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Dual route for subtask order control: Evidence from the psychological refractory paradigm

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A change in subtask order in the psychological refractory period (PRP) paradigm increases the effect of stimulus onset asynchrony (SOA) on the second response. We used a paradigm with cued, randomly determined subtask order to test the hypothesis that this SOA by order switch overadditivity reflects order control, via "copying" stimulus order. In Experiments 1a and 1b, overadditivity was evident only with insufficient opportunity for cue-based order control. In Experiment 2, overadditivity was decreased by using the same set of stimuli in the two subtasks, presumably by removing the opportunity to rely on stimulus order. In Experiment 3, removing the order cue increased the overadditivity, presumably because control was based solely upon copying stimulus order. The results indicate interactive top-down and bottom-up order control. Implications to theories of the PRP paradigm are discussed.

Most everyday tasks are complex and include several subtasks that can also be executed alone or in other contexts. For example, making instant coffee involves adding coffee grains, pouring hot water, stirring, adding milk and sugar, and so on. One key element that ensures successful performance is the execution of these subtasks in the correct order. It is essential that we do not pour the water before we have boiled it, or that we do not stir before we pour the hot water into the cup. The fact that we perform these tasks quite easily, by executing the subtasks in the correct order, suggests that the order is represented in some form (perhaps as a to-do list), and task execution involves activating this representation and then following it (e.g., Q1 Cooper & Shallice, 2000; Grafman, 1995; Lashley, 1951; Norman & Shallice, 1986, see also Botvinick & Plaut, 2004).

However, it is not sufficient to represent subtask order to ensure successful performance. It is also crucial tod keep track of the subtask being executed and to choose the next correct subtask according to the specific order plan. It is this online order control that was investigated in the current research. We used the psychological refractory period (PRP, see Pashler 1994, 1998, for review) in order to examine online order control. In the PRP paradigm, two stimuli, S1 and S2 (the stimulus for the first subtask and the stimulus for the second subtask, respectively) are presented in rapid succession, and each stimulus is responded to by a separate response (R1 and R2) resulting in two response times: RT1 and

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RT2. Thus, each trial includes two separate subtasks. We refer to them as *Subtask 1* and *Subtask 2*, respectively. The interval between the presentation of S1 and S2 (the stimulus onset asynchrony, the SOA) is manipulated, typically varying between 100 ms and 1,000 ms. The basic finding is that RT1 is not affected by SOA, while RT2 decreases as SOA increases (the so called PRP effect). To explain the PRP effect, Pashler and colleagues (Pashler, 1984, 1994, 1998; Pashler & Johnston, 1989; see also Welford, 1952) suggested that a central processing stage, responsible for the response selection, cannot operate concurrently for both subtasks. Thus, the response selection stage acts as a bottleneck, so that Subtask 2 must wait for this stage to complete for Subtask 1. According to the response selection bottleneck model, other processes such as perceptual processing or response execution operate in parallel for both subtasks.

The central assumption in the response selection bottleneck model (Pashler, 1994, 1998) concerning structural limitations has recently been challenged. Dissenting views see the bottleneck as not structural but strategic in nature (e.g., Logan & Gordon, 2001; Meyer & Kieras, 1997a, 1997b), or as dependent upon instruction-based capacity allocation (Navon & Miller, 2002; Tombu & Jolicoeur, 2003). The current study was not designed to address this debate, although it has implications for the debate. In order to avoid these issues, we studied conditions that promote a bottleneck, either strategic or structural. Proponents of the structural view have suggested that cautionary strategies produce a strategic bottleneck early in practice (i.e., Schumacher et al., 1999); consequently in our study participants took part in one session only. Another claim is that emphasizing the first response encourages a strategic bottleneck (Meyer & Kieras, 1997a, 1997b); for this reason, we employed such an emphasis. Moreover, we manipulated subtask order, so that the order of the subtask was random in every trial. Presumably, the PRP effect is due to a structural limitation under this manipulation (cf. Tombu & Jolicoeur, 2000).

As mentioned previously, we were interested in studying online order control in the PRP paradigm. To study order control, we manipulated subtask order. In each trial, participants performed two subtasks, letter (B vs. D) and colour (e.g., blue vs. pink). The order of these subtasks was varied randomly within each block, so that sometimes letter came before colour, and sometimes the order was reversed. Participants answered according to the instructed subtask order. Hence, they had to monitor which subtask was performed as Subtask 1 and which as Subtask 2. In what follows, we introduce a framework that specifies our assumptions regarding how order is controlled online in the PRP paradigm, then discuss evidence to support this framework, and finally present predictions to be tested in three experiments.

Order control in the PRP paradigm

Following Lashley (1951), we (Luria & Meiran, 2003) argued that subtask order is represented explicitly and separately from the subtask representations. We called this representation the *order-set*; it includes a list of subtasks in a specified order. This representation is analogous in many respects to a to-do list. Before executing a complex task, the appropriate order-set must be activated (e.g., making coffee), and inappropriate order-sets must be suppressed (e.g., making tea). The order-set is responsible for activating the subtasks according to the planned order (see Rubinstein, Meyer, & Evans, 2001, for a possible description regarding how such representations are being used).

Luria and Meiran (2003) argued that the order-set can be activated by both top-down and bottom-up factors. For example, the retrieval of the coffee-making plan following a request to prepare coffee constitutes top-down activation of the order-set. Alternatively, the order-set might be activated in a bottom-up manner by the sight of an instant coffee packet, for example (Shallice, Burgess, Schon, & Baxter, 1989). Other processes that are potentially involved in order control (such as lateral inhibition and self inhibition) are discussed in the General Discussion. We argue that such processes alone cannot explain our results.

We now turn to present our posited order control mechanism (see Figure 1). In our paradigm, there were two order-sets: "first colour second letter", and "first letter second colour". In addition to the order-sets, there were stimulus–response (S–R) rules for colour and letter. We assume that (a) S–R rules reside in active memory (e.g., Logan, 1978) perhaps in the form of a "prepared reflex" (Hommel, 2000), and (b) S–R rules relevant to a given task are treated as either a unit/object (Garavan, 1998) or an S–R mapping (Duncan, 1977; Shaffer, 1965). We further assume that the order-set activates the two S–R mappings in a graded manner. Moreover, the degree that a given S–R mapping becomes active determines the speed and efficiency of the relevant response selection. We suggest that the order-set is partly reconfigured prior to the initiation of R1-selection. Reconfiguration has two aspects. The first aspect is deciding which order is relevant. This step is assisted by the instructional cue (top-down activation) and can be carried out during the preparation period from the presentation of the cue until the presentation of S1 (see Fagot, 1994; Rubinstein et al., 2001, concerning task decision). The order-set can also be activated in a bottom-up manner essentially by copying the order in which S1 and S2 were presented. For example, if a letter is presented before a coloured rectangle, this activates the letter-then-colour order-set. This implies that this bottom-up activation of the order-set must await S2 presentation, or is at least stronger after S2 has been presented.

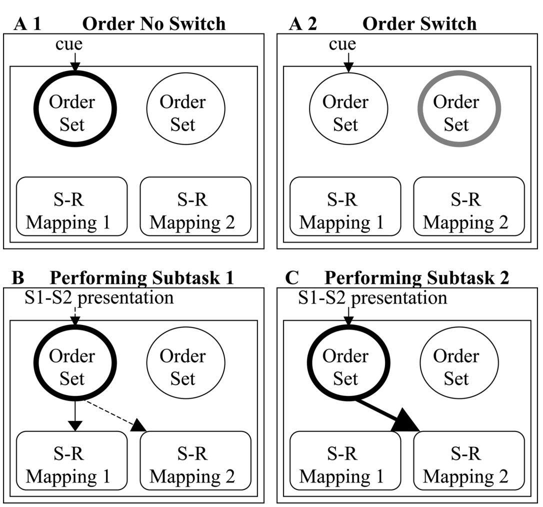

Figure 1. *Order control in the PRP paradigm. The integration of top-down (cue-based) processes with bottom-up (stimulus-based) processes. A1: order repeat. A2: order switch. B: performing Subtask 1. C: performing Subtask 2. PRP = psychological refractory period. S–R = stimulus–response. S1: first stimulus. S2: second stimulus.*

We use the terms bottom-up control because it reflects activation arising from the target stimuli, and we use the term top-down control because it reflects activation from the "top" of the schema (similar to a request for a cup of coffee made by a guest that activates the coffee making schema). These two modes of control are essentially stimulus based. In that respect, both are examples of exogenous acts of control. However, we chose the present terminology to emphasize the difference between control based upon a stimulus extrinsic to the tasks at hand and control by stimuli that are intrinsic to these tasks.

