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Research Article

Increased Control Demand Results in Serial Processing

Evidence From Dual-Task Performance

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ABSTRACT—***Increased demands on cognitive control trigger changes in processing mode. One such modulation involves a shift from parallel to serial processing. This study assessed the role of control demand in determining whether dual-task processing is performed serially or in parallel. We used two critical indices, based on the response-selection bottleneck model, to show that response selection was serial when a task switch was involved, but partly parallel when the simultaneous performance of the tasks did not involve task switching.***

The roles of control and executive processes in monitoring behavior have come to be of major interest in contemporary psychology. Although practice can result in automatic performance and the formation of habits, control processes are required to overcome habits and learned responses (Norman & Shallice, 1986). Control processes are triggered by a system that involves the anterior cingulate cortex. This system detects error-prone situations and conflict (Botvinick, Braver, Barch, Carter, & Cohen, 2001) and organizes and initiates task processes in order to create consistent, goal-directed behavior (E.E. Smith & Jonides, 1999). An increase in involvement of controlled processing also follows the detection of anxiety-invoking thoughts (Wegner, 1994) and is evidenced, for example, by the response slowing observed in trials following errors (Rabbitt & Vyas, 1981) or response conflict (e.g., Gratton, Coles, & Donchin, 1992). A recent study (Walton, Devlin, & Rushworth, 2004) showed that differential control demands within the same task (i.e., being instructed how to respond vs. selecting and monitoring for oneself how to respond) were associated with differential activation of brain regions.

The present study provides evidence that an important compensatory control adjustment is a shift from parallel to serial processing. We argue that when a task's control demands become low (as in the case of automatic performance), processing becomes more parallel (Beilock, Bertenthal, McCoy, & Carr, 2004; Gray, 2004; Hazeltine, Teague, & Ivry, 2002). The novel claim here is that the shift from serial to parallel processing is the result not of practice per se, but rather of the accompanying reduction in control demand. In two experiments using a dual-task paradigm, we obtained evidence for parallel processing when control demands were low and for serial processing when control demands were high. Control demands were operationalized by the requirement to switch tasks (cf. Braver, Reynolds, & Donaldson, 2003; Monsell & Driver, 2000). We chose to use the psychological refractory period (PRP) paradigm (Telford, 1931) because Pashler's (1984) bottleneck model provides a series of thoroughly validated indices for serial versus parallel processing of the two tasks in this paradigm.

THE PRP PARADIGM AND THE BOTTLENECK MODEL

The PRP paradigm (Telford, 1931) is one of the leading methodologies in dual-task investigations. In this paradigm, two stimuli, S1 and S2 (the stimuli for the first and second tasks, respectively) are presented in rapid succession, each receiving a separate response (R1 and R2), resulting in two response times: RT1 and RT2. The interval between the presentations of S1 and S2 (the stimulus onset asynchrony, SOA) is manipulated, and the basic finding is that RT1 is not affected by SOA, whereas RT2 decreases as SOA increases (the so-called PRP effect). To explain this effect, Pashler and his colleagues (Pashler, 1984,

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1994a, 1998; Pashler & Johnston, 1989; see also Welford, 1952) suggested that a central processing stage, responsible for response selection, cannot operate concurrently for the two tasks. Thus, response selection acts as a bottleneck, so that this stage must be completed for the first task before processing of the second task can continue. According to the response-selection bottleneck (RSB) model, perceptual processing and response preparation operate in parallel for the two tasks. The RSB model yields several attractive predictions, all of which have received substantial empirical support (see Pashler, 1998, for a review). We used indices based on this model as markers for parallel versus serial response selection.

Recently, researchers have challenged a central assumption in the RSB model (Pashler, 1994a, 1998), namely, the assumption that structural limitations are the reason for serial processing. Dissenting views see the bottleneck as strategic rather than structural (e.g., Logan & Gordon, 2001; Meyer & Kieras, 1997a, 1997b). These views suggest that serial processing may be invoked in conditions marked by cross talk and increased error probability, which also increase control demands.

PRP AND TASK SWITCHING

Traditionally, the PRP paradigm involves two different tasks (e.g., a tone that is responded to vocally and a letter that is responded to manually). Thus, there is a task switch from the first to the second task embedded in this paradigm. An interesting question is whether this aspect of the paradigm's design is responsible for the serial response selection.

