOA [$F(3,96) = 4.08$, $MS_e = 24.72$, $p < .05$].

The S2 factor also had a main effect on the error rate [$F(1,32) = 4.50$, $MS_e = 32.95$, $p < .05$]. More errors occurred when S2 was small (4.3%) than when it was large (3.6%). S2 also interacted with the between-subjects factor of response mapping [$F(3,32) = 3.04$, $MS_e = 32.95$, $p < .05$]. Furthermore, we found a significant three-way interaction between SOA, numerical distance, and S2 [$F(3,96) = 3.01$, $MS_e = 28.16$, $p < .05$]. Thus, the difference of error rates between small and large S2 was predominant at a short SOA and for numbers that were far from 5 (see also Table 1).

Altogether, the error data closely mirror the pattern of the RT results.

Table 1
Error Rates (in Percentages) in Experiment 1 Depending on Stimulus Onset Asynchrony (SOA), Numerical Distance (ND; Near/Far) of the Stimulus in the Second Task (S2), the Stimulus in the First Task (S1; Small/Large), and S2 (Small/Large)

			SOA (msec)			
ND	S1	S2	0	100	300	900
Near	Small	Small	3.1	3.3	5.4	5.9
		Large	3.9	3.7	7.4	3.9
	Large	Small	6.5	4.4	5.6	4.8
		Large	3.1	3.3	5.4	4.6
Far	Small	Small	2.4	3.9	5.2	3.0
		Large	3.9	2.8	3.3	4.1
	Large	Small	5.0	5.6	3.3	2.0
		Large	3.0	1.9	2.0	1.7

Discussion

Experiment 1 was designed to provide evidence for parallel memory retrieval in Task 2 of a dual-task paradigm when both tasks required the same stimulus categorization. One way to provide such evidence was to replicate the cross-talk findings of Logan and Schulkind (2000) by showing that stimulus categorization in Task 2 influences central processing in Task 1. Such cross-talk-based evidence for parallel memory retrieval was found in large category match effects in Task 1. That is, responses in Task 1 were considerably faster when S1 and S2 belonged to the same category (e.g., both digits smaller than 5) than when they belonged to different categories.

More important for the aim of this study, the second type of evidence was the clear underadditive interaction between numerical distance and SOA in Task 2. On the basis of the locus-of-slack logic, smaller Task 2 numerical distance effects at a short SOA than at a long SOA can be taken as evidence that the processes responsible for the numerical distance effect can take place in parallel with bottleneck processing in Task 1. Because these processes surely use information about number size, it follows that Task 2 semantic memory retrieval must have occurred in parallel with Task 1 bottleneck processing (see also Oriet et al., 2005).

A further important finding is that numerical distance in Task 2 influenced category match effects in Task 1, a particular type of cross-talk effect not provided by Logan and Schulkind (2000). That is, Task 2 numbers far from 5 produced larger category match effects in Task 1 than did numbers close to 5. Thus, numerical distance in Task 2 seemed to modulate the level of cross-talk between the two tasks. This suggests that numbers activated their associated size representations with strengths proportional to their distances from the criterion value of 5. For these strengths to influence Task 1 responses, of course, implies that the semantic memory retrieval of S2 size representations must have occurred simultaneously with Task 1 processing.

In sum, Experiment 1 shows that both the cross-talk approach and the locus-of-slack approach can simultaneously provide evidence for parallel semantic memory retrieval in conditions with identical task sets, which generalizes and extends previous findings.

EXPERIMENT 2

The purpose of Experiment 2 was to determine whether the locus-of-slack approach would also provide evidence for parallel semantic memory retrieval in conditions with different task sets. In contrast to Experiment 1, the participants were required to perform a vowel/consonant judgment on letters in Task 1 and to judge numbers as smaller or larger than 5 in Task 2. According to Logan and Schulkind (2000), no evidence for parallel memory retrieval should be found in this situation, because the information sources relevant for the two tasks do not overlap.

It is important to note that the cross-talk logic applied by Logan and Schulkind (2000) seems insufficient to detect parallel semantic memory retrieval processes in Task 2 in the present experimental design. With different stimulus categorizations and task sets being used in the two tasks, the information retrieved for one task will be irrelevant to the other task. With different sets in the two tasks, then, there is no categorical overlap and, hence, no possibility for category match effects to occur. As was mentioned in the introduction, however, the locus-of-slack logic can still be used to reveal parallel memory retrieval even with distinct task sets.