Figure 1 summarizes our working assumptions regarding how the order-set is activated and how it operates. The first step in multistep task execution is to activate the correct order-set (e.g., Figure 1A), which would then activate the S–R mappings in the correct order. The activation of the order-set is partially completed before initiating Subtask 1. Order-set activation can be done in advance (in a top-down manner using a cue). However, if the order is not activated in advance, as in the case of a short preparation time, responses are slowed. This is due to the relatively inactive state of the set, resulting in weaker S–R mapping activation.

As a result of the subtask order activation, the order-set activates S–R Mapping 1 (Figure 1B, solid line) while maintaining preparation for the subsequent Subtask 2 (Figure 1B, dashed line). The reason why preparation for Subtask 2 is maintained is that the execution of Subtask 2 is imminent, and the onset of S2 is unpredictable.

In this case there is no need to maintain readiness for the Subtask 1 (Figure 1C). The mechanisms of keeping readiness for future action (Subtask 2) are analogous or even identical with the intention-superiority effect (Goschke & Kuhl, 1993), which refers to the enhanced activation of planned tasks.

When Subtask 2 is performed, especially given long SOA, the S–R mapping of Subtask 1 is relatively inactive, creating an asymmetry between the two subtasks. The reason for this state of relatively inactive S–R Mapping 1 is that it has already been executed, and that consequently there is less of a reason to maintain readiness for it. A similar phenomenon is the intention-inferiority effect, which refers to the decreased activation of already-performed tasks (Marsh, Hicks, & Bink, 1998; Marsh, Hicks, & Bryan, 1999).

The order-set is a representation in memory, and as such it maintains its activation between trials. Thus, following task execution, the order-set is primed to activate the subtasks in the same order as that in the previous trial (Figure 1A1). This explains the order repetition effect, or switching cost. Whenever an order switch occurs (see Figure 1A2), the alternative order-set must be activated. This takes longer than an order repetition because of the order-set being less primed, or retrieval competition, or both. In Figure 1A2, the fact that it is a switch trial is represented by the cue activation of Order-Set 1 coupled with an already activated Order-Set 2.

Relevant evidence

Order-set activation

Relevant evidence that the order-set is activated during performance in the PRP paradigm comes from studies in which the subtask order was varied (i.e., De Jong, 1995; Luria & Meiran, 2003; Pashler, 1990). For example, Luria and Meiran varied subtask order unpredictably and presented a cue that signalled the upcoming order before each trial began. Responses for both Subtask 1 and Subtask 2 were associated with an order-switching cost/repetition benefit—namely, RTs were prolonged for order switch trials as compared to trials involving an order repetition. The RT1 order-switching cost provides strong evidence that the order-set persisted between trials, rather than separate subtasks or separate S–R mappings. The reason is that an order switch trial involves a local Subtask 1 switch relative to the preceding trial (e.g., letter–*colour*, *letter*–colour). However, an order-no-switch trial involves a Subtask 1 local repetition (e.g., colour–*letter*, *letter*–colour). If there were only separate subtask representation, Subtask 1 should have been faster in an order switch trial than in an order no-switch trial, due to local subtask repetition. The fact that we found large order switch cost in RT1 is evidence that the activation of the order-set persisted between trials, indicating that the order-set was activated in the first place.

Luria and Meiran (2003) ruled out another hypothesis concerning an associative activation of Subtask 2 through the activated Subtask 1. According to this hypothesis (see, e.g., Hübner, Futterer, & Steinhauser, 2001), task control is based on activating the first element, which automatically activates additional elements. However, this hypothesis predicts order-switching cost to be absent in R2, given long SOA, whereas we consistently found such costs.

A recent fMRI study (Szameitat, Schubert, Müller, & von Cramon, 2002), which used a similar subtask order manipulation, found that the inferior frontal sulcus and the middle frontal gyrus were more activated in order switch trials than in order no-switch trials.

Top-down order-set activation

Luria and Meiran (2003) manipulated the order cue to S1 interval and showed that increasing this interval reduced the order-switching cost. A similar finding was reported by De Jong (1995), who manipulated the intertrial interval and used a fixed and predictable list of subtask orders. Moreover, the effect in both studies was due to preparation effects being more pronounced in switch trials than in no-switch trials, resulting in an overadditive interaction between order switch and preparation time. These results provide evidence that participants are able to prepare order information in advance in a top-down manner.

Bottom-up order-set activation

Importantly, order switching also modulated the PRP effect, so that the interaction between SOA and order switch in R2 was overadditive (greater SOA effects were observed in order-switched trials). The underlying causes of this interaction are the focus of the present research. Luria and Meiran (2003) argued that this overadditvity results from bottom-up activation of order information. It was suggested that one of the processes used in order-set reconfiguration is a bottom-up process based upon copying the stimulus order, as described above. An increase in SOA makes it easier to keep track of the S1–S2 order. In support, De Jong (1995), who also studied order-switching effects, found fewer reversal errors (responding in the wrong order) as SOA increased. Accordingly, this bottom-up activation of the order-set should be more pronounced with long SOAs and after S2 has been presented, due to the ease in determining the S1–S2 order. Consequently, increasing the SOA results in a stronger activation of the order-set via bottom-up processes, especially in switch trials, in which the appropriate order-set is relatively inactive. This, in turn, results in a stronger activation of the S–R rules. The effect is greater on RT2 than on RT1 because, when the SOA is long, it is implied that Subtask 1 has passed response selection in the majority of trials. As a result, RT2 becomes faster, especially in switch trials, leading to a smaller RT2 order-switching effect as SOA is prolonged. In the present paper we tested predictions that were based on this account of the overadditive interaction between order switch and SOA.

The assumptions regarding top-down and bottom-up order control are also based upon a trend towards significant three-way interaction between order switch, SOA, and order preparation time in R2 (Luria & Meiran, 2003; Exp. 2). Order preparation time was manipulated as the order cue to S1 interval (cue–target interval, CTI). The overadditive interaction between order switch and SOA was more pronounced in the short preparation time than in the long one. This trend is important for our arguments. Specifically, as preparation interval was prolonged, there was enough time for the order-set to be activated solely by top-down (cue-based) order control, and this left less room for bottom-up activation. As a result, the SOA by order switch interaction became additive (it disappeared), which is in line with our account regarding bottom-up control as responsible for the overadditivity. However, when the preparation interval was short, top-down control did not complete, leaving room for bottom-up activation, which in turn caused the SOA by order switch interaction to become overadditive.

Relations to other PRP models

It is interesting to compare the assumptions from our framework to existing PRP models. For now, we discuss only how the various models explain subtask order control and delay the treatment of all other issues to the General Discussion.

Interestingly, Pashler's bottleneck model (1998) does not incorporate any mechanism for order control. It only assumes that the response selection mechanism operates on a "first-come first-served" basis. Thus, this model would not predict any order-switching cost. Pashler's model is not refuted by evidence for order control, however, because it is possible that order is being controlled by a mechanism that is outside the scope of that model. For example Hartley and Little (1999) argued that there is a separate S–R mapping instantiation process, which is invoked before the response selection stage. Q2

The executive process interactive control (EPIC, Meyer & Kieras, 1997a, 1997b) includes a specific assumption in order to simulate performance in a variable subtask order design. According to EPIC, when there is uncertainty regarding subtask order, both subtasks are put into a deferred mode until there is a decision regarding the current order. Thus, EPIC architecture represents subtask order by giving a priority to the proper Subtask 1, when the order is determined. However, it does not encompass a memory of the order in which the subtasks were executed in the preceding task, and it therefore cannot account for finding order-switching cost (De Jong, 1995; Luria & Meiran, 2003).

Recent capacity-sharing models (Navon & Miller, 2002; Tombu & Jolicoeur, 2003) proposed that more capacity is allocated to the subtask that served as Subtask 1 in the previous trial, causing a bias towards repeating subtask order (Tombu & Jolicoeur, 2003). However, this assumption cannot explain the order-switching cost found in Subtask 2 even given long SOA (Luria & Meiran, 2003).

Finally, Logan and Gordon's (2001) model assumes a hierarchical order representation, although this assumption is not specifically modelled. This would enable their model to account for any order-switching cost effects. In the General Discussion we discuss how these models can account for our results regarding bottom-up and top-down order control.

The current research

Our aim was to investigate bottom-up and top-down online order control in the PRP paradigm. According to our model, subtask order is determined by both bottom-up and top-down processes. Experiments 1a and 1b were designed to replicate the three-way interaction between order switch, SOA, and CTI in R2 found by Luria and Meiran (2003). This interaction is critical for our explanation; in the original study only the planned contrast was significant, while the standard test of the interaction was not.