Previous studies have suggested that task switching may lead to serial processing. This paradigm involves completely serial stimulus presentation (so that a stimulus is presented only after a response to the previous stimulus is emitted), and the task that must be performed may change from one stimulus to the next (e.g., a switch between magnitude and parity judgments). Oriet and Jolicoeur (2003) recently showed that task switching resulted in completely serial processing, even in the case of perceptual operations. The same perceptual operations are carried out in parallel in the PRP paradigm. We suggest that the increased serial processing associated with task switching (relative to the PRP paradigm) results from increased control demands. Specifically, unlike the PRP paradigm, in which the stimuli and responses in one task do not overlap with those of the other, the task-switching paradigm usually involves overlapping stimuli and responses, and this overlap increases the control demands during a task switch (Meiran, 2000a, 2000b). We go one step further and suggest that response selection (in addition to perceptual operations) would become more parallel if control demands were lowered further. In the present study, we reduced the control demands in the PRP paradigm by having subjects perform pairs of trials belonging to the same task. Thus, there was no requirement to control task order (De Jong, 1995; Luria & Meiran, 2003), and task switching was not involved.

PARALLEL PROCESSING IN THE PRP PARADIGM WITH REDUCED CONTROL DEMANDS

Logan and Schulkind (2000), using the PRP paradigm, showed that RT1 was facilitated if the response categories of R1 and R2 matched. The fact that R2 identity affected RT1 even before RT2 was executed is evidence for parallel processing. Note that this category-match effect was observed only when the PRP paradigm involved a task repetition and was not observed when the paradigm involved a task switch. Schumacher, Seymour, Glass, Kieras, and Meyer (2001; see also Hazeltine et al., 2002) showed that response selection was performed in parallel after practice, and practice is generally believed to reduce control demands. Similarly, experts' performance suffered when the task was manipulated so that the experts executed it serially (Beilock et al., 2004; Gray, 2004), which shows that their natural tendency was to perform the task in parallel.

Pashler (1994b) addressed the question of whether task switching leads to serial processing in the response-selection stage by using a serial performance task, so that the same task, with different stimuli, was repeated 5 to 10 times. On some occasions, preview of the next stimulus was available. Pashler manipulated perceptual stages by presenting either a low- or a high-intensity stimulus and response-selection stages by using either an arbitrary or a congruent mapping between the stimuli and the responses. According to the RSB model, increasing the difficulty of perceptual stages should not lead to an increase in RT when preview is available (because perceptual operations can be done in parallel); however, increasing the difficulty of response selection should increase RTs even with a preview (because response-selection stages are serial). Pashler's results were in line with the RSB model: Preview reduced the effect of manipulations affecting perceptual processing, but the effect of the difficulty of response selection was unchanged by preview. Thus, Pashler concluded that "the RSB is not caused by the need to switch tasks" (p. 161). We do not contest this conclusion, but only note that his study did not include a task-switch condition for comparison. It was therefore impossible to assess whether task switching affected the degree of serial processing.

THE PRESENT STUDY

The goal of the present study was to assess whether increased control demands (task switching) make response selection more serial. To this end, we compared a standard PRP paradigm, which involved a task switch (the *switch condition*), with a condition in which the first task was repeated (the *repeat condition*); in both cases, two distinct stimuli requiring separate responses were presented. We used two critical indices based on the PRP model to test whether response selection was serial or partly parallel.

EXPERIMENT 1

If any stage of the first task up through response selection is prolonged, RT1 should be naturally prolonged. According to the RSB model, response selection is performed serially, so all of the RT1 prolongation should be carried over to RT2, and responses in the two tasks should be prolonged to the same extent (Fig. 1; see Karlin & Kestenbaum, 1968, and M.C. Smith, 1969, for empirical support). However, this prediction holds only when the SOA is short, because only then must the second task wait for the response-selection stage of the first task to end; at longer SOAs, response selection for the first task is completed before S2 appears, so that RT2 is unaffected by the first task. We tested whether the same pattern of RTs would be obtained when the first task was repeated. Participants performed a letter task (classifying the letter as a vowel or consonant) and a digit task (classifying the digit as odd or even), so each task had two possible responses. In some blocks, the first task had two possible stimuli, so that it had two stimulus-response (S-R) rules, and in other blocks, the first task had eight possible stimuli (eight S-R rules). This manipulation would presumably affect the duration of the response-selection stage of the first task (Sternberg, 1969).[1]

