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Online Order Control in the Psychological Refractory Period Paradigm

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The authors examined the role of online order control in the psychological refractory period (PRP) paradigm. In the first 2 experiments, participants switched between color–letter and letter–color orders so that subtask order was isolated as the only element being switched. The results indicated that order switching impaired the 2 PRP responses and modulated the PRP effect. Importantly, these effects were reduced by advance preparation, demonstrating that order representation was activated before the subtasks themselves. Preparation for subtask order did not reflect preparation for hand order, as shown in Experiment 3. In addition, there was no evidence that subtask order information dissipated between trials. The relevance of the results to theories of the PRP paradigm and task switching is discussed.

Many everyday tasks consist of multiple actions. While performing these multistep tasks, one has to follow a series of subtasks, and often each subtask is dependent on the outcome of a preceding one. Because each subtask can also be independent—namely, it can be executed alone—organization of subtasks in the proper order is a key element for successful performance. This article focuses on providing evidence that explicit subtask order information is used for online order control and is activated in the initial stages of multistep tasks.

Models of action address representation of order by assuming that order is explicitly (e.g., Cooper & Shallice, 2000; Grafman, 1995; Norman & Shallice, 1986) or implicitly (e.g., Botvinick & Plaut, 2003) represented. By "explicit," we mean that the information concerning order is not an emergent property of the system but exists as a separate representation.

Sequence-learning studies indicate that using a constant order of actions or stimuli facilitates performance relative to conditions in which the order varies. Nonetheless, the gain depends on various conditions such as the complexity of the subtasks or on the way they are linked to the global task (Carlson & Sohn, 2001; Lundy, Wenger, Schmidt, & Carlson, 1994; Wenger & Carlson, 1995, 1996). Overall, these studies demonstrate that participants can track order consistency and make use of this consistency to facilitate performance.

Other pieces of evidence illustrating that subtask order information is used for control come from the performance of patients with neurological damage. The action disorganization syndrome describes patients with frontal lobe lesions, whose performance in everyday tasks is confused and includes frequent errors. Specifically, these patients tend to perform actions in the wrong sequence, such as drinking from a cup and then adding coffee granules (Humphreys & Forde, 1998; Schwartz, Reed, Montgomery, Palmer, & Mayer, 1991; Sirigu et al., 1995). Along a similar line, a positron emission tomography study conducted by Partiot, Grafman, Sadato, Flitman, and Wild (1996) indicates that different brain regions represent knowledge about the components of a task and knowledge about the temporal order of events.

In contrast to the studies just reviewed, we examined the dynamic properties of order control. The logic of our experiments was the same logic used in many areas of cognitive psychology, namely, inferring temporary activation of a representation in a given processing event from performance on the following processing events. This logic has been used to study activation of word semantics (e.g., semantic priming; Neely, 1991), inhibition of representations (negative priming; Tipper, 1985), and activation of task sets (task switching; e.g., Allport, Styles, & Hsieh, 1994; Rogers & Monsell, 1995), to name just a few examples. The underlying assumption in all of these studies is that the activation state that enabled performance in event $n - 1$ did not decay immediately and therefore affected performance in event n. In the present experiments, we studied activation of order representation by examining its effect on trial-to-trial subtask order switching.

Because we were interested in controlling a sequence of subtasks rather than a sequence of motor responses (e.g., Hayes, Davidson, Keele, & Rafal, 1998; Krampe, Mayr, & Fuchs, 2000), we decided to use the psychological refractory period (PRP) task as our model of a multistep task. This task involves presenting two stimuli in rapid succession. The stimuli (S1 and S2) come from different classes (in our experiment, a color patch and a letter) and are followed by two responses (R1 and R2). For example, a given trial could begin with the presentation of a blue patch followed by the letter *B*. The responses ("blue" and "B") are then indicated by two keypresses. We studied the influence of changing subtask order between trials. Specifically, participants alternated between two sequences: color–letter and letter–color. The PRP paradigm qualifies as a multistep task (Monsell, 1996) because (a) it is constructed from two single-step subtasks and (b) the order of responding is important and needs to be monitored (De Jong, 1995). In our switch condition, participants needed to monitor the stimulus and response sequence because these elements changed relative to the preceding trial. Even when the order of stimulus

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presentation and responding was fixed along a block of trials, some monitoring was apparently required to control the sequence of stimulus perception and the responses within each trial.

Our choice of the PRP paradigm was made because this paradigm has been explored extensively (also in the context of changing subtask order, as described subsequently). Another important reason is that the paradigm enables one to isolate the effects of order switching, as we did in the first two experiments. Most important, a dominant model of the PRP paradigm (Pashler, 1994a, 1998) does not refer to order control. It would therefore be nontrivial to show evidence of order control in this paradigm. In the following sections, we introduce relevant terminology concerning task switching, review relevant literature on the PRP task, and, finally, review experiments that have already examined the influence of order switching using the PRP paradigm.

Task Switching

We adopted Fagot's (1994) terminology (which originally referred to single-step tasks) to describe our experimental conditions. In our experimental condition, we had two subtask *orders*, Order A and Order B (e.g., Order A representing "color-then-letter" and Order B representing "letter-then-color"). Performance was studied in two conditions: (a) fixed-order blocks (e.g., AAAA . . . or BBBB . . . ; performing the same order in succession, here a series of trials all involving "color-then-letter," for example) and (b) random blocks involving both orders presented in random succession (e.g., AABAB . . .). The random blocks involved both switch trials (e.g., BB*A*AA, in which the order had just been changed) and no-switch trials (e.g., B*B*A*A*) in which the order repeats itself.

These three conditions—fixed-order blocks, switch trials, and no-switch trials—enable important effects to be isolated, as described by Fagot (1994). He termed the reaction time (RT) difference between fixed-task (in our study, fixed-order, e.g., AAAA) and switch trials *task alternation cost*. Alternation cost can be divided into *mixing cost*, the difference in RT between the fixed-order list and no-switch trials, and *switching cost* (the original term was *shifting cost*), the difference in RT between switch trials and no-switch trials. Switching cost reflects the dynamics of changing control from one task to another associated task after having just switched to a new subtask order.

In regard to the current study, the presence of order-switching cost would provide strong evidence that order information was activated in the preceding trial. Specifically, if order information is activated in the course of task performance and this information remains active after the trial has ended, it should be more difficult to change orders than to repeat orders, and this should result in order-switching cost. The reason is that, in the case of an order switch, the preceding order information needs to be suppressed and the upcoming order information needs to be activated.

One could argue that any prediction concerning task-switching cost is trivial because such a cost is found whenever there is a task switch. However, we already know from studies with simple tasks that task-switching cost is not always found. Specifically, Jersild (1927), who conducted the first systematic examination of task switching, showed that switching cost has its boundary conditions. When there was no overlap between the stimuli and responses of the two tasks, he did not find task-switching cost, and actually there was a small switching gain. This finding was later replicated by Spector and Biederman (1976) and Allport et al. (1994). As with simple tasks, switching during complex tasks is likely to be associated with a cost only if certain conditions are met.

According to Meiran (2000a; see also Rubinstein, Meyer, & Evans, 2001), the presence of switching cost is confined to situations in which there is ambiguity. This ambiguity needs to be resolved by time-consuming control processes. In simple speeded classification tasks, this ambiguity refers to the fact that either the stimuli or the responses are shared by the potential tasks, making them bivalent. When stimuli and responses are univalent, so that they are separate for the potential tasks, there is no switching cost (Jersild, 1927; Meiran, 2000b; but see Mayr, 2001, for a small and probably nonsignificant effect in this condition). Note that this was exactly the case in our first two experiments: The stimuli and responses of the two subtasks were univalent; there was no overlap between the color and letter subtasks. In other words, there was no ambiguity at the local level of the subtasks. However, there was ambiguity at the more global level of subtask *order*. Thus, order-switching cost for the two responses would indicate that participants activate a representation of the global task set (subtask order information) rather than treating the experimental situation as involving only separate single-step tasks.

Moreover, from the perspective of local task switching, it should be *easier* to perform the first subtask in a given order in the case of an order switch, because this task was performed recently in the last trial. For example, if the order changes (trial n: color–*letter;* trial $n + 1$: *letter*–color), it should be easier to perform the letter task in trial $n + 1$, because this task was also the last subtask in the preceding trial. Thus, if participants treat the subtasks as separate, we should obtain a switching benefit for the first subtask in cases in which there was an order switch. Finding switching costs in both responses would provide strong evidence that participants take subtask order information into account during online control so that the effect overcomes the potential benefit due to local repetition effects.

Further support for the claim that explicit order information is activated in the course of task preparation would come from reductions in switching costs as a consequence of preparation. Such modulation would imply that it is possible to activate subtask order information in advance of the execution of the subtasks themselves. As in the study of switching single-step tasks, such an indication of advance preparation would constitute an important piece of evidence that our measure (order-switching cost) taps control processing (e.g., Allport et al., 1994; Meiran, 1996; Rogers & Monsell, 1995).

In contrast to order-switching cost, order-mixing cost should not be regarded as evidence for online order control. Mixing cost does not signify the need to prepare toward a new order or the need to activate new order information, because in both no-switch trials and fixed-order trials the same order is being repeated. Mixing cost may reflect the need to maintain readiness for two orders, the reloading of order information in each trial, or the accumulated order learning effects (see Los, 1996, for a review). Regardless of the specific mechanism, mixing cost does not directly reflect the activation of order information during online control. Thus, mixing cost and switching cost reflect different processes.

The PRP Task

In a typical PRP task, two stimuli, S1 and S2, are presented in rapid succession, separated by a variable stimulus onset asynchrony (SOA). Each of these stimuli demands a different response, R1 and R2. Thus, the paradigm involves two subtasks, the S1–R1 subtask and the S2–R2 subtask. Usually, quick responding to S1 is emphasized. We decided to refer to the entire S1–S2–R1–R2 complex as a single task and to describe each of its components, S1–R1 and S2–R2, as subtasks (Subtask 1 and Subtask 2, respectively). This choice was made to avoid terminological confusion.

The main findings from studies using the PRP task in a constant order include a reduction in RT to S2 (RT2) as SOA is prolonged. This finding is called the *PRP effect*. In contrast to RT2, RT1 is typically unaffected by SOA. To explain the PRP effect, Pashler and colleagues (Pashler, 1984, 1990, 1994a, 1994b; Pashler & Johnston, 1989), who relied on early ideas from Welford (1952), divided RT into three processing stages: a perceptual processing stage, a response selection stage, and a response execution stage (Sternberg, 1969). They suggested that response selection constitutes a bottleneck; that is, this stage cannot be carried out simultaneously for the two subtasks, and thus processing for R2 cannot access the response selection mechanism until it is freed from R1 (see Figure 1).

Pashler (1994a, 1998) derived four critical predictions from this model, all of which were supported empirically. These predictions refer to the pattern of interactions between SOA and variables related to the relative difficulty of the three processing stages involved in generating R1 or R2. At present, it is important to note that Pashler predicted either additive effects of SOA and difficulty or underadditive interactions between these variables, depending on which processing stage was being affected by the difficulty manipulation. He did not predict overadditive interactions between SOA and the various difficulty manipulations, although the model could account for those interactions in certain conditions. For example, Hartley and Little (1999), who found overadditive interactions between SOA and task difficulty, elaborated Pashler's model to account for these interactions by assuming an additional processing stage preceding response selection in the more difficult condition.