Applying the locus-of-slack logic Oriet et al. (2005) demonstrated underadditive effects of numerical distance with SOA in a slightly different experiment. However, the authors argued that their evidence of parallel processing was due to the fact of using *highly dissimilar* tasks that minimized the level of central resources required to switch from Task 1 to Task 2. If they are correct, at this point, it is still unclear what *level of dissimilarity* is needed to demonstrate parallel memory retrieval. For this reason, in Experiment 2, we extended their approach by decreasing the level of dissimilarity between tasks. In contrast to their study with an auditory Task 1 and a visual Task 2, we used tasks that depended on the same input modality (visual letter and visual number judgment). It is known, for instance, that auditory stimuli are associated with more automatic processing than are visual stimuli (e.g., Posner, Nissen, & Klein, 1976). Therefore, one could assume that it is easier to switch from an auditory to a visual task, as in Oriet et al., as compared with switching from a visual to a visual task, as would be required in the present Experiment 2.

In summary, Experiment 2 allowed us to test whether evidence for parallel memory retrieval can be found in conditions with different task sets. Furthermore, if parallel memory retrieval is indeed possible in these conditions, this would clearly show that the demand on resources for switching between tasks is not modality dependent. In this case, the locus-of-slack logic that we applied predicts an underadditive interaction between numerical distance in Task 2 and SOA. Such a result would be opposite to the conclusion of Logan and Schulkind (2000) and would replicate the findings of Oriet et al. (2005) in a task context of the same input and output modality.

Method

Participants. A sample of 36 students (26 female, mean age = 20.7 years) at the University of Otago who had not participated in Experiment 1 took part in Experiment 2. All had normal or corrected-to-normal vision. The participants attended a single experimental session lasting about 75 min and received course credit.

Apparatus and Stimuli. Task 2 stimuli in Experiment 2 were identical to those in Experiment 1, but capitalized letter stimuli were presented in Task 1. The letters were a set of vowels (A, E, I, O, and U) and a set of five consonants randomly chosen for each participant, and they were presented in the same font as S1 in Experiment 1. The same four response fingers were used as in Experiment 1, except that, in this experiment, the two fingers on the right hand were assigned to the vowel (V) and consonant (C) responses. Other than that, the apparatus and procedure were identical to those in Experiment 1.

Results

Two participants were replaced due to high error rates (>15%). Incorrect trials in either task were excluded from the data analysis (5.3%). The same outlier procedure as that in Experiment 1 was applied to the data of Experiment 2, which resulted in the further exclusion of 1.8% of the trials from the RT data analyses. Separate repeated measures ANOVAs including the within-subjects factors of S1 (vowel vs. consonant), S2 (small vs. large), numerical distance (near vs. far), and SOA (0, 100, 300, or 900 msec) and the between-subjects factor of S–R mapping (SLVC, SLCV, LSVC, or LSCV) were conducted on RT1 and RT2.

Task 1 performance. As is shown in Figure 2, RT1 was affected by SOA [$F(3,96) = 6.58$, $MS_e = 82{,}468.19$, $p < .01$], with responses being slightly faster at long SOAs than at short SOAs (761, 781, 823, and 811 msec for SOAs of 900, 300, 100, and 0 msec, respectively). Responses were also slightly faster for vowels (780 msec) than for consonants (807 msec) [$F(1,32) = 6.23$, $MS_e = 34{,}899.65$, $p < .05$]. Numerical distance did not affect RT1 ($F < 1$). There was a significant interaction between numerical distance, SOA, and the between-subjects factor of response map-

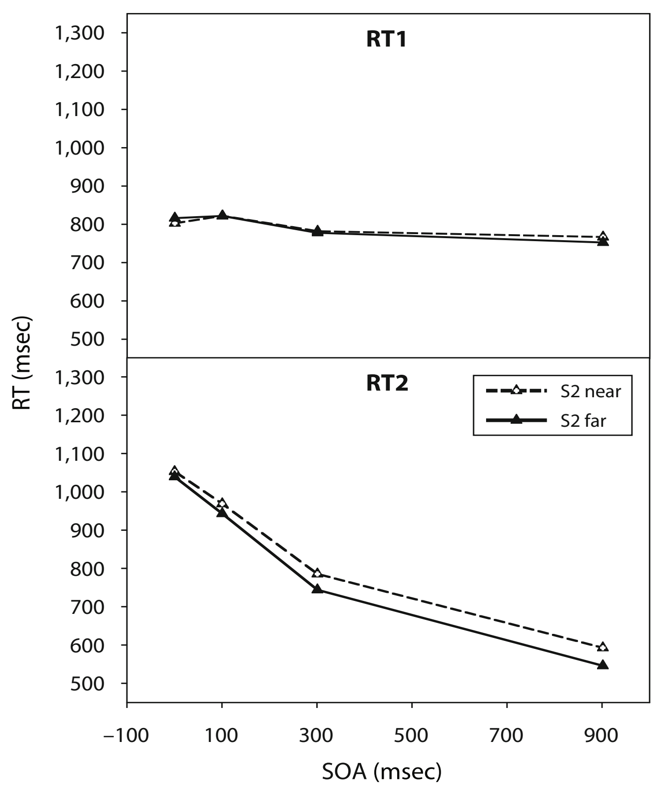

Figure 2. Response times (RTs) for Task 1 and Task 2 in Experiment 2 depending on numerical distance of the Task 2 stimulus (S2) to 5 (near vs. far) and stimulus onset asynchrony (SOA).