Experiments 2 and 3 were mirror images of one another. In Experiment 2 we removed the opportunity for bottom-up order control, while in Experiment 3 we removed the opportunity for top-down order control. According to our framework, the reason for the overadditive interaction between order switch and SOA is bottom-up order activation. It therefore follows that removing the opportunity for bottom-up control would reduce or even eliminate overadditivity. In contrast, removing the opportunity for top-down control would enhance overadditivity.

Our analysis is concentrated on RT2. The reason is that according to our framework, we predicted to find larger bottom-up effects after the presentation of S2. This means that the processing of R1 has already been started, and given long or even intermediate SOA, R1 could have already been selected by the time S2 was presented so it would be less affected by the bottom-up activation. Thus, we expected to find similar bottom-up effects on RT1 and RT2, but RT1 effects would probably be smaller than those in RT2.

EXPERIMENT 1A

Our account is based upon a trend towards three-way interaction between order switch, SOA, and CTI (Luria & Meiran, 2003, Exp. 2). Specifically, we argue that the overadditive interaction between SOA and order switch in R2 is only evident in short preparation time (short CTI). If there is sufficient preparation before the presentation of S1, this interaction becomes additive. Thus, it was important to replicate this trend (it was nonsignificant in the original study) before proceeding to Experiments 2 and 3. In an attempt to increase the statistical power of this interaction, we used a much larger sample (49 participants as opposed to only 12 in the original study) and included only two preparation intervals (a short one and a long one). The other conditions were the same as those in the original study.

Method

Participants

A total of 49 undergraduate students from Ben-Gurion University 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. (35.6-cm) monitor controlled by software written in MEL. We used the letters B and D (subtending approximately 0.38° × 0.28° of a visual angle from a viewing distance of 60 cm) and rectangles in the colours 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 colour 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 from 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 colour stimulus (both keys are positioned on the left side of a QWERTY keyboard). 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 are positioned on the right side of a QWERTY keyboard). The letter and the colour rectangle were presented very close to each other, approximately 0.38° from one another.

Design and procedure

All participants took part in a single 45-minute session. The first three blocks were considered practice and consisted of 40 trials, each. In the first two practice blocks, the order of the subtasks was constant (first block: colour then letter, second block: letter then colour). In the third practice block the order of the subtask was randomly determined in each trial (either colour then letter or letter then colour). The remaining four experimental blocks consisted of 55 trials each, with a randomly determined subtask order. Consequently, the order could change relative to the preceding trial (an order switch) or repeat relative to the preceding trial (an order no-switch).

A trial began with the presentation of a fixation point 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 and always above S1. After a random CTI of 300 or 1,200 ms, S1 was presented, followed by S2, separated by one of three randomly determined SOAs (100, 250, or 750 ms). All stimuli remained visible until the second response was emitted. The colour stimulus was always presented on the left side of the fixation point, and the letter stimulus was always presented on the right side. After the second response was emitted there was a pause of 1,200 ms until the next trial began.

Participants received written instructions to respond to each stimulus as quickly as possible while maintaining high accuracy. They were also encouraged to respond to the first stimulus as quickly as possible. Previous studies using the PRP paradigm identified a strategy sometimes used by participants who group their responses; that is, they 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 S1 was presented, and after participants made their R1, the trial ended, and the next trial began.

Results

All trials with an error in either R1 or R2 were excluded from the RT analysis. RTs greater than 4,500 ms or less than 100 ms were also omitted from the RT analysis. In addition, "catch trials" (in which only one stimulus was presented, which occurred on 5% of the trials) were not analysed. Overall 7% of the trials were excluded from the analysis. We first report the RT2 results, which are the focus of the current research, and then report the RT1 where we expect to find the same patterns of results but probably weaker (because bottom-up activation is larger in RT2). The alpha level was set at .05 in all the experiments.

RT2

An analysis of variance (ANOVA) on RT2 with order switch (switch vs. no switch), SOA (100, 250, or 750 ms), and CTI (300 or 1,200 ms) as independent variables yielded significant effects that included order switch, $F(1, 48) = 114.30$, $MSE = 22{,}117.50$; SOA, $F(2, 96) = 399.84$, $MSE = 15{,}980.15$; CTI, $F(1, 48) = 10.47$, $MSE = 12{,}182.46$; Order Switch × SOA, $F(2, 96) = 7.31$,

$MSE = 8,352.23$; Order Switch × CTI, $F(1, 48) = 9.13$, $MSE = 8,646.94$; SOA × CTI, $F(2, 96) = 6.11$, $MSE = 8,300.12$, and Order Switch × SOA × CTI, $F(2, 96) = 3.33$, $MSE = 6,580.30$. The presence of a significant three-way interaction replicates a similar trend found by Luria and Meiran (2003). This three-way interaction is presented in Figure 2. Importantly, the reduction in order-switching cost between the short and long SOAs (indicating the size of the overadditive interaction) was significant in the short CTI, $F(1, 48) = 16.30$, $MSE = 7,482.62$, but nonsignificant in the long CTI, $F(1, 48) = 1.9$, $p = .17$. The size of the overadditive interaction was 101 ms in short CTI and only 31 ms when CTI was long.

A similar ANOVA on the proportion of errors (PE) revealed a significant main effect of order switch, $F(1, 48) = 8.82$, $MSE = 0.004$, due to a reduction of .016 in PE between the order switch and the order no-switch conditions. The interaction between SOA and CTI was also significant, $F(2, 96) = 3.26$, $MSE = 0.003$. For short CTI the PE in the short SOA was .072, in the intermediate SOA it decreased to .051, and in the long SOA it increased to .064. This pattern was reversed for the long CTI: When SOA was short the PE was .054, while PE increased to 0.63 in the intermediate SOA and then decreased to.052 in the long SOA. The overall error rate was .06.

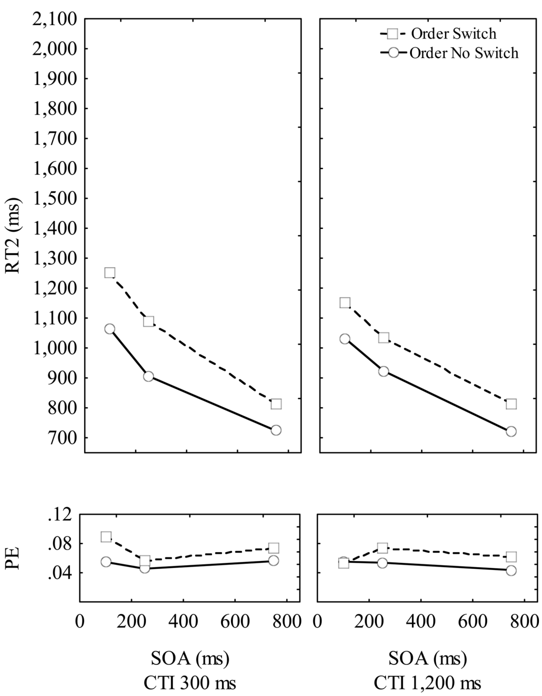

Figure 2. *Mean RT2 (ms) and mean PE as a function of stimulus onset asynchrony (SOA) and cue target interval (CTI) in Experiment 1a. RT2 = RT in the first subtask. PE = proportion of errors.*

RT1

The trends in RT1 were generally similar to those in RT2, but sometimes smaller in magnitude and did not reach significance. The design of the ANOVA was the same as that in the previous analysis. It yielded significant main effects of order switch, $F(1, 48) = 101.87$, $MSE = 27,008.78$, SOA, $F(2, 96) = 37.70$, $MSE = 14,874.78$, and CTI, $F(1, 48) = 41.04$, $MSE = 15,478.17$. The interaction between order switch and CTI was also significant, $F(1, 48) = 11.42$, $MSE = 10,476.86$. This interaction reflected a reduction of 56 ms in order-switching cost due to preparation (from 165 ms to 109 ms in the short and the long CTI, respectively). The three-way interaction between order switch, SOA, and CTI approached significance, $F(2, 96) = 2.82$, $p = .06$. As can be seen in Figure 3, when CTI was short there was a nonsignificant reduction of 41 ms in the order-switching cost with increasing SOA, $F(1, 48) = 2.29$, $p = .13$. Albeit smaller than the 101-ms interaction found in RT2, the same pattern was found both in RT1 and in RT2. In contrast, in the long CTI this pattern was reversed, and the order-switching cost increased by 42 ms with increasing SOA, $F(1, 48) = 4.18$, $MSE = 5,422.02$. Note, however, that the long CTI condition is not predicted to show evidence for stimulus-based order-set activation. Indeed, we found additive effects of SOA and order switch in RT2, long CTI.