It should also be added that Pashler's (1994a, 1998) model has been criticized on several grounds. For example, there are investigators who suggest an additional bottleneck at the response execution stage (De Jong, 1993). Moreover, it is currently disputed whether the fact that response selection acts as a bottleneck represents a structural limitation (De Jong, 1993; Pashler, 1984, 1990, 1994a, 1998), instruction-based capacity allocation (Navon & Miller, 2002), or an optional strategy (e.g., Logan & Gordon, 2001; Meyer & Kieras, 1997a, 1997b; Meyer et al., 1995; Schumacher et al., 1999). Finally, Hommel (1998) has shown evidence for S1 and R1 activation by R2, which suggests that R2 is activated before S1 and R1 processing is completed (cf. Logan & Gordon, 2001; Logan & Schulkind, 2000).

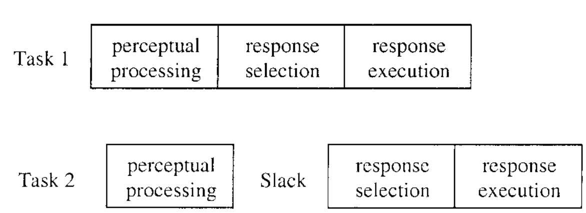

Figure 1. The response selection mechanism (based on Pashler, 1994a, Figure 2). The response selection stage represents a bottleneck, whereas other processing stages for Task 1 and Task 2 can take place in parallel. From "Dual-Task Interference in Simple Tasks: Data and Theory," by H. Pashler, 1994, *Psychological Bulletin, 116,* p. 224. Copyright 1994 by the American Psychological Association. Adapted with permission of the author.

To deal with this theoretical dispute, we designed conditions in which most or all theories would predict a response selection–related bottleneck, strategic or structural. Specifically, Schumacher et al. (1999) showed that additive effects of SOA and response selection difficulty were replaced by underadditive interactions after considerable practice. They interpreted these results as evidence that postponement of response selection was a cautionary strategy used in early stages of practice. In the present study, the conditions were such that practice was limited (relative to Schumacher et al.), and R1–R2 order frequently changed. Such conditions should promote a cautionary strategy.

The present study was not designed to address the question of whether there is a structural bottleneck; rather, we concentrated on another assumption included in Pashler's (1994a, 1998) model. This model is unique in explaining the PRP effect without any reference to order control. Presumably, the PRP effect is due to the structural bottleneck regardless of order control (see especially Tombu & Jolicœur, 2000).

In alternative models, order control is explicitly taken into consideration in explaining the PRP effect. For example, one of the order-control mechanisms in the executive control theory of visual attention (ECTVA; Logan & Gordon 2001) involves inhibiting response counters. The executive-processes interactive control architecture (EPIC; Meyer & Kieras, 1997a, 1997b) is also equipped with mechanisms that control order. It includes goals (that enable the performance of a particular task), steps (that help control when exactly to execute an action during the course of a task), and notes (that contain information regarding task progress and task strategies). Thus, another way of evaluating these models without debating the structural bottleneck would be by examining whether increasing the demands on order control by order switching would produce additive or interactive (overadditive) effects with SOA. If interactive effects are found, this implies that the PRP effect is modulated by order control, a fact that cannot be easily explained by Pashler's (1994a, 1998) model as it is presently formulated. This is especially true for overadditive effects, as elaborated earlier. Finding interactive effects does not necessarily challenge the structural bottleneck; rather, it challenges Pashler's model from another perspective, because it demonstrates that order control must be considered. Specifically, we argue that the overadditive interaction between order and SOA reflects the need to determine subtask order.

In addition, finding an overadditive interaction between SOA and order switching is highly important from the task-switching perspective. Specifically, the task-switching effect could merely reflect changes in readiness (see especially Fagot, 1994; see also Allport & Wylie, 2000). This "readiness" account represents a serious threat to the arguments that switching cost reflects a change in processing mode (e.g., Meiran, 1996, 2000a, 2000b;

Rogers & Monsell, 1995). The "readiness" account is consistent with the fact that the task-switching effect does not usually interact with various "task execution" processes (e.g., Gopher, Armony, & Greenshpan, 2000). There are a number of exceptions to this rule, such as the interaction between task switching and response repetition (e.g., Fagot, 1994; Kleinsorge & Heuer, 1999; Meiran, 1996, 2000a; Rogers & Monsell, 1995) and the interaction between task switching and congruence (e.g., Meiran, 2000a). If found, an interaction between order switching and SOA will add an important piece of evidence favoring the "changing mode" hypothesis.

Finally, our results will help us in elucidating the mechanisms that control subtask order. We suggest that subtask order is represented explicitly and that this information is activated during online control. This suggestion is nontrivial, because there are other conceivable strategies. One is to select the first subtask and rely on two associations that are held simultaneously: "IF [the color subtask is first] THEN [start executing the letter subtask as second]" and "IF [the letter subtask is first] THEN [start executing the color subtask as second]." Another possibility is based on a variety of inhibition mechanisms such as self-inhibition, namely inhibiting the subtask just performed (MacKay, 1987), or on lateral inhibition (Norman & Shallice, 1986). In the General Discussion section, we argue that the results support our conjecture concerning an explicit order representation and are incompatible with the just-mentioned alternative strategies.

Order Switching Using the PRP Task

In the present experiments, we included conditions in which subtask order changed between trials. Thus, our manipulation of task switching was actually switching the order of the subtasks relative to the preceding trial (e.g., color–letter after letter–color). We termed this *order switch*. There are two studies that have already explored the consequences of order switch. However, as will become clear soon, both of these studies explored only a subclass of the components of order switching. Importantly, the most critical effects, RT switching cost and reduction of switching cost by preparation, were not studied. Pashler (1990) conducted three experiments in which he compared performance under fixed or random order. In the fixed condition, the order of stimuli presentation and responses was constant for an entire block of trials. In the random condition, this order varied unpredictably from trial to trial. Pashler did not compare performance in switch and no-switch trials; thus, the effects do not represent switching cost as we define it.

In addition to the usual PRP effect, Pashler found a decrement in performance in the random order relative to the fixed order. This cost was greater for R1 than for R2 (262 ms and 171 ms, respectively, in Experiment 1 and 121 ms and 24 ms, respectively, in Experiment 2). Interestingly, the PRP effect was more pronounced when the order was random than when it was fixed, resulting in a significant overadditive interaction between SOA and order mixing. Although Pashler's results confirm our predictions, it is impossible to rule out the possibility that these results reflect mixing cost rather than switching cost. As argued before, only switching cost and not mixing can serve as a direct index for activation of order information during online control.

De Jong (1995, Experiment 2) asked participants to perform the PRP task in random order and compared trials in which the order was the same as in the preceding trial (no-switch trials) with trials in which the order changed (switch trials). Thus, according to the present terminology, the comparison reflected order-switching cost, but this comparison was limited to analysis of errors. He found an increased error rate in switch trials relative to no-switch trials, caused by the fact that participants tended to respond as in the preceding subtask order. Unfortunately, he did not report switching effects on RT2, which means that the statistics concerning the interaction between order switch and SOA were not reported. Such effects were reported in Experiment 3, which involved two tasks: Task 1 was auditory–visual, and Task 2 was visual–auditory. In that experiment, De Jong compared participants' performance in a fixed task order (AAA . . . and BBB . . . ; e.g., performing the visual–auditory task throughout the block) and in alternating order (ABAB . . . , alternating between visual–auditory and auditory–visual). Thus, De Jong, too, did not compare RT in switch trials and in no-switch trials. The results indicated significant order-alternation costs in both RT1 and RT2 and, importantly, an overadditive interaction between order alternation and SOA. Finally, De Jong found that the order alternation cost in RT2 was reduced as a result of increasing the intertrial interval, suggesting that the subtask order information was activated before the beginning of the trial.

De Jong's (1995) results imply that the PRP effect is modulated, as we argue, by online order control. However, there are some alternative explanations that need to be ruled out. First, in Experiment 3, De Jong did not decompose alternation cost into switching cost and mixing cost. As explained earlier, only switching cost could serve as an evidence for activation of order information during online order control. Second, it is possible to explain De Jong's results by single-trial learning because, after execution of a particular order, participants may be tuned to repeating the same order (e.g., Meiran, Chorev, & Sapir, 2000).

Third, the order-alternation cost in R1 was only 11 ms (whereas it was a substantial 30–129 ms for R2). Albeit significant, the magnitude of this R1 cost is very small. We suggest that this small order-switching cost resulted from the fact that, in De Jong's (1995) third experiment, the order of the tasks was perfectly predictable. This enabled preparation for the upcoming switch that could start as early as during the execution of the second subtask in the preceding trial.

Another possible scenario is that, although the participants in De Jong's (1995) third experiment used order control, the observed effect was entirely due to local switches of subtasks rather than switches of order. Specifically, participants may have represented the tasks not as involving pairs of responses but, instead, as involving quadruples (or larger assemblies, even) of responses. Possible quadruples would be "auditory–visual–auditory–visual" for one of the fixed-order conditions and "auditory–visual–visual–auditory" for the task-alternation condition. In such a case, the observed "order-alternation cost" in R2 could simply reflect differential subtask expectancies. Specifically, in the "order-alternation" condition, a given subtask (e.g., the auditory subtask) came after two executions of the alternative subtask (e.g., "auditory" coming after "visual–visual"). In contrast, in the "fixed-order" condition, the same subtask came only after one execution of the alternative subtask ("auditory" coming after only one execution of “visual”; see Fagot, 1994; see also Dreisbach, Haider, & Kluwe, 2002; Ruthruff, Remington, & Johnston, 2001; Sohn & Anderson, 2001; and Sohn & Carlson, 2000, for subtask expectancy effects). This alternative explanation could be resolved if subtask order were varied randomly, as in the present experiments.

Finally, the decrease in the order-alternation cost by increasing the intertrial interval could reflect two distinct processes. One process is the dissipation of the task set adopted in the preceding trial. The other process is preparation based on the identity of the order in the upcoming trial (Allport et al., 1994; Meiran, Chorev, & Sapir, 2000). The reason is that there were no task cues, because task order was perfectly predictable. This means that the precise moment when order preparation began could not be determined, and thus the reduction in switching cost could reflect set dissipation, set preparation, or both.

To rule out these alternative explanations, it is necessary to show the order-switching effect unconfounded by an order-mixing effect, to show this phenomenon in experiments involving randomly chosen subtask orders (which disable forming response quadruples and similar larger chunks), and to show that order-switching cost decreases with preparation toward the upcoming order. In some respects, our study should be viewed as an elaboration of De Jong’s original examination aiming at ruling out the alternative explanations described earlier.

The significance of the present work is twofold. From the PRP perspective, we believe that De Jong’s (1995) theoretical points are highly important because they indicate that the PRP paradigm involves nontrivial cognitive control, in sharp contrast to Pashler’s (1994a, 1998) view, which explains the PRP effect without any reference to issues of order control. Therefore, ruling out the various alternative explanations of De Jong’s results is essential. From the task-switching perspective, the results are important in providing evidence that the order-switching cost reflects a modulation of processing mode rather then merely a change in readiness (Allport & Wylie, 2000; Fagot, 1994).