If serial response selection in the PRP paradigm is indeed due to task switching, then parallel processing would be expected in the repeat condition. That is, some overlap between the response-selection stages of the two tasks would be allowed, and not all of the prolongation of RT1 due to having eight rather than two S-R rules would be carried over to RT2 (see Fig. 1). We expected a full carryover from RT1 to RT2 in the switch condition (the usual condition), but less prolongation of RT2 than RT1 in the repeat condition.

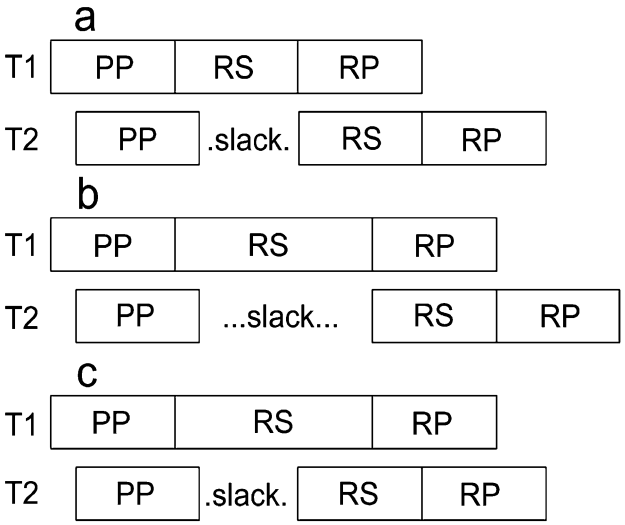

Fig. 1. The psychological refractory period paradigm and effects of difficulty of the first task (T1). According to the response-selection bottleneck model, response selection for T1 must be completed before response selection for the second task (T2) can begin, so when stimulus onset asynchrony is short, there is a period of slack between perceptual processing and response selection for T2 (a). If response selection (or an earlier stage) for T1 is prolonged because of task difficulty (b), response selection for T2 is delayed to the same extent; that is, the prolongation is fully carried over to T2. In contrast, if overlap of response selection in the two tasks is allowed (c), not all of the prolongation of T1 should be carried over to T2. PP = perceptual processing, RP = response production, RS = response selection.

Method

Participants

Thirty-eight students from Ben-Gurion University and Achva College, Israel, participated in this experiment.

Apparatus and Stimuli

Stimuli were presented on an IBM-PC clone with a 14-in. (35.6-cm) monitor. We used eight letters from the Hebrew alphabet and eight digits (each subtending approximately 0.38° × 0.28° of visual angle from a viewing distance of 60 cm). Participants had to classify each letter as either a consonant or a vowel (the letter task) and each digit as either odd or even (the digit task). In addition, we used a plus sign as a fixation point. Participants pressed the "z" and "x" keys with the middle and index fingers of their left hands in responding to the stimulus that appeared on the left side of the fixation. They pressed the ">" and "/" keys with the index and middle fingers of their right hands in responding to the stimulus that appeared on the right side of the fixation.[2] The mappings between the keys and the responses were counterbalanced across participants. S1 and S2 were presented very close together, approximately 0.38° from one another.

Design and Procedure

Participants took part in a single session. The first three blocks were considered practice and consisted of 20 trials each. The first practice block had the standard PRP design, involving different tasks (letter and digit). In the second practice block, the first task (either the letter or the digit task) was repeated, and in the third block, the first task was also repeated, but it had only two S-R rules (only two possible stimuli), rather than the eight S-R rules (eight possible stimuli) in all other practice blocks. Half of the participants performed the letter task as their first task, and the other half performed the digit task as the first task.

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[1] There are claims that this manipulation may affect the perceptual stages as well. However, the RSB model makes exactly the same prediction even if this is the case.

[2] Note that we used two manual responses, a procedure that is usually associated with larger likelihood of inducing output interference. However, increasing task interference, if anything, should have obscured any signs for parallel processing.