ping [$F(9,96) = 2.51$, $MS_e = 3,893.78$, $p < .05$], but the nature of this interaction was unclear, and we suspect that the significant result was a Type I error.

Several other significant interactions suggested, despite our expectations, that Task 1 responses actually were affected by some sources of cross-talk from Task 2 processing. First, there was an interaction between S1 and S2 [$F(1,32) = 10.17$, $MS_e = 4,853.06$, $p < .01$], reflecting the fact that Task 1 responses to vowels were even faster when S2 was small (770 msec) than when it was large (790 msec). No such S2 influence was found for responding to consonants (811 and 805 msec) in Task 1, however. This interaction suggests some sort of cross-talk based on a correspondence between the semantic categories *small* and *vowel*, which we can only speculate might emerge because there are only a few vowels in the alphabet. As would be expected from a cross-talk explanation, the interaction between S1 and S2 depended on SOA [$F(3,96) = 4.32$, $MS_e = 5,173.734$, $p < .01$]. In fact, a separate ANOVA confirmed that there was no interaction of this kind at the longest SOA ($F < 1$). Interestingly, the pattern of interaction between S1 and S2 on RT1 was more pronounced when numerical distance in Task 2 was *far* than when it was *near*, as suggested by a three-way interaction between S1, S2, and numerical distance [$F(1,32) = 4.57$, $MS_e = 4,361.49$, $p < .05$].

Task 2 performance. RT2 was strongly affected both by SOA [$F(3,96) = 1,069.61$, $MS_e = 21,453.77$, $p < .001$] and by numerical distance [$F(1,32) = 40.16$, $MS_e = 7,292.13$, $p < .001$]. Replicating the well-known numerical distance effect, responses were faster when digits were far from 5 (820 msec) than when they were near to 5 (852 msec). Most important, however, numerical distance interacted underadditively with SOA [$F(3,96) = 3.63$, $MS_e = 5,587.51$, $p < .05$]. Specifically, the numerical distance effect decreased monotonically with increasing temporal overlap (i.e., effects of 47, 41, 26, and 14 msec for SOAs of 900, 300, 100, and 0 msec, respectively). This is almost identical to the pattern of effects observed in Experiment 1. Again, the effect of numerical distance was not reliable at the shortest SOA [$t(36) = 1.47$, $p = .150$].

Further results of the ANOVA on RT2 included effects that might have been caused by propagation of Task 1 effects onto Task 2. There was, for instance, a main effect of S1, with responses in Task 2 being faster when S1 was a vowel (824 msec) than when it was a consonant (847 msec) [$F(1,32) = 5.86$, $MS_e = 24,917.13$, $p < .05$]. Again, this difference was detectable only when S2 was small (811 vs. 853 msec), but not when it was large (838 vs. 841 msec), which was confirmed by the interaction between S1 and S2 [$F(1,32) = 9.25$, $MS_e = 11,945.84$, $p < .01$]. As in Task 1, this result pattern was more pronounced when numerical distance was *far* than when it was *near*, as indicated by the significant interaction between S1, S2, and numerical distance [$F(1,32) = 4.79$, $MS_e = 5,592.92$, $p < .05$]. Specifically, whereas in conditions with a far distance to 5, responses to vowels were considerably faster when S2 was small (787 msec) than when it was large (827 msec), this difference was strongly reduced when the numerical distance to 5 was short (834 vs. 850 msec). The interactive effects of S1 and S2 on RT2 also depended on SOA [$F(3,96) = 4.58$, $MS_e = 7,277.56$, $p < .01$].

There was an SOA, S1, and response mapping interaction on RT2 [$F(9,96) = 3.33$, $MS_e = 6,477.97$, $p < .01$], for which we do not have an explanation. At the shortest SOA, Task 2 responses were faster when S1 was small than when it was large (1,055 and 1,114 msec, respectively), but only if the small S1 was mapped onto the middle finger. At the longest SOA, however, the same difference in RT2 between small and large S1 (533 and 568 msec, respectively) was found only when the small S1 was mapped onto the index finger. Also, the interaction between S2 and response mapping suggests that responses to S2 were fastest for stimuli mapped onto an index finger, rather than a middle finger [$F(3,32) = 5.41$, $MS_e = 17,055.28$, $p < .01$].