A similar ANOVA on PE revealed significant main effects of order switch, $F(1, 48) = 54.06$, $MSE = 0.002$, and CTI, $F(1, 48) = 5.88$,

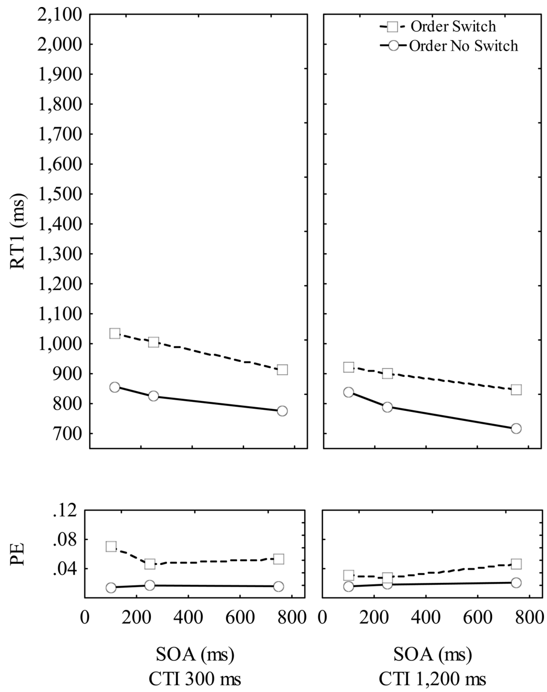

Figure 3. *Mean RT1 (ms) and mean PE as a function of stimulus onset asynchrony (SOA) and cue target interval (CTI) in Experiment 1a. RT1 = RT in the first subtask. PE = proportion of errors.*

$MSE = 0.002$. The interaction between order switch and CTI was also significant, $F(1, 48) = 12.38$, $MSE = 0.001$. This interaction reflected a .02 reduction in PE in the order switch condition with increasing CTI, while in the no-switch condition the difference was only .002 and was in the opposite direction. The overall error rate was .032.

Discussion

Most importantly, we were able to replicate the trend for a three-way interaction between order switch, SOA, and CTI in R2 that was found by Luria and Meiran (2003). In this experiment, the interaction was significant as a result of increasing its statistical power. As predicted, the overadditive interaction between order switch and SOA was significant in the short CTI but not when CTI was long. This suggests that the order-set was reconfigured when there was enough time for the top-down cue-based processes to complete their course, leaving little room for additional activation of the set by bottom-up factors.

Note that even in the long preparation interval there was a pattern towards overadditivity in R2 (although it was not significant). Such a result accords with our hypothetical mechanism because we do not claim that activation of the order-set is only cue based or based upon copying S1−S2 order. We do argue, however, that those processes take an important part in online order control and that bottom-up S1−S2-based activation is largely responsible for the aforementioned overadditive interaction. Further elaboration on these issues is found in the General Discussion.

We also found an overadditive pattern in the short preparation time in R1. This pattern is in line with our argument that bottom-up activation affects mostly R2 (after S2 was presented), but also affects R1 to a lesser extent. When preparation time was long, and presumably there was much less need for bottom-up control, the overadditive pattern changed also in R1 (and even reversed).

We replicated additional core results of Luria and Meiran (2003)—namely, we found an order-switching cost in R1 and R2 that was reduced (but not abolished) by preparation. The size of the switching cost and the other effects were also roughly identical in the two studies. In R1 the switching cost was 137 ms (compared to 124 ms in the original study), and preparation reduced it by 56 ms (compared to 48 ms in the original study). In R2 there was an overall switching cost of 131 ms (compared to 117 ms in the original study), which was reduced by 46 ms due to preparation (compared to 50 ms in the original study). Given long SOA, RT2 was shorter than RT1. Averaging the two CTIs in the switch condition, RT2 was 69 ms shorter than RT1, $F(1, 48) = 16.57$, $MSE = 7096.27$. In the no-switch condition, the difference was in the same direction but smaller (24 ms), and it did not reach statistical significance, $F(1, 48) = 2.32$, $p = .13$. This is in line with our assumption that when Subtask 1 was performed both S−R rules were active (maybe not to the same extent), but when

Subtask 2 was performed the S–R rules for Subtask 1 were not activated (see also Logan & Gordon, 2001). Accordingly, it is faster to perform a given task as Subtask 2 (long SOA) than as Subtask 1.

Before turning to test our model, we need to generalize our findings and to rule out an alternative explanation. In Experiment 1a, we used two manual responses so that order switch was confounded with hand switching, thus it is possible to argue that order switching was found because of the need to switch the responding hands. Luria & Meiran (2003) addressed this alternative account. In their third experiment, the responding hand order was constant but subtask order was still random. Interestingly, subtask order switching was found even when it was not accompanied by hand switching, indicating that the cost for changing the subtask order was not an outcome of hand switching. Nevertheless, in order to further generalize this conclusion, we replicated Experiment 1a, using one manual and one vocal response. It is most important to replicate the three-way interaction between CTI, SOA, and order switch in RT2, so we can safely argue that using two manual responses is not crucial for finding order-switching cost or for the aforementioned triple interaction serving as evidence for bottom-up activation of the order-set.

EXPERIMENT 1B

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

Method

Participants
A total of 14 undergraduate students with similar attributes to those in Experiment 1a took part in this experiment.

Apparatus and stimuli
We used the letters B, D, and P, and rectangles in the colours blue (MEL Color 1), pink (MEL Color 5), and green (MEL Color 10). Participants pressed the *z* (left), *x* (middle), and *c* (right) keys with the middle and index fingers of their left hand, respectively, in responding to the colour stimulus. Participants responded vocally to the letter stimulus, and their choice was recorded by the experimenter.

Design and procedure
The design of the practice blocks was similar to that in Experiment 1a. The remaining six experimental blocks consisted of 72 trials each, all of them involved a random subtask order. The CTI was either 150 or 1,000 ms (randomly determined), and the SOA was 50, 300, or 800 ms (randomly determined).

Results

By using the same criterion as that in Experiment 1a, we excluded overall 9% of the trials (out of which 5% were “catch trials”). Two separate analyses were performed on RT results, of RT2 and of RT1.

RT2
An ANOVA on RT2 with order switch (switch vs. no switch), SOA (50, 300, or 800 ms), and CTI (150 or 1,000 ms) as independent variables yielded significant effects that included order switch, $F(1, 13) = 47.49$, $MSE = 5{,}386.84$; SOA, $F(2, 26) = 358.76$, $MSE = 11{,}757.46$; CTI, $F(1, 13) = 116.76$, $MSE = 7{,}005.32$; Order Switch × CTI, $F(1, 13) = 13.76$, $MSE = 4{,}406.90$; and SOA × CTI, $F(2, 26) = 31.85$, $MSE = 4{,}148.15$.

Most importantly, the three-way interaction between order switch, SOA, and CTI was significant, $F(2, 26) = 3.54$, $MSE = 2{,}863.41$ (see Figure 4), replicating a similar result from Experiment 1a. The reduction in order-switching cost between the short and long SOA (indicating the size of the overadditive interaction) was 66 ms in the short CTI condition, $F(1, 13) = 1.69$, $p = .055$ (one-tailed), but only 19 ms in the long CTI condition, $F < 1$.

A similar ANOVA on the PE revealed significant main effects: order switch, $F(1, 13) = 8.66$, $MSE = 0.001$, indicating more errors in switch trials (.04) than in repeat trials (.03); SOA, $F(2, 26) = 10.84$, $MSE = 0.002$; and CTI, $F(1, 13) = 7.18$, $MSE = 0.002$. In addition, the interaction between SOA and CTI was significant, $F(2, 26) = 7.39$, $MSE = 0.001$, indicating that the PE was highest (.09) when both CTI and SOA were short relative to all other conditions. The overall PE was .04.

RT1

The design of the ANOVA was the same as that in the previous analysis. It yielded significant main effects of order switch, $F(1, 13) = 50.86$, $MSE = 7{,}371.00$, SOA, $F(2, 26) = 16.59$, $MSE = 4{,}604.71$, and CTI, $F(1, 13) = 131.44$, $MSE = 8{,}159.14$. The interactions between order switch and CTI, $F(1, 13) = 20.92$, $MSE = 3{,}163.65$, and between SOA and CTI, $F(2, 26) = 18.76$, $MSE = 2{,}010.49$, were also significant. The order switch by SOA interaction indicated that order switch cost was reduced from 134 ms to 55 ms along the CTI. The SOA by CTI interaction indicated that SOA had an effect only in the short CTI condition, $F(1, 13) = 30.04$, $MSE = 7{,}173.23$, but not in the long CTI condition ($F = 2.12$, $p = .16$). The three-way interaction was not significant, $F < 1$ (see Figure 5).