In all of the experiments described here, we studied both order-mixing cost and order-switching cost. Our strategy was strictly analogous to that employed by Meiran, Chorev, and Sapir (2000), who studied switching between single-step tasks. In Experiment 1, we began studying set dissipation by manipulating the interval between R2 in trial $n - 1$ and the order cue in trial n (the *response–cue interval;* RCI). We did so while keeping the preparatory interval (the *cue–target interval;* CTI) short and constant. This made it possible to determine whether set dissipation affected switching cost. The goal of Experiment 2 was to study reductions in switching costs as a result of preparation by using a constant and long RCI and by manipulating CTI. Because in these two experiments hand order was confounded with subtask order, we conducted a third experiment in which we replicated our main results from Experiment 2 without this confounding factor.

Experiment 1

Our goal in the first experiment was to demonstrate that order information is activated during online order control by measuring RT switching cost. If participants activate order information and this information remains active for some time, then we can predict order-switching cost for both responses. If, however, only the subtask sets are activated, there will be order-switching gain in the first subtask, because this subtask was last performed in the preceding order (color–*letter*, *letter*–color). In addition, we wanted to explore the possibility that activation of order information dissipates (e.g., the strategy used by Meiran, Chorev, & Sapir, 2000).

Method

Participants

Twelve undergraduate students from Ben-Gurion University of the Negev participated in this experiment as part of a course requirement. All participants reported having normal or corrected-to-normal vision and hearing.

Apparatus and Stimuli

Stimuli were presented on an IBM-PC clone with a 14-in. (35.56-cm) monitor controlled by software written in MEL (Schneider, 1995). We used the letters *B* and *D* (subtending approximately 0.38° × 0.28° from a viewing distance of 60 cm) and rectangles in the colors blue (MEL Color 1) and pink (MEL Color 5), subtending 0.38° × 0.66°. The rectangles were taken from the extended ASCII code. The cue for the color task was a white square (subtending 0.38° × 0.47°), and the cue for the letter task was a white arrow (subtending approximately 0.28° × 0.47°), both taken form the extended ASCII code. In addition, we used a plus sign as a fixation point. Participants pressed the *z* (left) and *x* (right) keys with the middle and index fingers of their left hand, respectively, in responding to the color stimulus (both keys were positioned on the left). They pressed the .> (left) and /? (right) keys with their index and middle fingers of their right hand, respectively, in responding to the letter stimuli (both keys were positioned on the right). The letter and the color rectangle were presented very close to each other, the difference between them subtending only 0.38°.

Design and Procedure

All participants took part in two sessions with a 2-hr recess in between. The first three blocks in each session were considered practice and consisted of 60 trials each in the first session and 12 trials each in the second session. The remaining experimental blocks consisted of 100 trials each.

A trial began with the presentation of a fixation for 500 ms, followed by an instructional cue indicating the order of stimuli in the upcoming trial. The cue was presented next to the fixation point (see Figure 2). After a fixed CTI of 150 ms, S1 was presented, followed by S2, separated by one of three SOAs (100, 250, or 750 ms). Both stimuli remained until the second response was emitted. The color stimulus always appeared on the left side of the fixation, and the letter stimulus always appeared on the right side of the fixation. After the second response, there was an RCI of 600, 2,100, or 3,100 ms. The SOA changed unpredictably between trials, whereas the RCI was fixed for an entire block of trials and varied between blocks.

We manipulated order switching by including three conditions. In the fixed-order condition, the order of subtasks was constant (e.g., either color-then-letter or letter-then-color). The remaining two conditions (switch and no switch) were taken from a random sequence in which color-then-letter and letter-then-color trials were intermixed. An instructional cue preceded every trial, even in the fixed-order condition, in which the cue was redundant. We counterbalanced the ordering of the three RCIs, the two fixed-order conditions, and the random-order condition between participants by forming six conditions. Each session included six experimental blocks. Over the two sessions, each participant performed six fixed-order blocks (three blocks with the color subtask first and three with the letter subtask first) and six random-order blocks (these conditions were counterbalanced to the extent possible).

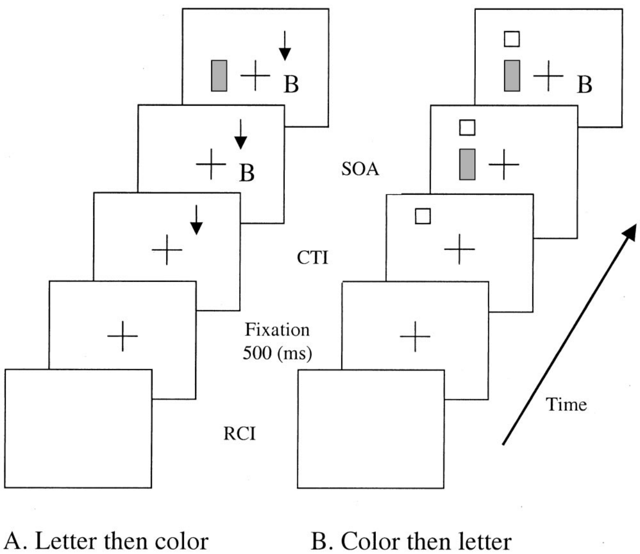

Figure 2. An example of the present experimental paradigm. There are two possible orders: letter then color (A) and color then letter (B). A cue signaling the upcoming order precedes the presentation of the stimuli. SOA = stimulus onset asynchrony; CTI = cue–target interval; RCI = response–cue interval.

Participants received written instructions to respond to each stimulus as quickly as possible while maintaining high accuracy. Participants were also encouraged to respond to the first stimulus as quickly as possible. Instructions concerning the specific condition were presented at the beginning of each block (color first, letter first, or random order). Previous studies using the PRP paradigm identified a strategy sometimes used by participants who group their responses, that is, delay R1 and emit R1 and R2 in rapid succession (Pashler & Johnston, 1989). As a means of discouraging response grouping, in 5% of the trials only the first stimuli appeared, and after participants responded, the trial ended and the RCI for the next trial began.

Results

The first five trials in each block were considered warm-up and were omitted from the analysis. All trials with an error for either R1 or R2 were excluded from the RT analysis. RTs greater than 3,000 ms or less than 100 ms were also omitted from the RT analysis. In addition, "catch trials" (in which only one stimulus was presented) were not analyzed. The alpha level was set at .05.

Four analyses were performed on RT results, two analyses of RT1 and two analyses of RT2. Within each pair of analyses, one analysis concentrated on order switching (switch vs. no switch) and the other analysis concentrated on order mixing (no switch vs. fixed order).[1]

Switching Cost

In this analysis, we compared switch trials with no-switch trials.

R1. An analysis of variance (ANOVA) on RT1 with order switch (switch vs. no switch), SOA (100, 250, or 750 ms), and RCI (600, 2,100, or 3,100 ms) as independent variables yielded significant main effects of order switch, $F(1, 11) = 30.04$, $MSE = 71,470.64$, and SOA, $F(2, 22) = 18.75$, $MSE = 22,615.52$. We found a 141-ms switching cost for RT1. We argue that this effect further indicates that the order of subtasks was activated in the course of online control; otherwise, it would have been easier to perform Subtask 1 in cases of an order switch, because this subtask had last been performed as Subtask 2 in the preceding trial. The interaction between order switch and SOA was not significant ($F < 1$); as can be seen in Figure 3, switching cost was not reliably affected by SOA. The main effect of RCI did not reach significance, nor did the interaction between RCI and order switch. Hence, we did not find any evidence for set dissipation in R1.[2]

The error proportion rate was very low (.018), implying that an ANOVA might not have been justified. We decided to conduct an ANOVA despite the low error rate, mainly to rule out a speed–accuracy trade-off, which was in fact ruled out. The ANOVA indicated significant effects of order switch, $F(1, 11) = 19.02$, $MSE = 0.008$, and RCI, $F(2, 22) = 4.04$, $MSE = 0.0024$. Order-switch effects on errors exhibited a trend similar to that of RT (more errors on switch trials). The number of errors increased with prolonged RCI (see Table 1).

R2. The design of the ANOVA was the same as in the previous analysis. It yielded significant main effects of order switch, $F(1, 11) = 31.75$, $MSE = 66,360.5$, indicating a switching cost of 140 ms, and SOA, $F(2, 22) = 100.03$, $MSE = 65,949.95$. The switching costs in RT2 and RT1 indicate that the subtask order information was activated because performance was affected by the preceding order. The interaction between order switch and SOA was significant, $F(2, 22) = 5.49$, $MSE = 11,064.14$ (see Figure 4). This overadditive interaction replicated a similar trend obtained by De Jong (1995, Experiment 3) and Pashler (1990, Experiments 1 and 3).

Despite the low error rate (.052), we conducted an analogous ANOVA on proportion of errors that revealed a significant main effect of RCI, $F(2, 22) = 6.14$, $MSE = 0.0047$. The interaction between order switch and RCI, $F(2, 22) = 4.85$, $MSE = 0.0024$, was also significant. There were fewer errors as RCI was prolonged and, for short RCI only, more errors occurred in switch trials than in no-switch trials (see Table 1).

Distributional analyses. To ensure that switching cost was both robust and evident throughout the RT distribution, we examined the effect for the lower, median, and upper quartiles of the RT distribution. Finer grained analyses (e.g., centiles) were precluded because of the small number of observations per condition (an average of 13). RT1 order-switching costs were 107, 133, and 179 ms for the first through third quartiles, respectively. RT2 costs

[1] All of the analyses of variance also originally included the subtask (color or letter) variable. For ease of presentation, and because the effects of task were unimportant for this study and did not replicate in all of the experiments, we have omitted these findings from the main Results section. Whenever the interaction of task with order switch or with order mix was significant, we report the results in a footnote.

[2] The three-way interaction between order switch, task, and SOA, $F(2, 22) = 5.43$, $MSE = 5,317.76$, also reached significance. In an attempt to clarify the source of this interaction, we conducted several follow-up analyses. We found that, for no-switch trials that involved color responses, the simple linear effect of SOA was not significant, $F(1, 11) = 3.01$, $p > .10$, although this effect was significant for letter responses, $F(1, 11) = 27.50$, $MSE = 286,217.2$. These differences between the two tasks did not replicate in Experiment 2.

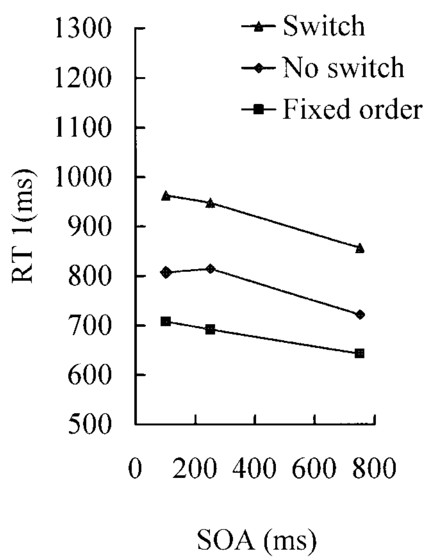

Figure 3. Mean RT1 (reaction time in the first subtask, in milliseconds) as a function of stimulus onset asynchrony (SOA) and order (switch, no switch, or fixed order) in Experiment 1.