Error analysis. The same form of data analysis was also conducted for the error data, which are shown in Table 2. The error rate was affected by SOA [$F(3,96) = 4.30$, $MS_e = 37.49$, $p < .01$], with fewer errors committed at long SOA (4.2%, 5.7%, 5.7%, and 5.7% for SOAs of 900, 300, 100, and 0 msec, respectively). Clearly, the participants produced more errors when the digits in Task 2 were close to 5 (6.3%) than when they were far from 5 (4.4%), which was confirmed in the main effect of numerical distance [$F(1,32) = 17.29$, $MS_e = 64.50$, $p < .001$; see also Table 2], mirroring the RT data.

Discussion

Experiment 2 tested for evidence of parallel semantic memory retrieval in dual tasks with different task sets (i.e., stimulus categorizations). When Task 1 required a vowel/consonant decision about a letter and Task 2 required a small/large decision about a number, the effect of the S2's numerical distance from the small/large boundary clearly interacted with SOA (see Figure 2). This underadditive interaction extends Experiment 1's locus-of-slack based findings of parallel semantic memory retrieval to conditions with nonidentical task sets. Therefore, Experiment 2 provided further evidence that participants can retrieve semantic categories in parallel even when they switch task sets from Task 1 to Task 2, as had been suggested by the findings of Oriet et al. (2005). Most important, however,

Table 2
Error Rates (in Percentages) in Experiment 2 Depending on Stimulus Onset Asynchrony (SOA), Numerical Distance (ND; Near/Far) of the Stimulus in the Second Task (S2), Stimulus in the First Task (S1; Vowel/Consonant), and S2 (Small/Large)

			SOA (msec)			
ND	S1	S2	0	100	300	900
Near	Vowel	Small	6.5	6.5	7.4	5.4
		Large	6.5	5.9	8.7	4.8
	Consonant	Small	7.6	8.5	5.9	5.7
		Large	6.1	6.7	5.2	3.7
Far	Vowel	Small	3.7	4.3	3.3	4.4
		Large	4.4	4.1	5.6	4.3
	Consonant	Small	5.4	5.4	4.8	2.2
		Large	5.4	4.3	4.8	3.3

our findings extend the results of Oriet et al. by showing that evidence for parallel retrieval is not bound to tasks involving different input modalities. Thus, the findings of parallel memory retrieval in conditions with different task sets is not specific to the automatic processing associated with stimuli in an auditory format. Following their line of argument, our results show that using the same visual input modality for different tasks does not critically increase resource demands for switching between tasks, so that enough spare resources are available for parallel retrieval processes in Task 2. In sum, evidence for parallel memory retrieval in dual-task situations is not contingent upon the use of tasks with different input modalities in the PRP paradigm.

Furthermore and somewhat unexpectedly, in Experiment 2, we also found that RT1 was affected by cross-talk from Task 2 processing. Responses in Task 1 were influenced by S2 size categories and by numerical distance of S2 to the boundary criterion 5. These cross-talk effects provide additional evidence that parallel semantic retrieval in Task 2 influences the processing of S1.

EXPERIMENT 3

Although Experiment 2 showed that using the visual modality for both tasks does not eliminate the possibility of parallel memory retrieval in Task 2 of the PRP paradigm, the letter judgment and the size judgment tasks still pose quite dissimilar task requirements. Experiment 3 was conducted to provide a stronger test for parallel memory retrieval in *highly similar* (but not identical) task conditions. For this reason, we extended Experiment 2 of Logan and Schulkind (2000) by using locus-of-slack logic as well as cross-talk logic. Specifically, the participants performed a parity judgment on the number stimulus for Task 1 and a size judgment on the number for Task 2. In this condition, Logan and Schulkind did not find evidence for parallel memory retrieval, and they attributed the absence of parallel retrieval to the implementation of different task sets. Oriet et al. (2005), on the other hand, argued that the demands on resources for switching between parity and size judgments might have been responsible for Logan and Schulkind's null result. Note that Oriet et al. did not test for this possibility in their study.

Contrary to what Oriet et al.'s (2005) analysis suggests, however, the mere application of the cross-talk logic may have concealed any evidence of parallel retrieval in Logan and Schulkind's (2000) experiment. If so, the application of locus-of-slack logic might reveal that parallel retrieval is possible when using a parity and a size judgment task. In particular, if parallel memory retrieval is a general phenomenon and does not depend on demands of central resources in switching between parity and size judgment tasks, the locus-of-slack approach should reveal an underadditive interaction of Task 2 numerical distance and SOA.