A similar ANOVA on the PE revealed a significant main effect of order switch, $F(1, 13) = 7.73$, $MSE = 0.001$, SOA, $F(2, 26) = 11.45$, $MSE = 0.002$, and CTI, $F(1, 13) = 10.85$, $MSE = 0.001$. In addition, the interactions between order switch and SOA, $F(2, 26) = 8.18$, $MSE = 0.0007$ (indicating that the switch condition, short SOA yielded a PE of .08, relative to less than .04 in all other conditions), and SOA × CTI, $F(2, 26) = 12.91$,

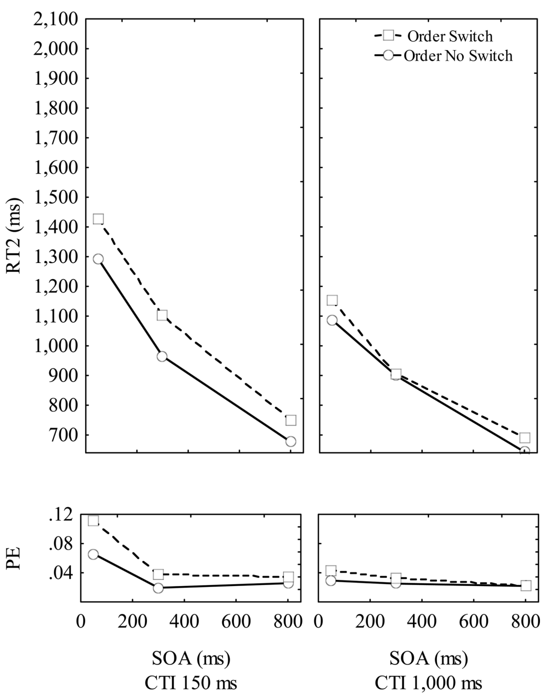

Figure 4. *Mean RT2 (ms) and mean PE as a function of stimulus onset asynchrony (SOA) and cue target interval (CTI) in Experiment 1b. RT2 = RT in the first subtask. PE = proportion of errors.*

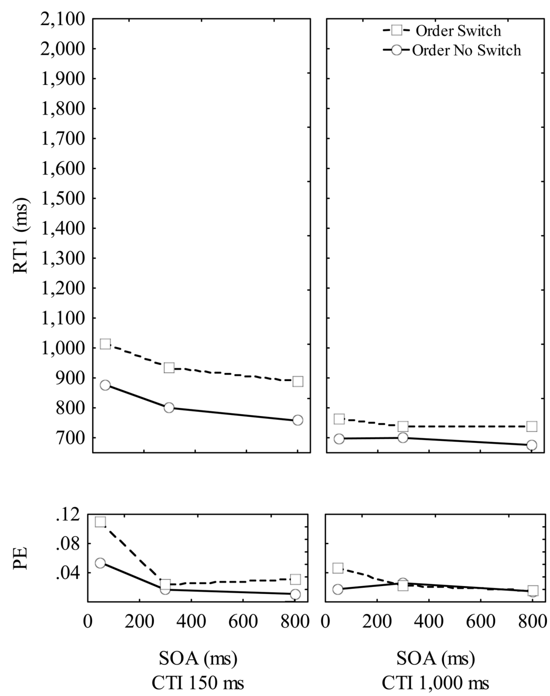

Figure 5. *Mean RT1 (ms) and mean PE as a function of stimulus onset asynchrony (SOA) and cue target interval (CTI) in Experiment 1b. RT1 = RT in the first subtask. PE = proportion of errors.*

$MSE = 0.0008$ (indicating that the short CTI and short SOA yielded a PE of .08, relative to about .03 or less in all other conditions), were also significant. The overall PE was .04.

Discussion

Most importantly, we were able to replicate the three-way interaction between order switch, SOA, and CTI in R2 found in Experiment 1a, but this time using one vocal and one manual response. The size of overadditive interaction was 66 ms in the short CTI but only 19 ms when CTI was long. Thus we argue that the results of Experiment 1a are not a special outcome of using two manual responses, and they can be generalized to other response modes. Replicating the results of Experiment 1a further strengthens our argument that the order-set was reconfigured when there was enough time for the top-down, cue-based processes to complete their course, leaving little room for additional activation of the set by bottom-up factors.

In summary, Experiments 1 and 1b served as a basis for our arguments regarding top-down and bottom-up order control. Now, we turn to directly test this account by removing the opportunity for bottom-up order control (Experiment 2) and for top-down order control (Experiment 3).

EXPERIMENT 2

According to our model, the reason for the overadditive interaction between order switch and SOA in R2 is the bottom-up order activation from S1–S2. Specifically, we argue that there is more need for order control in the case of an order switch, either because the order-set is relatively inactive, or because of possible retrieval competition due to the alternative order-set being active, or both. Part of this order control is achieved in a bottom-up manner, by copying the S1–S2 order of presentation. This mechanism is more effective as the SOA is prolonged because it becomes easier to determine the stimulus presentation order. In addition, when the order repeats itself relative to the preceding trial, there is less need for order control because the correct order-set is still active. Viewed from a different angle, the bottom-up order control is less effective in no-switch trials where the order-set is already in a relatively active state. The outcome of these two processes (increasing bottom-up activation as SOA is prolonged, affecting mostly order switch trials) is an overadditive interaction between order switch and SOA.

In this experiment we prevented bottom-up order control by presenting bivalent stimuli—namely, the stimuli for both subtasks were coloured letters so that each stimulus was compatible with both the colour and the letter subtasks. When bivalent stimuli were presented it was impossible to determine subtask order from S1–S2 presentation; hence we eliminated any bottom-up order control, leaving only top-down (cue-based) control. If the reason for the overadditive interaction between order switch and SOA is indeed bottom-up activation, using bivalent stimuli should cause this interaction to become additive (to disappear). In addition, we used univalent stimuli in a control condition. These stimuli were the same as those in Experiment 1a, so that each stimulus type could serve in one subtask only. This condition should have replicated the results from Experiments 1a (and 1b). In summary, we predicted that, in the univalent condition, the interaction between order switch and SOA would be overadditive. In contrast, for the bivalent condition we predicted that SOA and order switch would have additive effects.

Method

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

Participants

A total of 54 undergraduate students with similar attributes to those in Experiment 1a took part in this experiment.

Apparatus and stimuli

The letter stimuli in the univalent condition were the same as those in Experiment 1a. The colour stimuli were rectangles coloured light green (MEL Color 10) and light magenta (MEL Color 13). For the bivalent condition we used the same letters, but they were coloured either in light green or in light magenta. We used a new set of order cues. The cues for the colour task and the letter task were the Hebrew words for "colour" and "letter", respectively (in Hebrew both words have three letters), subtending approximately $0.38^\circ \times 1.05^\circ$.

Design and procedure

All participants took part in a one-hour session. The first four blocks in each session were considered practice and consisted of 25 trials. The remaining eight experimental blocks consisted of 48 trials each. The first three practice blocks were the same as those in Experiment 1a. In the fourth practice block the order was random, and the stimuli were bivalent (see below).

We manipulated bottom-up control by including two conditions. In the univalent condition, the stimuli were either a white letter or a coloured rectangle (as in Experiment 1a), so that each stimulus was compatible with only one subtask. In the bivalent condition, the stimuli were coloured letters so that each stimulus was compatible with both subtasks. In the bivalent condition subtask order cannot be determined from stimulus order, and the only possible method for determining subtask order is using the cue. Each participant performed four consecutive blocks in the univalent condition and four consecutive blocks in the bivalent condition. Half of the participants started out on the univalent blocks and then moved on to the bivalent blocks. For the other half the order was reversed.

A trial began with the presentation of a fixation point for 500 ms, which was then replaced by an instructional cue indicating the order of stimuli in the upcoming trial. After a fixed CTI of 250 ms, S1 was presented, followed by S2, separated by one of three SOAs (100, 300, or 750 ms). The first stimulus (the colour, the letter, or the coloured letter) always appeared below the fixation point, and the letter stimulus always appeared above the fixation point. After the second response, there was an interval of 1,500 ms before the fixation point for the next trial was presented.

Results

Two participants were excluded from the analysis because they had a very slow overall RT (slower than 2,000 ms in both R1 and R2). The analytic procedure was the same as that in Experiment 1a, except that instead of CTI, valence was the third independent variable. By using the same criterion as that in Experiment 1a, we excluded overall 6% of the trials (out of which 5% were "catch trials"). Two separate analyses were performed on RT results, of RT2 and of RT1.