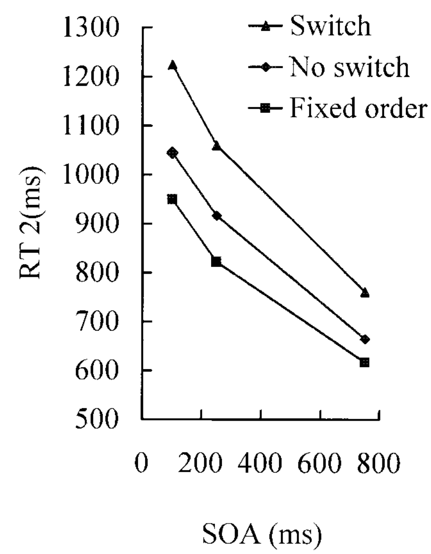

Figure 4. Mean RT2 (reaction time in the second subtask, in milliseconds) as a function of stimulus onset asynchrony (SOA) and order (switch, no switch, or fixed order) in Experiment 1.

were 111, 133, and 160 ms for the first through third quartiles, respectively. These results strongly suggest that switching costs were present throughout the entire distribution.

Mixing Cost

In this analysis, we compared trials in which the order was fixed (either color–letter or letter–color throughout the entire block) with trials from the random-order condition in which the same subtask order repeated itself relative to the preceding trial (no-switch trials). The design of the ANOVAs was the same as previously except that the switching contrast (switch vs. no switch) was replaced by the order-mixing contrast (no switch vs. fixed order).

Table 1
Error Proportions in R1 and R2, Experiment 1

RCI (ms)	Switch: SOA (ms) 100	250	750	No switch: SOA (ms) 100	250	750	Fixed: SOA (ms) 100	250	750
600									
R1	.09	.06	.05	.02	.03	.03	.02	.02	.01
R2	.10	.07	.09	.07	.08	.04	.05	.07	.08
2,100									
R1	.07	.04	.06	.03	.02	.03	.02	.02	.01
R2	.05	.04	.04	.04	.03	.04	.05	.04	.05
3,100									
R1	.05	.06	.04	.01	.01	.01	.02	.01	.01
R2	.05	.04	.05	.06	.04	.05	.06	.03	.06

Note. R1 = response in the first subtask; R2 = response in the second subtask; RCI = response–cue interval; SOA = stimulus onset asynchrony.

R1. An ANOVA on RT1 yielded significant main effects of order mixing, $F(1, 11) = 36.55$, $MSE = 29{,}624.7$, and SOA, $F(2, 22) = 13.39$, $MSE = 19{,}294.46$. The main effect of order mixing indicated a cost of 100 ms (from 782 ms in the random order to 682 in the fixed order). The interaction between order mixing and SOA, $F(2, 22) = 4.38$, $MSE = 4{,}001.47$, was significant. This interaction is presented in Figure 3. It appears that the decrease in RT due to increasing SOA was more pronounced in no-switch trials than when the subtask order was fixed. The interaction involving RCI and order mixing did not approach significance ($F = 1.54$).[3] Thus, although there was mixing cost in RT1, increasing the RCI did not significantly reduce this cost.

A similar ANOVA focusing on proportion of errors revealed no significant effects. The overall R1 error rate was .039.

R2. An ANOVA focusing on RT2 yielded significant main effects of order mixing, $F(1, 11) = 35.68$, $MSE = 18{,}948.8$, representing a mixing cost of 79 ms in RT2, and of SOA, $F(2, 22) = 114.07$, $MSE = 4{,}123.6$. The interaction between order mixing and SOA was also significant, $F(2, 22) = 3.91$, $MSE = 6{,}741.4$. This interaction is displayed in Figure 4. Note that there were overadditive interactions between both SOA and order mixing and between SOA and order switch. The largest PRP effect was obtained in the order switch condition, when order control is most needed. This effect decreased in the no-switch condition and decreased even more in the fixed-order condition.

[3] The three-way interaction between order mixing, task, and SOA reached significance, $F(2, 22) = 4.15$, $MSE = 3{,}029.72$. At the short and intermediate SOAs, mixing cost was larger in the letter task than in the color task, $F(1, 11) = 6.23$. At the long SOA, this difference was not significant, $F(1, 11) = 1.60$. This three-way interaction was not replicated in Experiment 2.

A similar ANOVA focusing on proportion of errors revealed no significant effects.[4] The overall R2 error rate was .055.

Discussion

As did Pashler (1990) and De Jong (1995), we found that order alternation was associated with a performance cost. Unlike these investigators, we compared switch trials and no-switch trials and found evidence for RT switching cost in both RT1 and RT2. We argue that this is evidence that participants activate an explicit representation of the subtask sequence during online order control. Furthermore, like De Jong and Pashler, we found that order switching–mixing interacted with SOA in RT2. The advantage of the present experiment was that we could decompose alternation cost into switching cost and mixing cost, and we found that both were present in RT1 and in RT2. This enabled us to provide evidence that the PRP effect is modulated by order control. Although this finding is not yet conclusive (see subsequent discussion), it demonstrates that order control is a contributing factor to the PRP effect. The fact that the interactions between SOA and switching–mixing were overadditive is also of importance (see the General Discussion).

As may be recalled, one of the main goals of the present experiment was to study set dissipation by manipulating RCI. Contrary to Meiran, Chorev, and Sapir (2000), who studied single-step tasks, we found no evidence for a reduction in switching cost as a result of dissipation in this experiment, either in R1 or in R2. This was seen in the fact that the interaction between RCI and order switch was not significant. Namely, order-switching cost was unaffected by RCI. In fact, increasing RCI reduced RT1 switching cost by only 3 ms and reduced RT2 switching cost by only 15 ms. It is possible that the RCI was not long enough for dissipation to show up. Although we cannot rule out this possibility, it should be noted that the RCIs in our experiment ranged up to 3,100 ms and that other studies (e.g., Meiran, Chorev, & Sapir, 2000) revealed that most of the dissipation took place within the first 1,000 ms.

A study conducted by Meiran, Levine, Meiran, and Henik (2000) can shed light on the possible reasons for the lack of a set dissipation effect. In their third experiment, these authors compared two groups that switched between two location tasks (e.g., up–down and right–left), the same tasks that were used by Meiran, Chorev, and Sapir (2000). One group used a bivalent response setup in which each keypress was used to indicate two different nominal responses (e.g., *up* and *left*). The second group used a univalent response setup in which each keypress indicated only one nominal response (e.g., *up*). Thus, the difference between the response setups was that for the first group, the meaning of the responses changed if the task changed, whereas for the second group the meaning of each response key was constant throughout the experiment. Meiran, Levine, et al. found that only the first group, which used bivalent responses, showed a reduction in switching cost as a result of dissipation. As a consequence, they argued that reduction in switching cost due to dissipation reflects the fast forgetting of newly updated response information. Therefore, the fact that in our paradigm responses did not change their indication may be the reason why we did not observe a reduction in switching cost as a result of dissipation. Another possibility is that the order set was not sensitive to dissipation in the same way that task sets of single-step tasks are.

Another point is that the main effect of SOA on RT1 was also significant. It is important to note that this trend is opposite to what is predicted by a response grouping strategy (see the *Method* section of this experiment). If participants had grouped their letter and color responses, they would have waited for the presentation of S2 to emit R1, and thus RT1 should have increased with increasing SOA. However, the opposite trend was observed in our experiment: RT decreased with increasing SOA. Although this is an unusual result in the PRP literature, a similar pattern was found by Pashler (1990, Experiments 1 and 3), who studied two manual responses with random ordering of task elements. This trend was not found in Pashler's Experiment 2, in which one vocal and one manual response were required (keeping the same apparatus and stimuli as in Experiment 1). We suggest that the pattern of decreasing RT1 with increasing SOA may reflect cross talk associated with preparing two manual responses (see Van Selst, Ruthruff, & Johnston, 1999, for a similar conclusion). Specifically, in our design, the spatial position of S2 conflicted with the spatial position of the R1 hand (cf. Hommel, 1998; Hommel & Schneider, 2002).

Although we found order-switching cost and order-mixing cost for both responses, it is possible to explain these effects by a single trial learning mechanism. It could be that executing a certain order primes that order. This would result in switching cost because, when we change orders, the system is suboptimally tuned to perform the new order. Such negative transfer or negative priming accounts are common in the task-switching literature (e.g., Allport et al., 1994; Allport & Wylie, 2000; Meiran, 1996, 2000a; Rogers & Monsell's, 1995, "micro-practice" hypothesis). This is precisely why De Jong's (1995) results, or the results from Experiment 1, cannot serve as conclusive evidence that order information is activated in the course of online order control. To demonstrate that single-trial learning does play a role in performance, and to further justify the plausibility of this negative transfer criticism, we conducted a special analysis. This analysis was similar to that of mixing effects, but we differentiated between repeating the same order twice (the no-switch condition) and repeating the same order three consecutive times (both taken from the random block).

In addition, we included SOA in this analysis. If single-trial learning takes place, this should result in a continuous improvement of performance with order repetitions, so that repeating the order three times should be faster than repeating it twice but slower than fixed order (repeating the same order for the entire block). The reason is that as the order is repeated it is being learned (or tuned), and this results in faster responding. This is exactly what we found. There were 65-ms and 46-ms decreases in RT1 and RT2, respectively, after three-order repetitions relative to two-order repetitions. Fixed-order trials were even faster than three-order repetitions, by 47 and 41 ms in the case of RT1 and RT2, respectively. These differences were significant, $Fs(2, 22) = 29.74$ and 19.55, $MSEs = 33{,}875$ and 3,506, for RT1 and RT2, respec-

[4] The three-way interaction between order mixing, task, and RCI, $F(2, 22) = 5.15$, $MSE = 0.0014$, was significant. For fixed-order color task trials, there was a decrease in error rate from the short to the intermediate SOA. This pattern was reversed for the letter task.

tively. In both cases, the interaction between repetition and SOA did not reach significance. Thus, even with this limited analysis, we could demonstrate single-trial learning resulting from priming or "tuning." The important issue is not the underlying mechanism, but that the mere presence of switching cost is not sufficient to argue that online order control entails activation of an explicit order representation. Although the lack of a significant interaction between advance order repetitions and SOA is suggestive (because order switch interacted with SOA, whereas the effect of further repetitions did not interact with SOA), it is not sufficiently conclusive. Thus, the purpose of Experiment 2 was to provide stronger evidence regarding this issue.

Experiment 2

The purpose of the second experiment was to study whether it is possible to activate order information before task execution. This advance activation would provide yet stronger evidence for activation of order information in the course of online control. Such an effect would be reflected in a reduction in switching cost as a result of preparation. As in Experiment 1, before each trial, a cue signaled the order of the upcoming trial. Preparation was manipulated by changing the CTI while keeping set dissipation time (RCI) long and constant (2,000 ms). In addition, we looked for a residual order-switching cost, namely whether, even after considerable preparation, some order-switching cost would remain (see Meiran, Chorev, & Sapir, 2000, who used the same rationale to isolate preparation effects). Another goal was to replicate the main results from Experiment 1.

Method

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

Participants

Twelve undergraduate students from Ben-Gurion University of the Negev participated in this experiment as part of a course requirement. All participants reported having normal or corrected-to-normal vision and hearing.

Design and Procedure

After presentation of the fixation point, an instructional cue was presented for a randomly changing CTI of 150, 600, or 1,500 ms. RCI was fixed at 2,000 ms. Given the results of Experiment 1, it is unlikely that any effects of task preparation on switching cost would reflect set dissipation. Thus, a reduction in switching cost due to increasing CTI could be attributed to task-set preparation. We used the same counterbalancing scheme as in Experiment 1.

Results

The analytic procedure was the same as in Experiment 1, except that RCI was replaced by CTI in all of the ANOVAs.