If, however, not the method but, as was suggested by Oriet et al. (2005), the proposed processing characteristics of the parity–size dual-task situation are responsible for preventing parallel memory retrieval, the locus-of-slack method should provide an additive pattern between numerical distance and SOA. In that case, the need for central resources required for the switch between different tasks could represent the decisive factor preventing parallel memory retrieval in dual tasks, although other explanations would not be excluded.

Method

Participants. A sample of 36 students (29 female, mean age = 22.1 years) at the Dresden University of Technology took part in Experiment 3. All had normal or corrected-to-normal vision. The participants attended a single experimental session lasting about 75 min and received €6.50 or course credit.

Apparatus and Stimuli. The experiment was conducted in a darkened room. The stimuli were displayed on a 17-in. color monitor that was connected to a Pentium III PC. The Task 1 stimuli were the digits 2, 3, 7, and 8, and the Task 2 stimuli were the digits 1, 4, 6, and 9. The same four response fingers were used as in Experiment 1, except that, in this experiment, the two fingers on the right hand were assigned to the *odd* (O) and *even* (E) responses (Task 1). Other than that, the apparatus and procedure were identical to that in Experiment 1.

Results

Incorrect trials in either task were excluded from the data analysis (4.4%). For Task 1, trials in which responses were faster than 200 msec or slower than 2,300 msec were excluded. Similarly, trials in Task 2 were excluded when the responses were faster than 200 msec or slower than 2,500 msec. This outlier procedure resulted in the further elimination of 3.4% of the trials from the RT data analysis. Separate repeated measures ANOVAs including the within-subjects factors of S1 (odd vs. even), S2 (small vs. large), numerical distance (near vs. far), and SOA (0, 100, 300, or 900 msec) and the between-subjects factor of S–R mapping (SLOE, SLEO, LSOE, or LSEO) were conducted on RT1 and RT2 (note that O and E denote odd and even numbers in Task 1).

Task 1 performance. RTs for Task 1 are shown in Figure 3. RTs were not affected by SOA ($F < 1$). Instead, we found a significant main effect of numerical distance in Task 2 on RT1 [$F(1,32) = 16.29$, $MS_e = 7{,}262.12$, $p < .001$]. That is, responses in Task 1 were faster when S2 was far from 5 (880 msec) than when the stimulus in Task 2 was near 5 (901 msec). We interpret this finding as an overall effect of Task 2 difficulty on RT1. In keeping with capacity models of PRP, faster responses in Task 1 may be a consequence of low resource demands in Task 2 processing (i.e., far from 5), whereas a larger RT1 would be predicted when resource demands in Task 2 increase (Tombu & Jolicœur, 2002, 2003, 2005). This interpretation is supported by a complete lack of any cross-talk-like interactions (e.g., S1 × S2, $F < 1$) on RT1. The effect of numerical distance in Task 2 on RT1 did not interact with SOA [$F(3,96) = 1.28$, $MS_e = 8{,}974.76$, $p = .285$]. No further significant effects were found.

Task 2 performance. As can be seen in Figure 3 (lower panel), mean RT2 clearly decreased as SOA increased [$F(3,96) = 570.74$, $MS_e = 25{,}938.25$, $p < .001$], replicating the usual effect of task overlap. Also, the numerical distance of S2 strongly influenced RT2 [$F(1,32) = 98.00$, $MS_e = 21{,}105.14$, $p < .001$]. Most important for the pur-

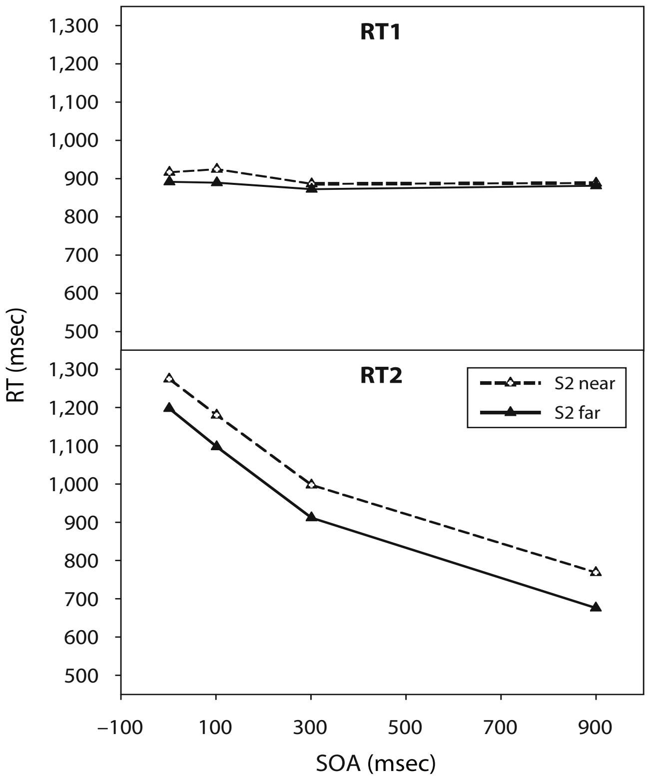

Figure 3. Response times (RTs) for Task 1 and Task 2 in Experiment 3 depending on numerical distance of the Task 2 stimulus (S2) to 5 (near vs. far) and stimulus onset asynchrony (SOA).