RT2

An ANOVA on RT2 with valence (bivalent vs. univalent), order switch (switch vs. no switch), and SOA (100, 300, or 750 ms), as independent variables yielded significant main effects: valence, $F(1,\ 52) = 276.50$, $MSE = 121{,}536.77$, indicating that mean RT in the bivalent condition was 460 ms slower than that in the univalent condition; order switch, $F(1,\ 52) = 197.65$, $MSE = 17{,}926.61$, indicating an order-switching cost of 149 ms in RT2; and SOA, $F(2,\ 104) = 1{,}247.03$, $MSE = 12{,}226.27$; the overall PRP effect was 527 ms. The interactions between valence and SOA, $F(2,\ 104) = 7.00$, $MSE = 10{,}186.04$, and between order switch and SOA, $F(2,\ 104) = 6.00$, $MSE = 8{,}962.01$, were also significant. The interaction between valence and SOA indicates that the effect of valence was overadditive with SOA: The difference between the bivalent condition and the univalent condition was 475 ms in the short SOA, but only 418 ms in the long SOA, $F(1,\ 52) = 7.39$, $MSE = 11{,}823.79$. The interaction between order switch and SOA was also overadditive: The difference between the order switch and the order no-switch decreased from 185 ms in the short SOA to 125 ms in the long SOA, $F(1,\ 52) = 10.29$,

$MSE = 9{,}432.10$. This trend replicates previous results by De Jong (1995), Luria and Meiran (2003), and the present Experiments 1a and 1b.

Of greatest interest is the three-way interaction between valence, order switch, and SOA. This interaction was significant, $F(2,\ 104) = 3.49$, $MSE = 8{,}560.03$ (see Figure 6). As predicted, a series of contrasts showed that the overadditive interaction between order switch and SOA (short vs. long) was significant in the univalent condition, $F(1,\ 52) = 19.02$, $MSE = 7{,}287.7$, but was not significant in the bivalent condition, $F < 1$, reflecting the fact that the size of this interaction was 19 ms in the bivalent condition but 101 ms in the univalent condition.

A similar ANOVA on PE revealed significant main effects of valence, $F(1,\ 52) = 21.07$, $MSE = 0.003$, and order switch, $F(1,\ 52) = 24.42$, $MSE = 0.002$. The interaction between valence and order switch was significant, $F(1,\ 52) = 7.40$, $MSE = 0.001$, indicating that the difference in PE was .026 in the bivalent condition, but it was only .009 in the univalent condition. The overall PE was .04.

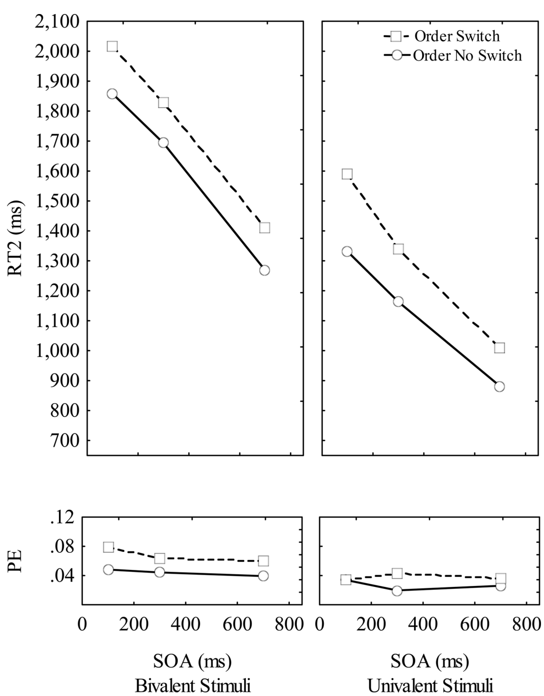

Figure 6. *Mean RT2 (ms) and mean PE as a function of stimulus onset asynchrony (SOA) and valence in Experiment 2. RT2 = RT in the first subtask. PE = proportion of errors.*

RT1

Overall, we observed the same pattern in RT1 as in RT2, although not significant. The design of the ANOVA was the same as that in the previous analysis. It yielded significant main effects: valence, $F(1,\ 52) = 119.43$, $MSE = 114{,}984.85$, Q3
indicating that the bivalent condition was 293 ms slower than the univalent condition; order switch, $F(1,\ 52) = 236.15$, $MSE = 14{,}187.28$, indicating that order switch trials were 145 ms slower than order no-switch trials; and SOA, $F(2,\ 104) = 29.89$, $MSE = 9{,}102.48$, indicating a decrease in RT along SOA from 1,141 ms (short SOA), to 1,120 ms (intermediate SOA), to 1,071 ms (long SOA).

The interaction between valence and order switch, $F(1,\ 52) = 5.16$, $MSE = 7{,}561.49$, was significant, indicating that the order-switching cost was larger for the univalent stimuli than for the bivalent stimuli (159 and 131 ms, respectively). The three-way interaction between valence, order switch, and SOA was not significant, $F = 1$ (see Figure 7). However, the same pattern as that in R2 was also observed in R1—namely, in the bivalent condition the effect of order switch and SOA was additive ($F < 1$, 3 ms), but it was overadditive in the univalent condition, $F(1,\ 52) = 5.28$, $MSE = 5{,}348.33$, indicating that order-switching cost was reduced by 47 ms along the SOA.

A similar ANOVA on PE revealed significant main effects of valence, $F(1,\ 52) = 15.78$, $MSE = 0.002$, and order switch, $F(1,\ 52) = 34.84$, $MSE = 0.001$. Error proportion was higher in the bivalent condition (.03) than in the univalent condition (.02), and was higher in the order switch condition (.03) than in the order no-switch condition (.02). No other effects approached significance, and the overall RT1 error rate was .03.

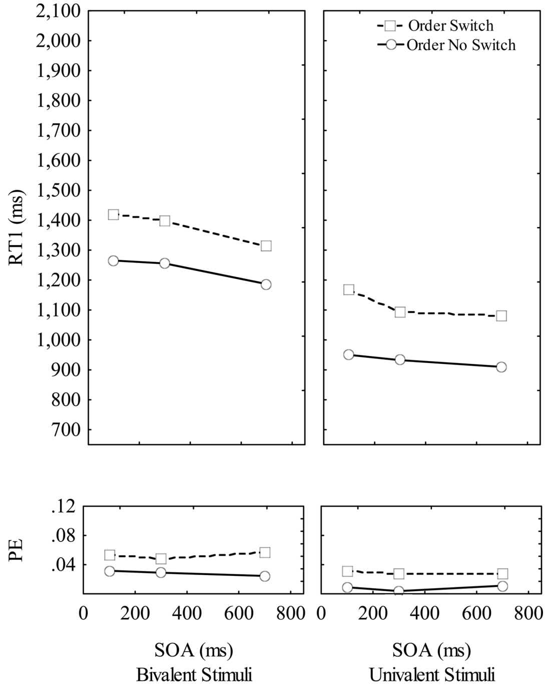

Figure 7. *Mean RT1 (ms) and mean PE as a function of stimulus onset asynchrony (SOA) and valence in Experiment 2. RT1 = RT in the first subtask. PE = proportion of errors.*

Discussion

Our prediction was borne out. The interaction between SOA and order switch in R2 was significant (overadditive) only in the univalent condition. Exactly the same pattern was observed for RT1 (although not significant probably because bottom-up activation is larger in RT2, because it relies on S1−S2 presentation). We argue that in the bivalent condition there was no opportunity for the S1−S2 bottom-up order control that we discuss, which is why the effects of SOA and order switch were statistically additive. The size of the interaction between order switch and SOA was 101 ms in the univalent condition, but only 19 ms (nonsignificant) in the bivalent condition. This specific pattern was predicted by our model. Note that RTs were much slower in the bivalent condition. This probably reflects interference from the irrelevant dimension in S1 and S2, as discussed in the task-switching literature (Allport & Wylie, 2000; Meiran, 2000; Waszak, Hommel, & Allport, 2003).

We argue that "losing" the overadditive interaction in the bivalent condition is not a trivial finding. The reason is that overadditive interactions are evident when the general difficulty level in one factor increases, as if difficulty served to magnify an existing effect. However, the pattern we found here was just the opposite to what one would expect from such a difficulty magnification—namely, increasing task difficulty (the bivalent condition) caused the overadditive interaction to disappear.

EXPERIMENT 3

In this experiment, we eliminated the opportunity for cue-based, top-down order control. In the critical condition, we omitted the order cue and only manipulated the fixation-to-S1 interval in an analogous manner to the CTI manipulation. This manipulation enabled general, nonspecific preparation such as alertness (Posner & Boies, 1971) and predicting target onset (Niemi & Nataanen, 1981).

According to our reasoning, in the absence of an order cue, participants are forced to control the subtask order via copying S1−S2 order. If this bottom-up order control is responsible for the overadditive interaction between SOA and order switch, as we argue, preventing top-down (cue-based) control should increase this overadditivity. In a control condition, similar to the present Experiments 1a and 1b, we presented an order cue and manipulated the CTI. The reason for varying the CTI was to constrain our interpretation. First, we predicted that, in the control condition, the overadditivity would disappear in the longest CTI, as found already, showing that, when possible, top-down control can dominate. However, such a reduction in bottom-up control was not predicted for the cue-absent condition. Second, according to Koch (2001), participants become involved in cue-based preparation towards a task switch only when being exposed to CTI variation. Although Koch's observation refers to single-step tasks, we suspected that a similar process would also be found here.