Switching Cost

R1. An ANOVA of RT1 yielded a significant main effect of order switch, $F(1, 11) = 43.63$, $MSE = 38{,}436$, indicating an overall switching cost of 124 ms. Again, this was a much larger cost than that found by De Jong (1995). The main effects of SOA, $F(2, 22) = 8.41$, $MSE = 61{,}967.2$, and CTI, $F(2, 22) = 11.48$, $MSE = 15{,}860.4$, were significant as well. The interaction between order switch and CTI, $F(2, 22) = 4.40$, $MSE = 6{,}919.9$, also reached significance. Increasing CTI affected switch trials (there was a difference of 98 ms between the short and the long CTI) more than it affected no-switch trials (45 ms; see Figure 5). In other words, switching cost was reduced from 158 ms in the short CTI to 110 ms in the intermediate CTI and 105 ms in the long CTI. The interaction between SOA and order switch was not significant, $F = 1.38$ (see Figure 6), meaning that SOA affected switch trials and no-switch trials alike. Importantly, the simple main effect of order switch was significant at the longest CTI, $F(1, 11) = 42.54$, $MSE = 9{,}484.2$, indicating a residual switching cost of 105 ms in R1.

A similar ANOVA on error proportion revealed significant effects of order switch, $F(1, 11) = 17.39$, $MSE = 0.0032$, as well as a two-way interaction between order switch and CTI, $F(2, 22) = 4.07$, $MSE = 0.0014$.[5] The overall R1 error rate was .021. Error proportions are presented in Table 2.

R2. An ANOVA focusing on RT2 yielded significant main effects of order switch, $F(1, 11) = 35.70$, $MSE = 41{,}091.7$, indicating a switching cost of 117 ms, and SOA, $F(2, 22) = 221.40$, $MSE = 24{,}908.3$. The interactions between order switch and SOA, $F(2, 22) = 4.39$, $MSE = 7{,}206.8$, and between order switch and CTI, $F(2, 22) = 3.75$, $MSE = 5{,}823.8$, also reached significance (see Figures 7 and 8). Switching cost was reduced from 140 ms to 118 ms and 90 ms in the three CTIs, respectively.

More important, the simple main effect of order switch was significant at the longest CTI, $F(1, 11) = 16.53$, $MSE = 17{,}985.4$, indicating a significant residual switching cost in R2 as well. The size of this residual cost was 90 ms.

Previous results (De Jong, 1995) indicated a significant triple interaction among order switch, SOA, and intertrial interval, whereas in our experiment the triple interaction among order switch, SOA, and CTI did not reach significance ($p < .48$; see Figure 9). There are some differences between our experimental procedure and De Jong's that could account for this discrepancy. For example, De Jong used an alternating order without cues and used only two intertrial intervals, manipulating these intervals between sessions. This probably amplified the effect. To increase the statistical power of the comparison, we pooled the short and intermediate SOAs, as well as the short and intermediate CTIs, and compared them with the longest SOA and CTI. This planned contrast was significant, $F(1, 11) = 5.49$, $MSE = 1{,}737.82$, thereby replicating the trend found by De Jong.[6] Follow-up simple interaction analysis indicated that the interaction between order switch and SOA was significant at the short CTI, $F(2, 22) = 3.92$,

[5] The three-way interaction between order switch, task, and CTI was significant, $F(2, 22) = 3.91$, $MSE = 0.01$. For switch trials, there was a reduction in error rate from the short to the intermediate SOA in the color task. This pattern was reversed for the letter task; namely, the error rate increased from the short to the intermediate SOA.

[6] In another study, conducted by Greenberg (2000), that involved the same procedure as in the present experiment (with the exception of the number of participants [48] and the use of only the two extreme CTIs), this triple interaction between switch, SOA, and CTI reached significance, $F(2, 94) = 4.35$, $p < .05$, $MSE = 7{,}496.18$, again replicating De Jong's findings. The remaining effects were the same as in the present experiment.

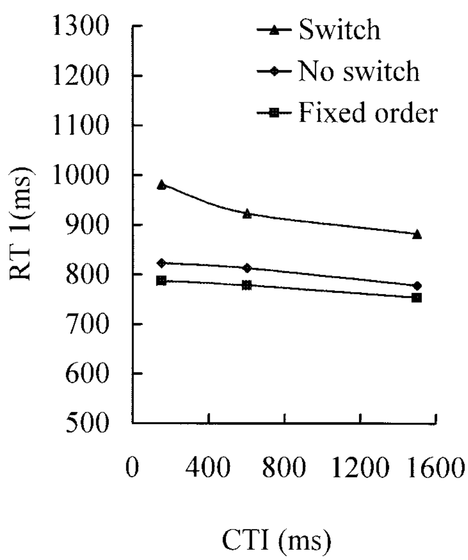

Figure 5. Mean RT1 (reaction time in the first subtask, in milliseconds) as a function of cue–target interval (CTI) and order (switch, no switch, or fixed order) in Experiment 2.

MSE = 9,749.78, but nonsignificant at the long CTI ($F < 1$). To increase the statistical power of this test, we replaced the 2-*df* effect of SOA by 1 *df* through pooling the short and intermediate SOAs and compared them with the long SOA. This increase in power did not result in a significant interaction between SOA and order switch at the long CTI ($F < 1$).

The only reliable source of variance in error proportions was the interaction between order switch and SOA, $F(2, 22) = 3.62$, $MSE = 0.0021$. The trend of this interaction was similar to the RT trend (for switch trials the error rate was relatively high and

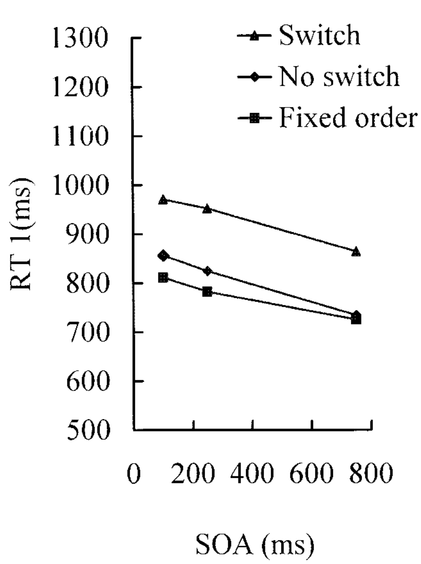

Figure 6. Mean RT1 (reaction time in the first subtask, in milliseconds) as a function of stimulus onset asynchrony (SOA) and order (switch, no switch, or fixed order) in Experiment 2.

Table 2
Error Proportions in R1 and R2, Experiment 2

CTI (ms)	Switch: SOA (ms)			No switch: SOA (ms)			Fixed: SOA (ms)		
	100	250	750	100	250	750	100	250	750
150									
R1	.05	.04	.03	.01	.01	.01	.02	.01	.01
R2	.05	.05	.01	.05	.02	.04	.04	.03	.03
600									
R1	.03	.04	.03	.00	.01	.00	.02	.01	.02
R2	.05	.04	.03	.02	.03	.03	.03	.04	.04
1,500									
R1	.01	.03	.02	.02	.01	.01	.01	.01	.01
R2	.05	.05	.03	.04	.05	.04	.04	.03	.04

Note. R1 = response in the first subtask; R2 = response in the second subtask; CTI = cue–target interval; SOA = stimulus onset asynchrony.

decreased with increasing SOA, and for no-switch trials the error rate was constant; see Table 2). The overall R2 error rate was .038.

Distributional analyses. As in Experiment 1, we conducted a distributional analysis to ensure that switching cost was robust and was evident throughout the distribution. We examined the effect for the lower, median, and upper quartiles of the RT distribution. Finer grained analyses were precluded because there was an average of only 14 observations per condition. RT1 order-switching costs were 76, 116, and 168 ms for the first through third quartiles, respectively. The corresponding RT2 costs were 87, 104, and 139 ms. Again, these results strongly suggest that switching cost was present throughout the entire distribution. A similar decrease in switching cost in the case of fast RTs was reported by De Jong (2000), but De Jong found this decrease only when long preparation intervals were provided and interpreted it as evidence that participants do not always engage in advance reconfiguration. However, in the present experiment the RT1 effect was statistically equal at long and short CTIs ($F < 1$). In R2, this triple interaction among quartile, CTI, and order switch was nearly significant, $F(4, 44) = 2.10$, $p = .09$, but this trend was due to effects in the medians, whereas the pattern of larger switching cost in the slow responses was similar for long and short preparation intervals.

Mixing Cost

R1. An ANOVA of RT1 yielded significant main effects of order mixing, $F(1, 11) = 5.86$, $MSE = 18{,}488.4$ (representing a difference of 32 ms); SOA, $F(2, 22) = 9.02$, $MSE = 45{,}642.9$; and CTI, $F(2, 22) = 5.02$, $MSE = 11{,}948.6$. The interaction between order mixing and SOA (see Figure 6) was significant as well, $F(2, 22) = 4.81$, $MSE = 3{,}059.9$. More important, the interaction between CTI and order mixing was nonsignificant ($F < 1$), thus supporting our interpretation that advance loading of order information took place in switch trials but not in no-switch trials.

A similar ANOVA focusing on error proportions revealed a significant effect of order mixing, $F(1, 11) = 6.02$, $MSE = 0.0001$. The interaction between order mixing and CTI, $F(2, 22) = 8.33$,

$MSE = 0.0002$,[7] was also significant. There was an increase in error rate from the intermediate to the long CTI only for the fixed-order trials. The overall error rate was very low, .011.

R2. An ANOVA focusing on RT2 yielded significant main effects of order mixing, $F(1, 11) = 15.95$, $MSE = 14{,}948.2$, indicating a mixing cost of 47 ms, and SOA, $F(2, 22) = 391.80$, $MSE = 11{,}793.8$. No other effect approached significance. The nonsignificant ($F < 1$) interaction between SOA and order mixing is presented in Figure 7. A similar ANOVA on error proportion revealed no significant effects. The overall R2 error rate was .035.

Discussion

As in Experiment 1, we found evidence for both mixing cost and switching cost. The focus of the present experiment was the CTI manipulation. We found that increasing CTI reduced, but did not eliminate, switching cost in the case of both RT1 and RT2, indicating that switching cost was reduced as a result of preparation, but some residual switching cost was still found, resembling similar effects in single-step tasks (e.g., Fagot, 1994; Meiran, 1996; Meiran, Chorev, & Sapir, 2000; Rogers & Monsell, 1995). As in single-step tasks, the presence of a significant reduction in switching cost by preparation is consistent with the interpretation that order information is activated in the course of online control in the PRP paradigm. Moreover, the fact that not only the switching cost decreased with preparation, but also the interaction between order switch and SOA, provides important converging evidence for our arguments. As elaborated in the General Discussion section, we argue that the fact that the reduction of switching cost by preparation was nearly identical in the case of RT1 and RT2 reflects the fact that advance preparation took place before or during R1 selection. This conclusion, too, fits with the notion that order information serves to control subtask order in the present PRP task and is likely to do so in multistep tasks in general.

The reduction in switching cost as a result of preparation resulted from the fact that CTI reduced switch RT more than it reduced no-switch RT and fixed-order RT. In other words, the interaction between order switch and CTI was overadditive. However, no-switch and fixed-order trials were affected similarly by CTI. Moreover, it is reasonable to assume that, when the order is fixed, there is little or no need to reload order information. This supports our interpretation that the effect of CTI in these conditions does *not* reflect advance activation of order information because there is no need to load new order information. CTI-related speeding in no-switch trials and in fixed-order trials can be attributed to general preparation processes and, possibly, to direction of visual attention (Posner, 1980) to the location at which S1 was about to appear.