poses of Experiment 3, the effect of numerical distance in Task 2 did not depend on SOA ($F < 1$). In other words, numerical distance affected RT2 in an additive pattern, independently of the amount of task overlap. No other effects reached statistical significance. In contrast to Experiments 1 and 2, a large effect of numerical distance (77 msec) was found at the shortest SOA of 0 msec. An additional between-experiment ANOVA on numerical distance in the 0-msec SOA condition showed only an expected interaction between numerical distance and experiment [$F(2,105) = 13.18$, $MS_e = 3{,}751.31$, $p < .001$]. Further contrast analyses confirmed that this effect of numerical distance in Experiment 3 was significantly larger than those in Experiments 1 and 2 (SOA of 0 msec; both ps $< .001$).

Error analysis. The same form of data analysis was also conducted for the error data, which are shown in Table 3. Error rate was not affected by SOA [$F(3,96) = 2.11$, $MS_e = 45.09$, $p = .113$]. As in our previous experiments, the error data resemble the RT result pattern in that the participants produced more errors when the digits in Task 2 were close to 5 (5.3%) than when they were far from 5 (3.5%), which was confirmed in the main effect of numerical distance [$F(1,32) = 17.52$, $MS_e = 64.50$, $p < .001$; see also Table 3]. This difference in error rates was more pronounced at longer SOAs than at short ones, as indicated by the interaction between numerical distance and SOA [$F(3,96) = 4.70$, $MS_e = 47.16$, $p < .01$]. Further results include an interaction between numerical distance in Task 2 and S1 [$F(1,32) = 5.21$, $MS_e = 21.40$, $p < .05$]. The effect of numerical distance on produced errors was stronger when S1 was odd (5.5% vs. 3.1% for near and far distances, respectively) than when S1 was even (5.0% vs. 3.9%). Also, error rates were affected by the interaction between numerical distance in Task 2 and S2 [$F(1,32) = 12.43$, $MS_e = 24.44$, $p < .01$]. Here, the effect of numerical distance on produced errors was more pronounced when S2 was smaller than 5 (5.9% vs. 3.1%) than when S2 was larger than 5 (4.6% vs. 3.9%).

Discussion

Using parity and size judgment tasks (i.e., different tasks) in a dual-task situation, our Experiment 3 was an extension of Experiment 2 in Logan and Schulkind (2000). Logan and Schulkind did not find evidence for parallel retrieval in this condition. As was argued above, this may have been due to their use of the cross-talk approach, which may potentially have been unable to reveal parallel processing. Applying the locus-of-slack logic circumvented this problem and allowed testing for parallel memory retrieval even within the context of different task sets.

The results were straightforward: The underadditive interaction of numerical distance and SOA on RT2, found in Experiments 1 and 2, disappeared when the tasks were highly similar (i.e., parity and size judgment). This is a very important result because it clearly rules out the possibility that the mere application of the cross-talk logic may have been responsible for the absence of evidence for parallel memory retrieval in Experiment 2 in Logan and Schulkind (2000). Instead, our results are in accordance with the notion that parallel retrieval may be contingent upon the availability of resources needed for switching from Task 1 to Task 2 (Oriet et al., 2005).

GENERAL DISCUSSION

The aim of the present study was to investigate the boundary conditions of parallel memory retrieval in Task 2 of a dual-task situation. Previous cross-talk-based studies suggested that parallel memory retrieval in dual tasks is not possible in conditions with different task sets (Logan & Gordon, 2001; Logan & Schulkind, 2000), from

Table 3
Error Rates (in Percentages) in Experiment 3 Depending on Stimulus Onset Asynchrony (SOA), Numerical Distance (ND; Near/Far) of the Stimulus in the Second Task (S2), Stimulus in the First Task (S1; Odd/Even), and S2 (Small/Large)

			SOA (msec)			
ND	S1	S2	0	100	300	900
Near	Odd	Small	6.3	4.4	7.4	5.6
		Large	3.9	3.7	7.9	5.1
	Even	Small	7.2	6.3	6.5	3.9
		Large	4.2	2.5	6.0	3.7
Far	Odd	Small	4.2	2.1	3.5	2.5
		Large	3.7	3.2	2.5	3.2
	Even	Small	3.2	4.2	2.3	3.0
		Large	5.8	6.0	3.0	3.5

which Logan and Schulkind argued that parallel memory retrieval is contingent upon using the same task set in both tasks. Oriet et al. (2005), however, found evidence of parallel memory retrieval with different task sets, from which they argued that parallel memory retrieval may depend on resources that are free only when it is easy to switch from Task 1 to Task 2 processing.