Method

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

Participants

A total of 46 students with similar attributes to those in Experiments 1 and 2 took part in this experiment.

Design and procedure

All participants took part in a single one-hour session. Practice blocks were the same as those in Experiment 1a, except that the fourth practice block was in the cue-absent condition (see below). The remaining 10 experimental blocks consisted of 48 trials each. Half of the participants performed the five blocks of the cue-present condition first and then went on to the five blocks of the cue-absent condition, while for the other half of the participants this order was reversed.

In the cue-present condition, an instructional cue that signalled the upcoming subtask order was presented in each trial. The cues were the same as those in Experiment 2 (the Hebrew words for "colour" and "letter"), and the time between the presentation of the cue and the presentation of the S1 (the CTI) was randomly determined in each trial (either 150 or 700 ms). The second condition was the cue-absent condition, in which S1 appeared after the fixation point without an instructional cue. Thus, subtask order was determined solely by stimulus order. The time between the fixation and the first stimulus was randomly determined, and the fixation-to-S1 intervals were the same as the CTIs (either 150 or 750 ms).

Results

The analytic procedure was the same as that in Experiment 2, except that instead of valence, cue (present, absent) served as the third independent variable. In addition, a fourth independent variable was included. In this experiment it was termed preparation time and not CTI because in the cue-absent condition it was the fixation-to-S1 interval that varied. Using the same criteria as those in previous experiments, we excluded 5.5% of the trials from the analysis. Two separate analyses were performed on the RT results, one for RT1 and one for RT2.

RT2

An ANOVA on RT2 with cue (present, absent), order switch (switch vs. no switch), SOA (100, 300, or 750 ms), and preparation time (150 or 700 ms) as independent variables yielded significant main effects: order switch, $F(1, 45) = 179.57$, $MSE = 32{,}695.77$, indicating an overall order-switching cost of 146 ms; SOA, $F(2, 90) = 782.18$, $MSE = 24{,}670.38$; the size of the PRP effect was 444 ms; and preparation time, $F(1, 45) = 103.96$, $MSE = 27{,}540.34$; there was a 102-ms reduction in RT2 from the short to the long preparation time.

All the two-way interactions were significant: cue and order switch, $F(1, 45) = 8.29$, $MSE = 7{,}637.22$, indicating that order-switching cost was greater in the cue-absent condition than in the cue-present condition (161 and 130 ms, respectively); cue and SOA, $F(2, 90) = 9.61$, $MSE = 8{,}621.62$, indicating that the PRP effect was more pronounced in the cue-absent condition (460 ms) than in the cue-present condition (429 ms), $F(1, 45) = 4.69$, $MSE = 9{,}811.45$; order switch and SOA, $F(2, 90) = 14.41$, $MSE = 9{,}571.81$, indicating that the PRP effect was larger in the case of an order switch (479 ms) than for an order no-switch (409 ms), $F(1, 45) = 19.96$, $MSE = 11{,}774.92$; cue and preparation time, $F(1, 45) = 94.40$, $MSE = 11{,}412.38$, indicating that preparation affected the cue-present condition (164 ms) more than the cue-absent condition (39 ms); order switch and preparation time, $F(1, 45) = 30.69$, $MSE = 11{,}005.86$, indicating that preparation time reduced the switching cost from 181 ms in the short preparation time to 111 ms in the long preparation time. The two-way interaction between SOA and preparation time was also significant,

$F(2, 90) = 4.80$, $MSE = 10{,}279.84$. The decrease in RTs due to SOA was larger in the long preparation time (464 ms) than in the short preparation time (425 ms), $F(1, 45) = 6.81$, $MSE = 10{,}471.12$.

The three-way interactions between cue, order switch, and SOA, $F(2, 90) = 3.10$, $MSE = 8{,}206.61$, cue, order switch, and preparation time, $F(1, 45) = 13.71$, $MSE = 11{,}537.83$, and cue, SOA, and preparation time, $F(2, 90) = 3.60$, $MSE = 9{,}145.85$, were also significant. Importantly, the four-way interaction between cue, order switch, SOA, and preparation time did not reach significance, $F(2, 90) = 2.35$, $p = .10$, but in order to test our predictions, we conducted a planned comparison adopting a criterion of one-tailed significance. In this comparison, we contrasted the cue conditions (present vs. absent), switch conditions (switch vs. no switch) and the two extreme SOAs. This comparison was significant, $t(45) = 1.79$, $p < .05$. In order to further verify our prediction we made two additional one-tailed comparisons. We indexed the overadditive interaction as the decrease of the order-switching cost between the short and the long SOA. We then compared the size of this index between the cue-present condition and the cue-absent condition. The first comparison was limited to short preparation time, when top-down preparation was incomplete regardless of cue condition. This planned comparison was not significant, $t(45) = 0.07$, and the size of the overadditive interaction between order switch and SOA was 78 ms in the cue-present condition and 58 ms in the cue-absent condition. The second comparison was limited to the long preparation time, when, in the cue-present condition, there was ample room for top-down processes. Accordingly, this time the comparison was significant, $t(45) = 2.44$, $p < .05$; the size of the overadditive interaction between order switch and SOA was 35 ms in the cue-present condition but 112 ms in the cue-absent condition—namely, when there were top-down processes (long preparation time), the interaction between order switch and SOA was more pronounced in the cue-absent condition than in the cue-present condition. In the short preparation time (when there are mainly bottom-up processes) this overadditive interaction was statistically the same when comparing the cue-present and the cue-absent conditions (see Figure 8).

A similar ANOVA focusing on PE revealed only a significant main effect of preparation time, $F(1, 45) = 8.72$, $MSE = 0.002$. The error rate was higher for the short preparation time (.05) than for the long preparation time (.04). No other effects approached significance. The overall error rate was .05.

RT1

Overall, we observed the same pattern as that in RT2. The design of the ANOVA was the same as that in the previous analysis. It yielded significant main effects: cue, $F(1, 45) = 35.81$, $MSE = 34{,}629.08$, indicating that RT was 67 ms faster when a cue was presented; order switch, $F(1, 45) = 240.45$, $MSE = 24{,}459.24$, indicating an order-switching cost of 146 ms in RT1; SOA, $F(2, 90) = 38.08$, $MSE = 14{,}715.44$, indicating a decrease of 72 ms from the short to the long SOA; and preparation time, $F(1, 45) = 180.55$, $MSE = 25{,}948.23$, indicating that preparation time had decreased overall RTs by 130 ms.

The interactions between cue and order switch, $F(1, 45) = 13.60$, $MSE = 6{,}813.55$, and between cue and preparation time, $F(1, 45) = 115.95$, $MSE = 11{,}544.93$, were also significant. The three-way interaction including these variables (Cue × Order Switch × Preparation Time) was also significant, $F(1, 45) = 13.08$, $MSE = 9{,}211.04$. It appears that, in the cue-present condition, preparation reduced the switching cost by 105 ms, $F(1, 45) = 31.83$, $MSE = 11{,}977.01$, but in the cue-absent condition, switching cost was only modestly reduced by 22 ms, $F(1, 45) = 2.34$, $p = .13$. The three-way interaction between cue, order switch, and SOA was also significant, $F(2, 90) = 3.16$, $MSE = 6{,}922.00$ (see Figure 9). The simple interaction between order switch and SOA was significant in the cue-absent condition, $F(2, 44) = 3.58$, $MSE = 7{,}421.53$, but this simple interaction was