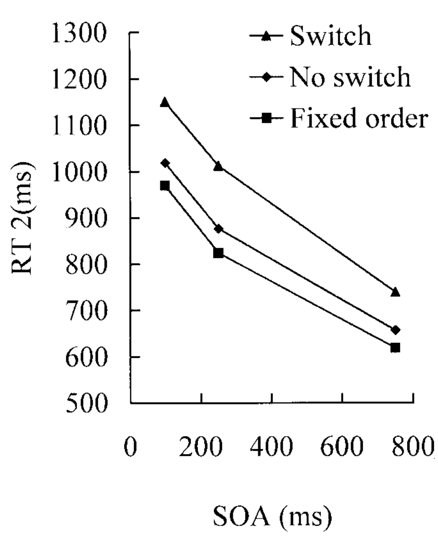

Figure 7. Mean RT2 (reaction time in the second subtask, in milliseconds) as a function of stimulus onset asynchrony (SOA) and order (switch, no switch, or fixed order) in Experiment 2.

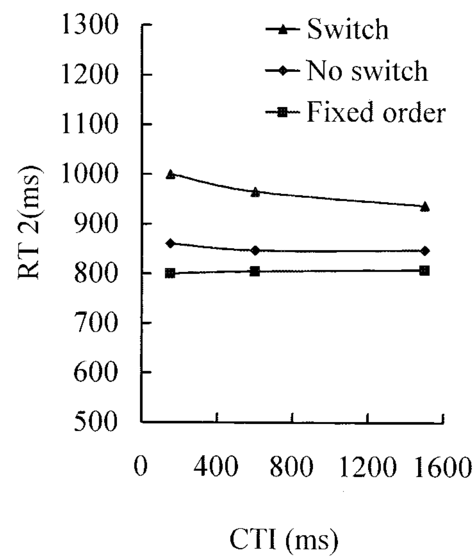

Figure 8. Mean RT2 (reaction time in the second subtask, in milliseconds) as a function of cue–target interval (CTI) and order (switch, no switch, or fixed order) in Experiment 2.

This experiment overcame all of the alternative explanations listed earlier. Because we isolated the effect of switching and manipulated preparation time, our results clearly indicate this modulation of the PRP effect by order switching. Namely, the overadditive interaction between order switch and SOA was significant only at the short CTI. This shows that, relative to no-switch trials, switch trials involve more control. This control operation may be completed before the targets are presented if a long CTI is provided. However, when the CTI is short, there is no time to complete this control operation, and consequently the PRP effect is increased.[8]

In both experiments, we found switching cost in R1 to be much larger than what was found by De Jong (1995): 141 and 124 ms in our Experiments 1 and 2, respectively, and only 11 ms in De Jong's third experiment. This difference probably reflects an im-

[7] The three-way interaction between order mixing, task, and SOA, $F(2, 22) = 3.80$, $MSE = 0.004$, was significant as well. In the fixed-order color task trials, there was a decrease in error rate from the intermediate to the long SOA, whereas for the letter task this pattern was reversed.

[8] Note that we manipulated CTI within blocks rather than between blocks. This probably reduced preparatory effects (cf. Rogers & Monsell, 1995). Nevertheless, we found a reduction in order-switching cost due to preparation.

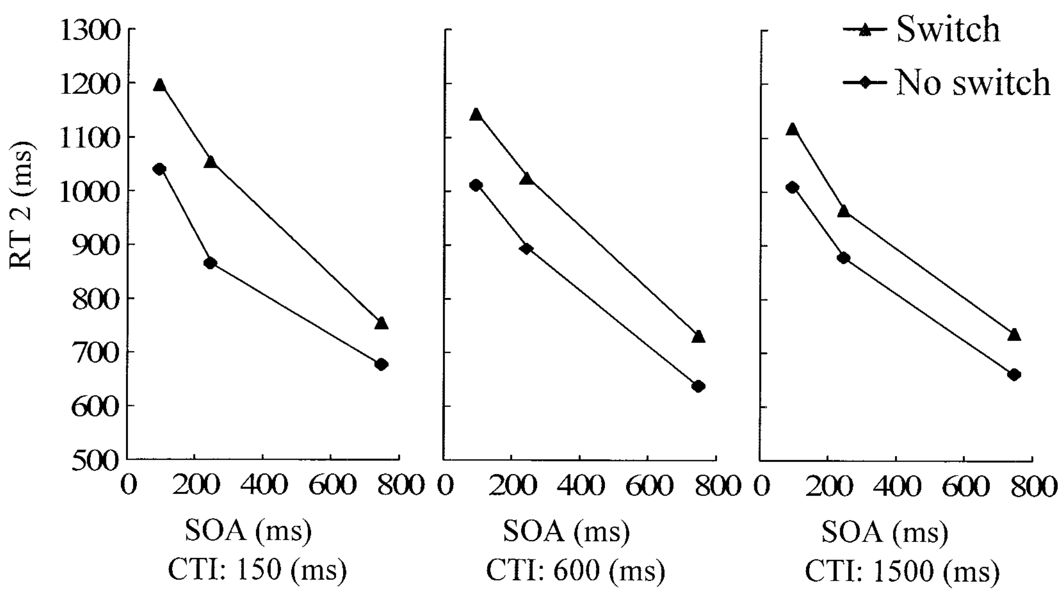

Figure 9. Mean RT2 (reaction time in the second subtask, in milliseconds) as a function of cue–target interval (CTI), stimulus onset asynchrony (SOA), and order (switch or no switch) in Experiment 2.

portant difference between our design and De Jong's. Namely, De Jong used a perfectly predictable subtask order, so the exact moment at which preparation starts could not be determined. It is possible that participants started to prepare toward the upcoming switch while executing the second subtask in the preceding trial, thus reducing cost in R1. However, in our procedure, the activation of order information probably began after presentation of the instructional cue.

Experiment 3

In both previous experiments, subtask order was confounded with hand order. Namely, when participants alternated between orders, they also alternated between hands. Consequently, the left hand was always associated with color responses, and the right hand was always associated with letter responses. The reason for this confounding was that we wanted to isolate subtask order as the only switched element. However, it is possible that the results obtained here are relevant only to cases in which order switching is related to hand order switching (see Pashler, 2000). To rule out this possibility, we used a fixed hand order in Experiment 3. Half of the participants always used their right hand to respond in the first subtask (either color or letter) and their left hand in the second subtask (either letter or color). This pattern was reversed for the remaining participants. Hence, hand order was constant throughout the experiment. The price paid for this change in experimental setting was that a task switch was now associated with a change in response meaning. For example, in switching from color–letter to letter–color, a given participant would use his or her left hand for color responses in trial $n - 1$ and use the same hand for letter responses in trial n. Thus, Experiment 3 should be evaluated in conjunction with Experiment 2, with attention paid primarily to the convergent conclusions.

Method

Except as noted subsequently, the apparatus and procedure were the same as in Experiment 2.

Participants

Twelve undergraduate students from Ben-Gurion University of the Negev participated in this experiment as part of a course requirement. All participants reported having normal or corrected-to-normal vision and hearing.

Design and Procedure

The procedure was identical to that of Experiment 2 except that hand order was fixed for the entire experiment. This was accomplished as follows: Half of the participants responded to the first stimulus (color or letter) with their right hand and to the second stimulus (letter or color) with their left hand. For this group, the first stimulus always appeared to the right of fixation, and the second stimulus appeared to the left. This pattern was reversed for the other half of the participants. The same response keys as in the former experiments were used; however, the nature of responses changed with task order. Because the right hand (or the left for the second group of participants) was the first responding hand throughout the experiment, pressing the .> key indicated the letter *D* or the color pink, and pressing the /? key indicated the letter *B* or the color blue, depending on the subtask. For the other participants, pressing the *z* key indicated the letter *B* or the color blue, and pressing the *x* key indicated the letter *D* or the color pink, depending on the subtask.

Results

The data from 1 participant were omitted from the analysis as a result of a very long RT1 (1,207 ms on average, as compared with an average of 772 ms [SD = 141 ms] for all other participants and 1,032 ms on average for the next slowest participant). It should be noted that the same pattern of significant and nonsignificant effects emerged when the results for this participant were included in the analyses. Thus, the results of 11 participants are reported. Otherwise, the analytic procedure was the same as in Experiment 2.

Switching Cost

R1. An ANOVA of RT1 yielded significant main effects of order switch, $F(1, 10) = 73.18$, $MSE = 11{,}629.67$, indicating an overall switching cost of 92 ms; SOA, $F(2, 20) = 14.71$, $MSE = 25{,}598.45$; and CTI, $F(2, 20) = 22.55$, $MSE = 41{,}576.62$. The interaction between order switch and SOA was significant, $F(2, 20) = 3.77$, $MSE = 6{,}902.98$ (see Figure 10). More important, the interaction between order switch and CTI reached significance as well, $F(2, 20) = 4.45$, $MSE = 10{,}122.76$. Increasing the CTI affected switch trials (there was a difference of 202 ms between the short and the long CTI) more than no-switch trials (131 ms), thus replicating the results of Experiment 2. The reduction in switching cost due to increasing CTI was 71 ms.

A similar ANOVA focusing on error proportion revealed significant effects of order switch, $F(1, 10) = 19.73$, $MSE = 0.0032$, and CTI, $F(2, 20) = 18.81$, $MSE = 0.009$. The two-way interaction between order switch and CTI was significant, $F(2, 20) = 11.65$, $MSE = 0.0009$. All trends were the same as the RT trends. The overall R1 error rate was .026. Error proportions are presented in Table 3.

R2. An ANOVA focusing on RT2 yielded significant main effects of order switch, $F(1, 10) = 61.92$, $MSE = 21{,}193.27$, indicating a switch cost of 115 ms; SOA, $F(2, 20) = 144.02$, $MSE = 41{,}810.86$; and CTI, $F(2, 20) = 17.74$, $MSE = 23{,}997.32$. The interactions between order switch and SOA, $F(2, 20) = 12.87$, $MSE = 6{,}918.7$ (see Figure 11), and between order switch and CTI, $F(2, 22) = 5.55$, $MSE = 9{,}402.8$, also reached significance. CTI had an effect of 149 ms on switch trials but only 73 ms on no-switch trials.

The simple main effect of order switch was significant in the last CTI for both R1, $F(1, 10) = 6.71$, $MSE = 13{,}070.4$, and R2, $F(1, 10) = 13.35$, $MSE = 17{,}023.4$, indicating a significant residual switching cost in both responses. Residual cost sizes were 52 ms for RT1 and 94 ms for RT2.

A similar ANOVA focusing on error proportions revealed a significant main effect of order switch, $F(1, 10) = 12.73$, $MSE = 0.0019$ (again the error rate in switch trials, .043, was higher than that in no-switch trials, .027; see Table 3).[9] The overall R2 error rate was .034.

Distributional analyses. We conducted a distributional analysis to ensure that switching cost was robust and was evident throughout the RT distribution. We examined the effect for the lower, median, and upper quartiles of the RT distribution. There were only about 15 observations per condition, on average. RT1 order-switching costs were 72, 94, and 112 ms for the first through third quartiles, respectively. The corresponding RT2 costs were 96, 122, and 140 ms. As in Experiment 2, the effect was statistically identical for short and long CTIs in the case of both RT1 and RT2 ($F < 1$). Thus, again we did not find evidence for De Jong's (2000) arguments.