In the present study, we investigated an alternative explanation for Logan and Schulkind's (2000, Experiment 2) failure to find evidence for parallel memory retrieval with different task sets. In three experiments, we tested whether their exclusive reliance on the cross-talk logic in the PRP paradigm may have been responsible for this failure. A common aspect of typical cross-talk experiments is that backward cross-talk effects seem to require that responses are based on the same type of category information (but see Miller, 2006, and Miller & Alderton, 2006, for different approaches). Thus, parallel semantic memory retrieval across different tasks would not necessarily be revealed with the cross-talk approach even if it did take place.

Therefore, we tested parallel semantic memory retrieval in conditions with both identical (Experiment 1) and nonidentical (Experiments 2 and 3) task sets. In addition to using the cross-talk logic for demonstrating parallel memory retrieval (Logan & Schulkind, 2000), we also used the locus-of-slack logic to determine whether Task 2 semantic memory retrieval could operate in parallel with Task 1 bottleneck processes (cf. Oriet et al., 2005).

Experiment 1 clearly showed that the two approaches led to the same conclusion in conditions with identical task sets. Large category match effects in Task 1 provided cross-talk-based evidence for parallel semantic memory retrieval, replicating the results of Logan and Schulkind (2000). That is, responses in Task 1 were considerably faster when both stimuli belonged to the same semantic category (e.g., S1 and S2 were both smaller than 5), as compared with conditions in which they belonged to different semantic categories. Similarly, evidence for parallel semantic retrieval was also found with the locus-of-slack approach. This evidence involved an overall numerical distance effect in Task 2, whereby responses were faster to digits far from the category boundary than to digits near that boundary (e.g., the *greater than 5* response was faster to 8 than to 6). Most important, this numerical distance effect interacted underadditively with SOA. On the basis of the locus-of-slack logic, this underadditivity suggests that at least some of the effects of numerical distance are absorbed into the slack time created while the bottleneck process handles Task 1. This means, in turn, that Task 2 semantic memory retrieval processes are not prevented by Task 1 bottleneck processing but, instead, can proceed in parallel with it. Thus, we conclude that Task 2 semantic memory retrieval does not require access to the bottleneck. This finding is also in accord with the conclusions of Oriet et al. (2005), because in conditions with identical task sets, switching from Task 1 to Task 2 may require only minimal resources, if any at all.

In connection with Experiment 1, an additional new finding was that numerical distance in Task 2 revealed a direct influence on the size of the category match cross-talk effect in Task 1 (at a short SOA). That is, numbers further from 5 produced a larger category match effect in Task 1 than did numbers closer to 5. This finding suggests that the representations of numbers are associated with different size-related strengths, rather than simply membership in task-specific categories, and that these strengths, in turn, modulate the influence of S2 on S1 processing. In addition, this interaction is further evidence that semantic memory retrieval processes associated with numerical distance must have taken place in Task 2 at short SOA, although they had no effect on RT2 because they were concealed by slack.

In Experiment 2, we used the dual-task procedure with different task sets in order to test the generalizability of our findings about parallel memory retrieval processes. Using the locus-of-slack logic in Experiment 2, we obtained a clear underadditive interaction of numerical distance and SOA, just as in Experiment 1. Critically, this underadditive interaction indicates that Task 2 semantic memory retrieval can occur in parallel with bottleneck processing in Task 1. This is a clear demonstration that parallel memory retrieval processes in dual tasks are not necessarily contingent upon the application of identical task sets, as was suggested by Logan and colleagues (Logan & Delheimer, 2001; Logan & Gordon, 2001; Logan & Schulkind, 2000). Moreover, these results highlight the limitations of testing for cross-talk-based evidence of parallel processing when using tasks requiring different semantic categorizations (see also Schubert, Fischer, & Stelzel, in press). Clearly, an advantage of the locus-of-slack logic is that it is possible to check for parallel Task 2 processing independently of the match between Task 1 and Task 2 characteristics.

Our findings of parallel memory retrieval in different task set conditions not only replicate the results in Oriet et al. (2005), but also extend their results by showing that this evidence is not contingent upon the use of different input modalities in the two tasks. That is, Experiment 2 demonstrated that the same underadditive result pattern can be found when Task 1 and Task 2 share the same input modality (i.e., visual–visual).