There were four types of experimental blocks: switch (two different tasks) with eight possible stimuli in the first task, repeat (the same task twice) with eight possible stimuli in the first task, switch with only two possible stimuli in the first task, and repeat with only two possible stimuli in the first task. Overall, participants performed eight experimental blocks (85 trials each), two blocks of each type. The specific order was counterbalanced across participants. Participants received written instruction before each block.

A trial began with the presentation of a fixation point for 500 ms. Then, S1 was presented adjacent to the right side of the fixation point, followed by S2 (presented adjacent to the left side of the fixation point); the onsets of the stimuli were separated by one of three randomly determined SOAs (100, 200, or 400 ms). All stimuli remained visible until the second response was emitted, after which there was a pause of 1,500 ms until the next trial began.

Participants received written instructions to respond to each stimulus as quickly as possible while maintaining high accuracy. They were also encouraged to respond to the first stimulus as quickly as possible. To discourage response grouping (Pashler & Johnston, 1989), we presented only S1 in 5% of the trials; in this case, after participants emitted R1, the trial ended and the next trial began.

Results

All trials with an error in either R1 or R2 were excluded from the RT analysis. RTs greater than 2,500 ms or less than 100 ms were also omitted. One participant was excluded from the final analysis because more than 10% of his responses were errors. Note that according to the RSB model, when RT1 is prolonged because of response-selection difficulty, one would expect a full carryover of this prolongation to RT2 only if the response-selection stage of the first task does not end before response selection for the second task begins. Accordingly, we did not analyze RT2s preceded by RT1s below 400 ms (the longest SOA). Alpha level was set at .05.

RT1

An analysis of variance (ANOVA) on RT1 with S-R numerosity (two or eight), SOA (100, 200, or 400 ms), and switching (switch or repeat) as independent variables yielded significant main effects for S-R numerosity, $F(1, 36) = 38.43$, $\eta_p^2 = .51$ (886 vs. 774 ms in the eight- and two-alternatives conditions, respectively, for an effect of 112 ms), and switching, $F(1, 36) = 8.36$, $\eta_p^2 = .18$ (810 vs. 850 ms in the switch and repeat conditions, respectively). The slowing in the repeat condition could be explained by the fact that repeating the same task increases the tasks' similarity, a condition known to increase interference (Hirst & Kalmar, 1987; Navon & Miller, 1987). The interaction between switching and S-R numerosity was not significant ($F < 1$). Numerically, the effect of S-R numerosity was 113 ms in the switch condition and 105 ms in the repeat condition (see Fig. 2).

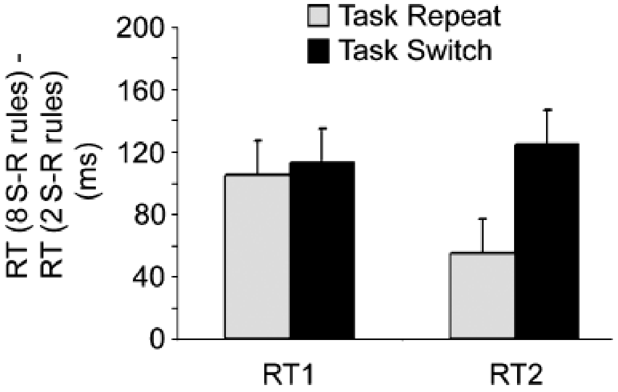

Fig. 2. Magnitude of the effect of the number of stimulus-response rules (S-R numerosity) as a function of task switching in Experiment 1. The effect of S-R numerosity was calculated by subtracting reaction time (RT) on trials with two S-R rules from RT on trials with eight S-R rules. RT1 = reaction time in the first task, RT2 = reaction time in the second task.

RT2

A similar ANOVA on RT2 yielded significant main effects of S-R numerosity, $F(1, 36) = 18.63$, $\eta_p^2 = .34$, and SOA, $F(2, 72) = 331.15$, $\eta_p^2 = .90$ (the usual PRP effect—210 ms in this case). The interaction between S-R numerosity and switching was significant, $F(1, 36) = 11.92$, $\eta_p^2 = .24$. The effect of S-R numerosity was 125 ms in the switch condition, but only 55 ms in the repeat condition (see Fig. 2). The interaction between SOA and S-R numerosity was not significant, $F = 1.26$.