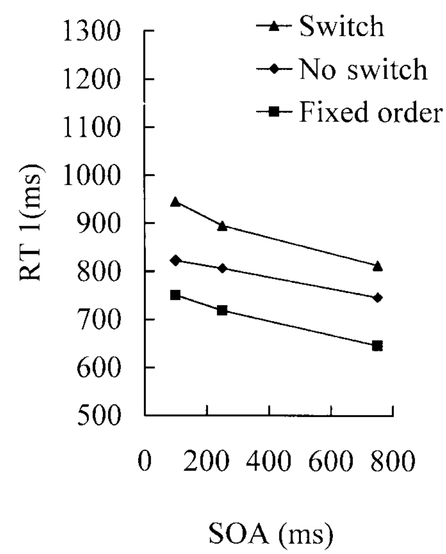

Figure 10. Mean RT1 (reaction time in the first subtask, in milliseconds) as a function of stimulus onset asynchrony (SOA) and order (switch, no switch, or fixed order) in Experiment 3.

Mixing Cost

R1. An ANOVA of RT2 yielded significant main effects of order mixing, $F(1, 10) = 23.22$, $MSE = 31{,}998.21$, representing a mixing cost of 87 ms; SOA, $F(2, 20) = 18.06$, $MSE = 16{,}092.15$; and CTI, $F(2, 20) = 18.98$, $MSE = 15{,}174.39$. The interaction between order mixing and CTI, $F(2, 20) = 6.20$, $MSE = 9{,}505.57$, was significant as well.[10]

A similar ANOVA focusing on error proportions revealed a significant effect of SOA, $F(2, 20) = 4.33$, $MSE = 0.0007$, representing a reduction in error rates from the short to the intermediate SOA (.018 and .009, respectively). The interaction between SOA and CTI was significant, $F(4, 40) = 3.76$, $MSE = 0.0005$. The overall error rate was very low, .001.

R2. An ANOVA focusing on RT2 yielded significant main effects of order mixing, $F(1, 10) = 23.94$, $MSE = 40{,}789.58$, indicating a 99-ms mixing cost; SOA, $F(2, 20) = 143.12$, $MSE = 30{,}590.29$; and CTI, $F(2, 20) = 6.48$, $MSE = 7{,}392.85$. The interaction between order mixing and CTI, $F(2, 20) = 6.38$, $MSE = 6{,}878.93$, was also significant, indicating that CTI had an

[9] The interaction between order switch and task was significant, $F(1, 10) = 8.62$, $MSE = 0.0014$ (the difference between switch and no switch was more pronounced in the color task).

[10] The three-way interaction between order mixing, task, and CTI was also significant, $F(2, 20) = 4.22$, $MSE = 3{,}050$. Apparently, for color task switch trials there was a reduction in RT between the intermediate and the long CTI, $F(1, 10) = 9.26$, $MSE = 6{,}739$, but there was no such reduction in the letter task ($F < 1$).

effect on no-switch trials (73 ms) but no effect on fixed-order trials (0 ms).[11]

A similar ANOVA focusing on error proportions revealed a significant effect of SOA, $F(2, 20) = 4.18$, $MSE = 0.0012$, indicating a reduction in errors from the short SOA (.029) to the long SOA (.019). The overall R2 error rate was .027.

Discussion

In this experiment, we replicated all of our main results from Experiments 1 and 2. Namely, we found order-switching cost for both responses, and this order cost was reduced by advance preparation (CTI) in the case of both R1 and R2. In addition, we found mixing cost and residual cost. The difference between Experiment 2 and Experiment 3 was that, in the latter, switch was not confounded with hand sequence. Thus, we argue that the subtask sequence is not (only) represented as a motor hand sequence; it probably involves more central cognitive processes as well. Note that, in this experiment, order switch was not isolated as the only switched element, meaning that an order switch was always coupled with a switch of response key meanings. Nonetheless, the fact that the results were strikingly similar to those of Experiment 2, especially concerning the reduction of switching cost as a result of preparation, seems to suggest that advance preparation referred to the order of subtasks and not to response meaning. Moreover, there is now considerable evidence of very limited ability for advance preparation of response meaning in multivalent response setups such as the ones used in the present experiment (e.g., see Meiran, 2000a, for a review and Meiran, 2000b, for empirical support). Thus, taken together, the results of Experiments 2 and 3 are most consistent with the notion that cognitive subtask order information was activated before task execution.

General Discussion

The goal of the present study was to provide evidence for online order control in the PRP paradigm and to show that this control is based on activating explicit sequence information. We argued that the most critical evidence in this respect is order-switching cost, which was reliable and sizeable in all three experiments. We can also conclude that activation of order information does not decay

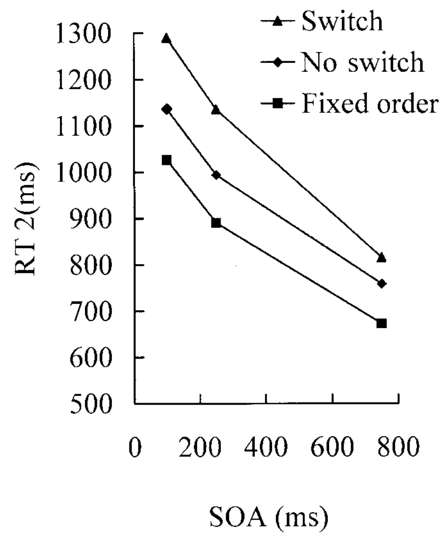

Figure 11. Mean RT2 (reaction time in the second subtask, in milliseconds) as a function of stimulus onset asynchrony (SOA) and order (switch, no switch, or fixed order) in Experiment 3.

within the time range (RCI, Experiment 1) studied in the present experiments and that order information can be partly activated before proper task execution (Experiments 2 and 3). Order-switching cost was previously studied with respect to errors (De Jong, 1995), but, to the best of our knowledge, this is the first demonstration of RT order-switching cost. Note that the design of the present experiments made it difficult to support our predictions, because the switch condition included a repetition of the subtask (e.g., color–*letter* followed by *letter*–color, with the letter subtask repeated in this example). In contrast, the no-switch condition involved a subtask switch (e.g., color–*letter* followed by color–*letter*). Although the pattern of the interaction between subtask switch and order switch still needs to be examined, the assumption that both forms of switch produce cost leads one to conclude that our estimates of order-switching cost were, in fact, underestimates.

Another novel finding for multistep tasks is the order-mixing cost for both responses. This finding is novel because De Jong (1995) and Pashler (1990) did not compare RT in switch and no-switch trials, and thus one cannot be certain whether the effect was due to order switching, order mixing, or both.

Implications for Task-Switching Theories

Some task-switching theories explain switching cost by changes in task readiness (especially Fagot, 1994; see also Allport &

Table 3
Error Proportions in R1 and R2, Experiment 3

CTI (ms)	Switch: SOA (ms) 100	250	750	No switch: SOA (ms) 100	250	750	Fixed: SOA (ms) 100	250	750
150									
R1	.05	.05	.07	.03	.00	.01	.02	.01	.01
R2	.06	.03	.04	.03	.04	.01	.03	.03	.02
600									
R1	.04	.04	.05	.02	.02	.01	.01	.01	.02
R2	.06	.04	.04	.03	.04	.03	.03	.03	.02
1,500									
R1	.02	.02	.02	.01	.02	.01	.02	.01	.01
R2	.04	.05	.03	.02	.02	.02	.03	.03	.03

Note. R1 = response in the first subtask; R2 = response in the second subtask; CTI = cue–target interval; SOA = stimulus onset asynchrony.

[11] The three-way interaction between order mixing, task, and SOA, $F(2, 20) = 3.72$, $MSE = 5{,}795.45$, was significant. A planned comparison revealed that the interaction between order mixing and SOA (intermediate vs. long) was significant for the letter task, $F(1, 10) = 15.31$, $MSE = 5{,}795.45$, but nonsignificant for the color task, $F = 1.7$. The triple interaction between order mixing, task, and CTI, $F(2, 20) = 3.66$, $MSE = 3{,}104.27$, was also significant. A planned comparison revealed that the reduction in RT for no-switch trials between the short and intermediate CTIs was more pronounced in the letter task than in the color task, $F(1, 10) = 8.45$, $MSE = 37{,}453.1$.

Wylie, 2000), whereas others argue that switching cost reflects a change in processing mode (e.g., Meiran, 1996, 2000a, 2000b; Rogers & Monsell, 1995). Our finding that order switch interacted overadditively with SOA supports the latter view. This provides evidence that order switching can change task execution processes; namely, order switching changed the processing mode of the PRP multistep task. How exactly this mode was changed is explained subsequently.

Implications for Models of the PRP Paradigm

The subtask order in our design could be determined through a first-come-first-served strategy without order control, because the two stimuli were separated by an SOA (see De Jong, 1995, on this point). This strategy is implied in Pashler's (1994a, 1998) model. According to this strategy, however, no order-switching cost is predicted.

In contrast to these predictions, we provided evidence that order information can be activated in advance of execution, because order-switching cost was reduced as a result of preparation. We also demonstrated that the PRP effect was modulated by such order control, as was evident in the overadditive interaction between SOA and order switch: The PRP effect increased when more control was required. Note, however, that the question of order control is independent from the question of whether there is a structural or strategic bottleneck. In fact, our interpretation of the results assumes the existence of such a bottleneck (cf. Tombu & Jolicœur, 2000).

Is it possible to explain the overadditive interaction between order switch and SOA using Pashler's model? Hartley and Little (1999) elaborated Pashler's model to explain an overadditive interaction between task difficulty and SOA. These authors suggested that an additional processing stage precedes response selection. This stage involves the instantiation of stimulus–response mappings. If the subtasks are easy, instantiation of *both* subtasks can take place before the response selection stage of R1. But if the subtasks are difficult, instantiation of the second subtask must wait until the end of the response selection stage of R1. When SOA is short, response selection of R2 must wait until the instantiation of R2 ends, thus prolonging RT2. When SOA is long, there is ample time for the instantiation of R2 to take place before response selection of R2 starts, without affecting RT2. Consequently, the instantiation of stimulus–response mappings prolongs RT2 in the short SOA but not in the long SOA, resulting in an overadditive interaction. Even this proposal does not seem to explain our results, because order switch and order mixing did not involve a change in tasks and, hence, did not involve a change in task difficulty. Nonetheless, an analogous explanation can be formed if we assume that there are yet-to-be specified processes related to and behaving similar to stimulus–response mapping instantiation. However, this line of explanation encounters difficulty because, even when the SOA was long and the additional control processes had sufficient time to be completed, there were order-switching costs of 96, 83, and 55 ms in Experiments 1, 2, and 3, respectively. Therefore, to fully account for our results, it is necessary to further assume that some processing stages in R2 are prolonged by order switching and order mixing. This implies that order control is involved in performance in the PRP paradigm, an effect that cannot be accounted for by Pashler's (1994a, 1998) model.

Unlike Pashler's (1994a, 1998) model, ECTVA (Logan & Gordon, 2001) involves explicit mechanisms for order control. Specifically, subtask order is controlled by several parameters that are sent from working memory and ensure proper task execution. These include a bias parameter that can "turn up" desired response categorizations (e.g., "bigger than 5") and a priority parameter that represents the importance of selecting stimuli that contain a certain property (e.g., "the one on the left"). In each trial, parameters for the first subtask are being sent to the response selection stage. After selection, counters in the response selection stage are being inhibited to prevent perseveration of R1, and new parameters for the second subtask are sent from working memory.