Experiment 3 was designed to test further the assumption that the amount of resources needed for switching from Task 1 processing to Task 2 processing determines whether or not parallel memory retrieval can take place in Task 2, as was suggested by Oriet et al. (2005). Using two task sets (i.e., parity vs. size judgment) between which it is known that switching requires cognitive resources (Sudevan & Taylor, 1987), the locus-of-slack logic allowed testing for parallel retrieval without the limitations associated with the cross-talk approach. Nevertheless, even though we applied a methodology that would allow the demonstration of parallel processing in conditions with different task sets, no evidence for this was found in Experiment 3. That is, the previously obtained underadditive interaction between numerical distance and SOA in Task 2 (Experiments 1 and 2) disappeared in this experiment. A locus-of-slack based interpretation of this additivity suggests that memory retrieval cannot operate in parallel with Task 1 bottleneck processing. This locus-of-slack based evidence against parallel retrieval disconfirms the hypothesis that the use of cross-talk logic has concealed evidence for parallel retrieval in conditions with different tasks. Instead, the present results of Experiment 3 are in accord with the interpretation of Oriet et al. (2005), supporting the view that the task combination itself and the resources required for switching between tasks in a PRP paradigm may determine whether parallel memory retrieval can occur.

Although our results are quite straightforward qualitatively, one aspect of debate might be the rather small size of the observed underadditivity between numerical distance and SOA in Experiments 1 and 2. The underadditivity reflects a linear decline of effect sizes of numerical distance in Task 2 with decreasing SOA, but the absolute magnitude of this decline is not large, as compared with the overall range of RTs and SOA effects. Nonetheless, the present underadditivity is comparable in size to the underadditivity observed in previous applications of locus-of-slack logic with similar paradigms (e.g., Oriet et al., 2005). A residual numerical distance effect of about 13 msec remained at the shortest SOA in both experiments, but importantly, the effects of numerical distance were not statistically significant at the shortest SOA in either Experiment 1 or Experiment 2. This suggests that the RT2 differences due to near versus far distance to the decision criterion were completely or almost completely absorbed into the slack. Given this result, the reported underadditivity in the present study may be, if not complete, only of a partial nature. In this respect, it is interesting to note that Oriet et al. (see also Lawson, Humphreys, & Jolicœur, 2000; Pashler, 1984) also reported residual effects of numerical distance at a short SOA. Oriet et al., for example, argued that only parts of the semantic activation in a number size judgment task can operate in parallel with the bottleneck. In particular, they suggested that only the activation of the size information (i.e., large vs. small), but not the comparison of the activated size information with the decision criterion, may operate in parallel (see Oriet et al., 2005, for details).

In future research, it may be important to identify more closely the type and nature of resources that are needed to switch between different task sets in a PRP paradigm. One possibility may be that the increased cognitive resources required in Experiment 3, as compared with Experiment 2, are linked to the specific characteristics of response mappings when bivalent stimuli are used (Allport, Styles, & Hsieh, 1994; Rogers & Monsell, 1995; Woodward, Meier, Tipper, & Graf, 2003). In other words, mapping bivalent stimuli to different responses in Tasks 1 and 2 might give rise to specific intertask response selection interference, which could be responsible for the additive result pattern.[2] It is also conceivable that the difficulty of mapping bivalent stimuli to the required responses may increase the resources needed to change from response selection in Task 1 to response selection in Task 2. To isolate such effects, it appears to be important to know which combinations of task sets allow parallel retrieval and which require serial retrieval. These questions are beyond the scope of the present article but provide interesting perspectives for future research.

Conclusion

The present experiments provided clear evidence that semantic memory retrieval in Task 2 can occur simultaneously with bottleneck processing in Task 1. Most important, our results extend the findings from previous research by showing that locus-of-slack based evidence for parallel semantic memory retrieval is not bound to dual-task situations in which the two tasks use the same task set and overlapping semantic categories. However, our results suggest that parallel memory retrieval is not a completely general phenomenon either, because it occurs only with certain task combinations. Whereas the present study focused on size judgments in the number domain, subsequent research may extend the present conclusions with different sorts of semantic category activation (e.g., valence judgments; Fischer & Schubert, in press). Furthermore, additional research will be needed to isolate exactly which conditions and task pairs can lead to parallel retrieval in dual-task situations.

AUTHOR NOTE

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NOTES

1. It is conceivable that these effects of Task 2 performance reflect effects of Task 1 that propagated onto Task 2. That is, anything that affects the time needed for Task 1 to clear the bottleneck will also necessarily affect RT2 (see Schubert et al., in press).

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