To directly test our predictions that there would be full carryover of RT1 prolongation in the switch condition but only partial carryover in the repeat condition, we compared the magnitude of the S-R numerosity effect in RT1 and RT2. As predicted by the RSB model, in the switch condition, the effect on RT1 was not significantly different from the effect on RT2, $F < 1$, indicating a full carryover, as in previous studies (Karlin & Kestenbaum, 1968; M.C. Smith, 1969). However, the same comparison was significant in the repeat condition, $F(1, 36) = 9.53$, $\eta_p^2 = .20$; the effect of S-R numerosity was 50 ms smaller in RT2 than in RT1. These results support our hypothesis that response selection is more parallel when tasks are repeated than when they are switched: Carryover of the S-R numerosity effect from R1 to R2 was incomplete when a task was repeated.

However, there is an alternative explanation that needs to be ruled out. Specifically, some processing stages may have become shortened in the repeat condition when only two S-R rules were used. For example, the duration of response selection for the second task may have been shortened in this condition (because the task was repeated). This could explain why we did not observe a full carryover of RT1 prolongation to RT2 while still allowing for response selection to be serial. We argue that this explanation is implausible because if some processing stages were shortened, there should have been an overall decrease in RT2 in the repeat condition (at least when there were two S-R rules). However, RT2 was 41 ms slower in the repeat condition than in the switch condition, $F(1, 36) = 3.11, p = .08$. Hence, the duration of processing stages in the repeat condition was, if anything, increased. In order to rule out this alternative explanation and to further strengthen our conclusions, we conducted another experiment. This time, we manipulated the difficulty of the second task in processing stages preceding response selection.

EXPERIMENT 2

In Experiment 2, we presented the name of a digit (e.g., "eight") as S2. In addition, on some occasions, we replaced two of the letters in the name with asterisks (e.g., "*i*ht"). This degradation manipulation should prolong the duration of the processing stages preceding response selection. According to the RSB model, if response selection is serial, manipulations affecting earlier, perceptual processing in the second task will be associated with greatly reduced effects when the SOA is short than when it is long (see Pashler & Johnston, 1989, and De Jong, 1993, for empirical support). The reason is that when the SOA is short, the prolongation of the perceptual stage of the second task is absorbed into the time when the second task waits for the response-selection process to be freed (the so-called cognitive slack; see Fig. 3a). However, if our hypothesis is correct and the repeat condition involves some parallel response selection, there is less slack, so an increase in time needed for perceptual processing will delay the response-selection process for the second task in the short-SOA condition (see Fig. 3b). Thus, we predicted that the effect of the degradation manipulation on RT2 would be larger in the repeat condition than in the switch condition. We expected this to happen only for the short and intermediate SOAs, because our long SOA (1,000 ms) would not involve any slack for both the repeat and the switch conditions.

Method

Except as noted, the apparatus and procedure were the same as in Experiment 1.

Participants

Ten students took part in this experiment. All had participated in a previous PRP experiment (not Experiment 1).

Apparatus and Stimuli

The stimuli for the digit task were eight Hebrew names for digits (e.g., the Hebrew equivalent of "eight"). On 50% of the trials (randomly determined), two letters were replaced by asterisks (e.g., "*i*ht" or ei*h*), and each digit name had two corresponding degraded stimuli. The letter task (the same as in Experiment 1) was presented first; stimuli for this task appeared above the fixation point. Stimuli for the digit task appeared below the fixation point.