Another relevant model is EPIC (Meyer & Kieras, 1997a, 1997b). When subtask order is fixed, EPIC delays the processing of the second subtask until the processing of the first subtask has reached a certain point. For example, if the order is color–letter for the entire block, EPIC delays the processing of the letter subtask ("a deferred mode") and starts processing the color task ("an immediate mode"). This means that the processing of the deferred subtask (letter) can continue only until a certain stage. Thus, only after the immediate subtask (color) has passed an unlocking point for the deferred subtask can processing of the deferred subtask proceed. The exact point until which the second subtask is deferred and the exact unlocking point of the first subtask are under strategic control, so they could, for example, change with task instruction. If the order is random, EPIC (Meyer & Kieras, 1997b) defers both subtasks until the presentation of the first stimulus, which determines which is the immediate subtask and which is the deferred subtask.

Our results favor models, such as EPIC (Meyer & Kieras, 1997a, 1997b) and ECTVA (Logan & Gordon, 2001), that incorporate order control. Moreover, our results can help in deciding among these models. Specifically, EPIC's account would explain the results in terms of strategic differences between random order conditions (in which both subtasks are in "deferred mode") and fixed order conditions (in which the first subtask is in "immediate mode"). This means that EPIC can explain the results concerning mixing costs but would have difficulty explaining the switching costs because it lacks trial-to-trial memory. ECTVA (Logan & Gordon, 2001) can accommodate the results more naturally by assuming that order-switching effects resulted from interference or compromise between parameters in working memory because the parameters of the preceding trial did not fully decay.

Order Sets and Order Control

Our account has two components. The first component is the assumption that each subtask order is represented explicitly and separately (Lashley, 1951) in an *order set*. The order set merely includes the ordered list of subtasks to be executed. In our experiments, there were two order sets, represented as "first color second letter" and "first letter second color." The second component of our explanation is the assumption that, when a given subtask is encountered in the order set, the corresponding stimulus–response mapping (e.g., Duncan, 1977; Shaffer, 1965) is activated.

Before the subtasks are executed in a specific order, the appropriate order set must be activated, and the inappropriate order set must be suppressed. This process of switching activated order sets is responsible for the order-switching cost. Processes similar to those involved in single-step task switching could explain the fact that switching cost is not abolished by preparation. These processes include using the target stimuli as set reminders (Rogers & Monsell's, 1995, "stimulus-cued completion of reconfiguration") and strengthening set representation by task execution (Meiran's, 1996, "retroactive adjustment").

Explaining the Overadditive Interaction Between SOA and Order Switch

Order switching had an overadditive interaction with SOA for RT2 but not RT1 in Experiments 1 and 2 (the presence of a significant overadditive interaction in Experiment 3 is not relevant here because subtask order was not the only switched element). This leads us to suggest that the interaction is not carried from R1 to R2 but is specific to R2.

We argue that, as in other demanding situations, participants delegate control to the environment, if possible. In the present case, the order of stimulus (S1–S2) presentation served as an order-set reminder and helped participants in completing the order reconfiguration. Specifically, it was possible to essentially copy the S1–S2 order into task order, implying bottom-up set activation. Such processes had only a minimal influence in no-switch trials, wherein order reconfiguration was less needed. Moreover, because the mechanism is based on *copying* S1–S2 order, the overadditive interactions were more pronounced in R2 than R1. The reason is that only after S2 was presented could S1–S2 order be perceived and influence order reconfiguration.

The reason for overadditivity is based on the relative ease of perceiving S1–S2 order. Specifically, when SOA was short, it was more difficult to perceive S1–S2 order (e.g., see De Jong, 1995, for support). This led to lesser bottom-up activation of the order set and, in turn, to a smaller activation of stimulus–response Subtask 2. The result was a prolongation in R2 selection at the short SOAs. In longer SOAs, the S1–S2 order was easily perceived, leading to stronger order-set activation and shorter R2 selection.

Activating a Subtask as R1 or as R2

The hypothesis just described leads to an interesting prediction. This prediction concerns performing a given subtask (color or letter) as R1 or R2. In the random order, the same subtask (i.e., the letter task) was performed occasionally as R1 or R2. However, we suggest that there is a difference between the two conditions. Unlike Subtask 1, which was primarily activated by the cue (top-down), Subtask 2 was activated by two sources: the cue (top-down) and the copying of S1–S2 order (bottom-up). Thus, it was predicted that, especially when the SOA was long, Subtask 2 would be more active than Subtask 1, resulting in fast R2 selection relative to R1 selection. In other words, we predict that the same subtask should take less time to perform as R2 (long SOA) than as R1. As before, only Experiments 1 and 2 are relevant because of the bivalent responses in Experiment 3. The results support the prediction in both switch and no-switch trials. In Experiment 1, a given subtask was associated with longer no-switch RT1s (807 ms and 722 ms for the long and short SOAs, respectively) than RT2s (only 665 ms, given the long SOA). A similar trend was found in switch trials. In R1, RTs were 963 and 857 ms for the short and long SOAs, respectively, as opposed to only 761 ms (given the long SOA) for RT2. The same trend appeared in Experiment 2. RT1s in no-switch trials were 856 and 734 ms for the short and long SOAs, respectively, as opposed to only 657 ms for RT2 (long SOA). In switch trials, RT1s were 971 and 864 ms for the short and long SOAs, respectively, as opposed to only 740 ms for RT2 (long SOA; all comparisons were significant at $p < .05$). Interestingly, Pashler (1990) also obtained the same trend in all of his three experiments. It is noteworthy that this trend was found even though participants were told to emphasize R1.

Ruling Out Alternative Explanations

To support the preceding hypothesis, it is important to rule out alternative explanations based on known mechanisms of response order control. First, self-inhibition (i.e., MacKay, 1987) could explain the order control observed in our experiments. This mechanism can account for the switching cost found in R1 as follows. When executing the order letter–*color* in trial n followed by *color*–letter in trial $n + 1$, for example, participants inhibit the color subtask in trial n so that their execution of the color subtask in the following trial $n + 1$ is impaired. However, the letter subtask (R2) in trial $n + 1$ is not inhibited. Thus, this mechanism cannot explain the R2 switching cost.

Second, lateral inhibition (Cooper & Shallice, 2000; Norman & Shallice, 1986) could also explain order control in our experiments. Lateral inhibition means that when the first subtask is being executed, it suppresses the second subtask, and when the second subtask is executed, it suppresses the first subtask. In this case, the stimuli may trigger execution of the subtasks. However this mechanism would not predict order-switching cost. Using the earlier example (letter–*color*, *color*–letter), after the color subtask in trial n is executed, the letter subtask becomes inhibited, so that performing the color task in trial $n + 1$ should not result in R1 cost, contrary to what we found. Again, lateral inhibition cannot account for R2 switching cost, because the second subtask is inhibited in both switch and no-switch trials.

Third, participants could hold two associations simultaneously. One is "IF [the color subtask is first] THEN [the letter subtask is second]," and the other is "IF [the letter subtask is first] THEN [the color subtask is second]." Thus, according to this possibility, it is necessary only to decide which subtask is first and then implement the proper association. Note that this strategy is plausible because we used only two subtasks. This mechanism cannot explain switching costs found in R2, at least given a long SOA. When the SOA is long, there is ample time for the proper association to switch before S2, so execution of the second subtask should not be impaired. Because we also found switching cost in R2 (given a long SOA), this possibility is ruled out as well.

To summarize, none of the alternatives discussed earlier could explain the present results, especially those concerning order-switching cost in R2. For this reason, a combination of these mechanisms also cannot explain the results.

Which Processing Stages Were Affected by Preparation?

Another interesting implication of our hypothesis concerns the reduction in order-switching cost by preparation. Presumably, the cue led to the activation of the correct order set and the suppression of the incorrect order set. This, in turn, led to the activation of Subtask 1. Thus, the earlier-mentioned preparation effects are predicted to affect processing stages before and including R1 selection.

As is evident, our explanation relies on Pashler's (1994a, 1998) bottleneck assumption (strategic or structural). Moreover, our explanation of the overadditive interaction between SOA and order switch assumes that the bottleneck is unaffected by order control (cf. Tombu & Jolicœur, 2000). Another assumption is that the duration of the R1 response selection stage does not change as a function of SOA. This assumption is essential whenever Pashler's model is used.

The analysis described here was conducted on the results of Experiment 2, because in this experiment subtask order was isolated as the only element that was being switched. Looking at the pattern of means, it was evident that the size of the reduction in switching cost due to preparation, given a short SOA, was similar in the case of RT1 and RT2 (36 ms and 46 ms, respectively), with only a 10-ms nonsignificant difference between them. Applying Pashler's (1994a, 1998) model, this pattern implies that preparation effects were located in processing stages at or before R1 selection, with consequent effects on R2. Specifically, a critical prediction in Pashler's model is that when SOA is short, increasing the duration of response selection (or preceding stages) in R1 should increase RT1 and RT2 to the same extent. To explain this prediction, we refer to the analogy used by Pashler. The analogy is made with respect to a teller in a bank, representing a bottleneck, and customers, representing R1 and R2. If the first customer (analogical to R1) hesitates before getting to the teller (processing stages preceding the bottleneck are prolonged) or dawdles while talking with the teller (the bottleneck stage is prolonged), this customer (R1) and the next customer waiting in line (R2) will be delayed to the same extent. Note that Pashler's prediction does not hold when SOA is long (see Figure 12). Under this condition, R2 does not need to wait, because R1 has already passed the bottleneck. Accordingly, we predicted no reduction in switching cost by preparation in RT2 given a long SOA. We found only a nonsignificant 2-ms reduction in switching cost due to preparation in RT2, given a long SOA. Thus, we suggest that the preparation effects were located in processing stages before or at R1 selection.

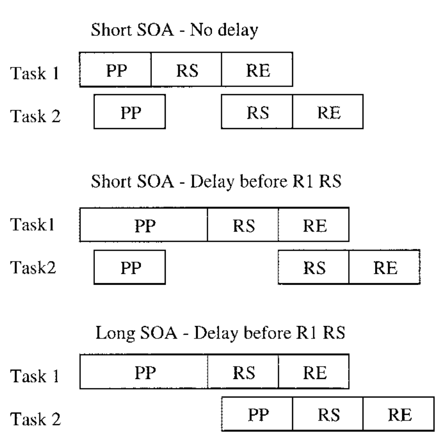

Figure 12. Illustration of preparation effects. When the perceptual processing (PP) stage is delayed in Task 1, it causes a similar delay to Task 2 in the short stimulus onset asynchrony (SOA) but has no influence on Task 2 in the long SOA. RS = response selection; RE = response execution; R1 = response to stimulus S1.

Summary

This work led to three main conclusions. First, the PRP effect is modulated by online order control. This result cannot be explained by using Pashler's (1994a, 1998) model as it is presently formulated, but it is in line with EPIC (Meyer & Kieras, 1997a, 1997b) and ECTVA (Logan & Gordon, 2001). Second, advance task preparation does not merely reflect changes in readiness, because our results showed that advance preparation modulated task-execution processes. Finally, order control is probably based on explicit representation of subtask order, and this representation is partly activated before task execution.

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