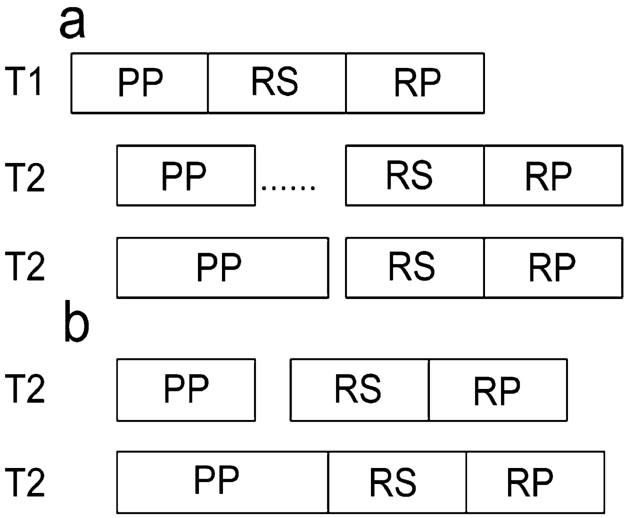

Fig. 3. The psychological refractory period paradigm and the effects of processing difficulty of the second task (T2). According to the response-selection bottleneck model (a), response selection for T2 cannot begin until response selection for the first task (T1) has been completed; under conditions with a short stimulus onset asynchrony, if perceptual processing for T2 is prolonged (cf. the two timelines for T2), reaction time for T2 is not affected because perceptual processing for this task can be completed during what would otherwise be slack. In contrast, if overlap of response selection for the two tasks is allowed (b), prolonging the perceptual stage of T2 should delay response selection for this task and therefore have a pronounced effect on reaction time for T2. PP = perceptual processing, RS = response selection, RP = response production.

Design and Procedure

There were two types of experimental blocks: switch (two different tasks) and repeat (the same task twice). For half the participants, the repeat condition was before the switch condition. For the other half, this order was reversed. S2 degradation was randomly manipulated within each block, so that degraded stimuli appeared on 50% of the trials. Participants performed three blocks of each type. The SOAs were 50, 300, and 1,000 ms.

Results

Except as noted, trimming criteria were the same as in Experiment 1. The RSB prediction was that the effect of stimulus degradation would decrease as SOA decreased. The assumption was that when the SOA was long, RT1 would be short enough that there was no need for the second task to wait for response selection for the first task to be completed. To meet this assumption, when we analyzed the long-SOA condition, we excluded from the RT2 analysis trials with RT1s above 1,000 ms.

RT1

An ANOVA on RT1 with degradation (degraded or not degraded), SOA (50, 300, or 1,000 ms), and switching (switch or repeat) as independent variables yielded significant main effects of

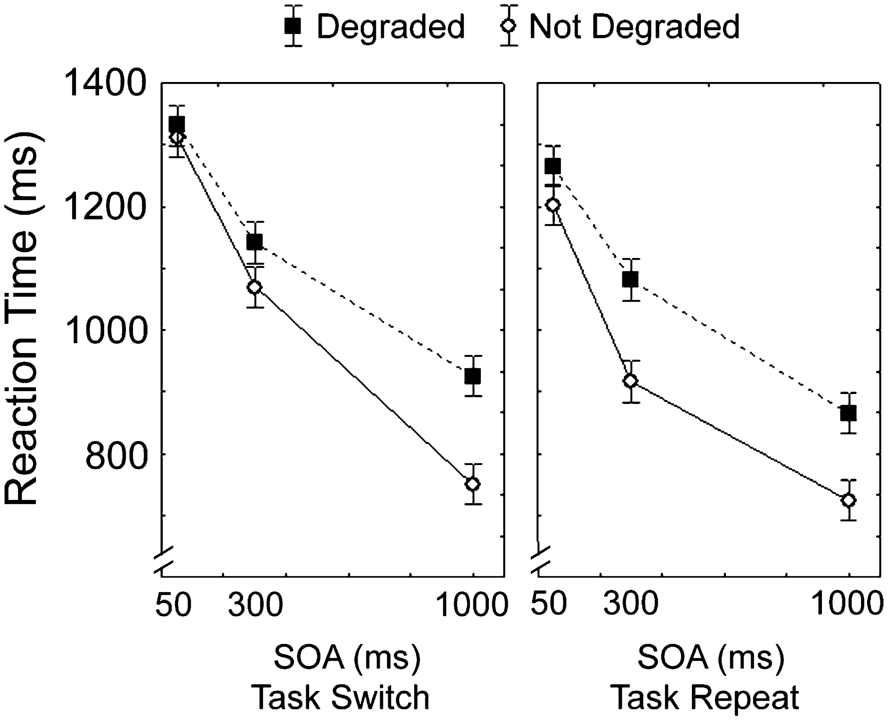

Fig. 4. Reaction time on the second task in the task-repeat and task-switch conditions of Experiment 2 as a function of stimulus onset asynchrony (SOA). Results for degraded and nondegraded stimuli are shown separately.

degradation, $F(1, 9) = 11.49$, $\eta_p^2 = .56$, and SOA, $F(2, 18) = 25.66$, $\eta_p^2 = .74$. The interaction between degradation and SOA was also significant, $F(2, 18) = 6.62$, $\eta_p^2 = .42$ (the size of the SOA effect was 63 ms in the not-degraded condition and 122 ms in the degraded condition), as was the interaction of SOA and switching, $F(2, 18) = 4.23$, $\eta_p^2 = .32$ (the size of the SOA effect was 69 ms in the repeat condition and 117 ms in the switch condition).

RT2

A similar ANOVA on RT2 yielded significant main effects of degradation, $F(1, 9) = 29.19$, $\eta_p^2 = .76$, and SOA, $F(2, 18) = 136.67$, $\eta_p^2 = .93$, indicating the usual PRP effect (in this case, an effect of 462 ms). The interaction between degradation and SOA was significant, $F(2, 18) = 11.96$, $\eta_p^2 = .57$; the degradation effect was 41 ms for the short SOA and increased to 169 ms for the long SOA. The interaction between SOA and switching was also significant, $F(2, 18) = 6.37$, $\eta_p^2 = .41$; the PRP effect was 494 ms in the switch condition and 440 ms in the repeat condition.

Most critically, the triple interaction of degradation, SOA, and switching was significant, $F(2, 18) = 4.14$, $\eta_p^2 = .31$. A comparison of the repeat and switch conditions provided further evidence for parallel processing in the repeat condition: At the short and intermediate SOAs, the effect of degradation was larger in the repeat condition than in the switch condition. Specifically, in the switch condition, the effect of degradation was 19 ms for the short SOA and 72 ms for the intermediate SOA. However, in the repeat condition, the effect of degradation increased to 63 and 165 ms at these two SOAs, respectively. This difference (averaging these two SOAs) was significant, $F(1, 9) = 8.74$, $\eta_p^2 = .49$. At the long SOA, the size of the degradation effect did not differ significantly between the repeat and the switch conditions, $F < 1$ (175 and 142 ms in the switch and repeat conditions, respectively; see Fig. 4).

In Experiment 2, degradation had an increased effect in the repeat condition relative to the switch condition. This result is important in ruling out the alternative explanation of the results of Experiment 1 (i.e., that task repetition shortened processing in general) because such an account would predict generally reduced effects in the repeat condition.

GENERAL DISCUSSION

We used the RSB model (Pashler, 1994a, 1998) in order to assess whether response selection in dual-task performance shifts from being serial to being more parallel if control demands are reduced. We reduced control demands by removing the task-switching requirement. Our results indicated that processing was serial when there was a task switch, but partly parallel when the task was repeated. In Experiment 1, when there was a task switch, prolongation of processing at or before response selection for the first task was fully transferred to RT2, indicating serial response selection; however, when the task was repeated, only about one half of the RT1 prolongation was transferred to RT2. In Experiment 2, S2 degradation had an increased effect in the repeat condition relative to the switch condition, given a short SOA, indicating a lesser degree of serial response selection in the repeat condition.

Note that we did not observe a trend for switching to increase all the effects; rather, relative to repetition, switching increased the effect of numerosity in Experiment 1 and decreased the effect of degradation in Experiment 2. The convergent results support our claim that task repetition results in parallel response selection.

According to the RSB model (Pashler, 1994a), the response-selection stage operates serially, whereas other early and late stages of processing can proceed in parallel. We have provided evidence that when control demands are low, response selection becomes more parallel. The idea that control processes adjust the degree of serial processing is in line with recent results by Oriet and Jolicoeur (2003) showing that early processing is performed serially in the task-switching paradigm. Thus, if control demand is high enough, serial processing can apply also to processes other than response selection.

It is important to note that even in the repeat condition, response selection was partly serial. For example, in Experiment 1, prolonging response selection in the first task had an effect on the second task as well (55 ms), $F(1, 36) = 6.03$, $\eta_p^2 = .14$, although it was much smaller than the effect on the first task. In Experiment 2, the effect of SOA was larger in the not-degraded condition than in the degraded condition, even in the repeat condition (the size of this interaction was 79 ms), $F(1, 9) = 7.93$, $\eta_p^2 = .46$.

SUMMARY

These two experiments provide evidence for partially overlapping response selection in dual-task conditions that involved task repetitions. The results indicate that control demands, rather than a structural limitation, play a role in determining whether processing is serial or parallel.

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