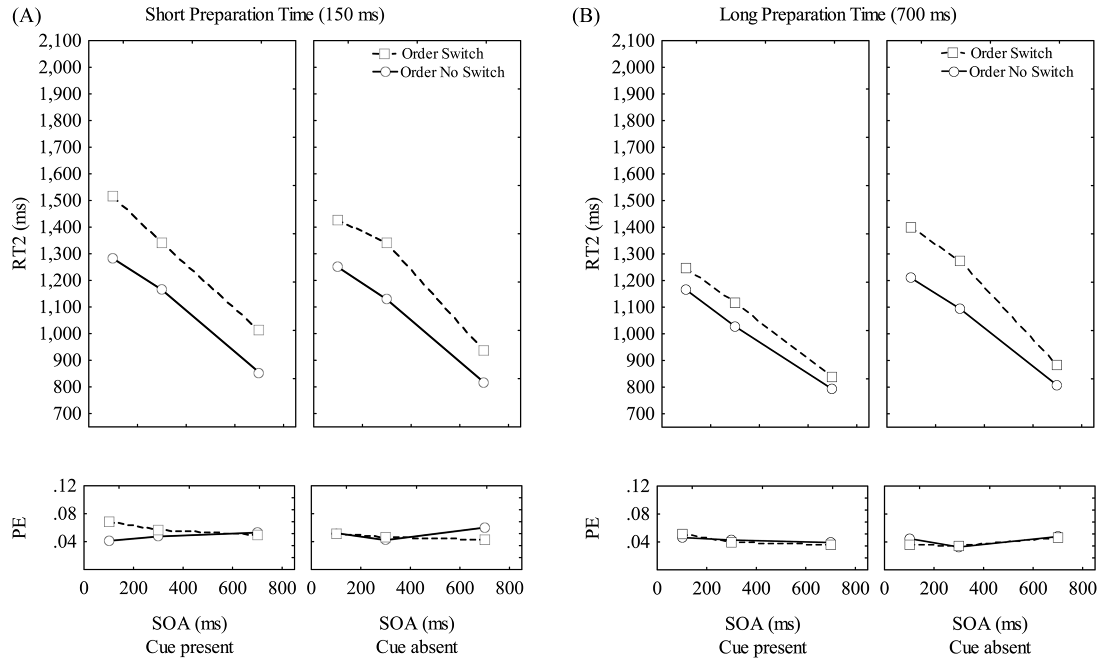

Figure 8. *Mean RT2 (ms) and mean PE as a function of stimulus onset asynchrony (SOA), preparation time, and cue in Experiment 3. Left panel: short preparation time. Right panel: long preparation time. RT2 = RT in the first subtask. PE = proportion of errors.*

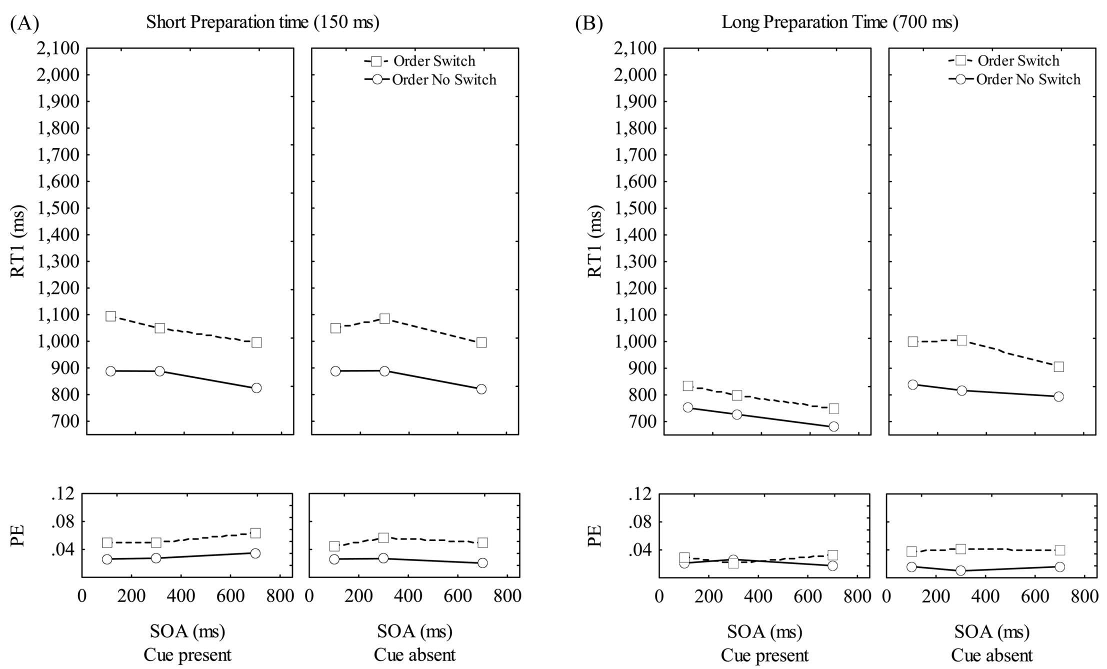

Figure 9. *Mean RT1 (ms) and mean PE as a function of stimulus onset asynchrony (SOA), preparation time, and cue in Experiment 3. Left panel: short preparation time. Right panel: long preparation time. RT1 = RT in the first subtask. PE = proportion of errors.*

not significant in the cue-present condition, $F(2, 44) = 1.09$.

Again the pattern of results for RT1 was (in general) the same as that for RT2, only smaller and mostly nonsignificant. When preparation time was short, the size of the overadditive interaction between order switch and SOA was 31 ms in the cue condition and 10 ms in the no-cue condition. When preparation time was long, the size of this interaction was 48 ms in the no-cue condition, $F(1, 45) = 4.09$, $MSE = 6{,}436.76$, but this pattern was reversed (−14 ms, *ns*) in the cue condition.

A similar ANOVA on PE revealed significant main effects of order switch, $F(1, 45) = 37.67$, $MSE = 0.003$, and preparation time, $F(1, 45) = 16.09$, $MSE = 0.003$. There were more errors when there was an order switch (.04) than when there was an order no-switch (.02), and error proportion was higher in the short preparation time (.03) than in the long preparation time (.02). The interaction between cue and order switch was also significant, $F(1, 45) = 5.61$, $MSE = 0.001$. The difference between order switch and order no-switch was more pronounced in the cue-absent condition (.026) than in the cue-present condition (.015). No other effects approached significance. The overall error rate was .03.

Discussion

As predicted, when the preparation interval was short, the overadditive interaction between SOA and order switch was apparent in both the cue-absent and the cue-present conditions. However, when the preparation interval was long, the overadditive interaction was only apparent in the cue-absent condition. We argue that when preparation time was long, it enabled top-down activation of the order-set. Hence, in the cue-present condition, there was no need for bottom-up order control. But, in the cue-absent condition, there was no top-down control, and all the control was bottom-up in nature. This resulted in an overadditive SOA by order switch interaction, even in the long preparation interval.

One could argue that our findings reflect the fact that, although the cue conditions were equal with respect to the cue/fixation-to-S1 interval, they differed with respect to the time allowed for set dissipation and the fixation-to-S1 interval—namely, in the cue-present condition, the fixation-to-S1 interval was either 650 or 1,200 ms (a constant 500-ms fixation plus a variable preparation time of 150 or 700 ms), but in the cue-absent condition, the fixation-to-S1 interval was either 150 or 700 ms (equal to preparation time in the cue-present condition).

Based on these differences between conditions, it is possible to argue that the overadditive interaction between SOA and order switch decreased as the fixation-to-S1 interval increased due to some sort of task-set decay process. There are two reasons to argue against this possibility. First, in the cue-absent condition, the size of the overadditive interaction *increased* numerically from 56 ms in the short preparation interval to 112 ms in the long preparation interval, $F(1, 45) = 2.08$, $p = .15$. Moreover, Luria and Meiran (2003) showed no effect of order-set dissipation on either RT or order-switching cost up to an intertrial interval of 3,100 ms.

GENERAL DISCUSSION

In this work, we presented a working framework for online order control in the PRP paradigm and tested some core predictions drawn from this framework regarding bottom-up and top-down order control. We focused specifically on the overadditive interaction between order switch and SOA in R2. According to our framework, the reason for the overadditivity is bottom-up order control that is based on "copying" the S1−S2 order of presentation. This bottom-up control was needed more in order switch trials (because of the relatively inactive state of the order-set), and it was enhanced as SOA was prolonged because it became easier to copy the S1−S2 order into mapping activation. Moreover, according to the framework, bottom-up order control and top-down (cue-based) order control interact.

Consequently, when the preparation interval is long enough for top-down processes to activate the order-set alone, the overadditive interaction is greatly reduced. This pattern was confirmed in Experiments 1a and 1b. In Experiment 2, we directly tested this prediction by eliminating the opportunity for bottom-up control. This was achieved by using a set of bivalent target stimuli on which both subtasks could be performed. This manipulation caused the overadditive interaction between SOA and order switch to decrease from 130 ms to a nonsignificant value of 16 ms. In Experiment 3, we eliminated the opportunity for top-down order control, thus emphasizing the role of bottom-up order control. As predicted, when preparation time was long, this manipulation increased the overadditive interaction relative to a condition in which top-down processes were present. However, when preparation time was short, and top-down control was not yet implemented, the overadditive interaction assumed a statistically similar size regardless of whether or not an order cue was present. The results from these three experiments support our framework that bottom-up and top-down order control interact, and that bottom-up control is, at the least, largely responsible for the overadditive interaction between SOA and order switch in R2.

Carryover from RT1 to RT2

Before discussing the implications of our findings, it is important to reject an alternative explanation that contributes all of the increase/decrease in the overadditive interaction between order switch and SOA to a carryover from RT1 to RT2. This alternative interpretation relies on the bottleneck assumptions (Pashler, 1994) that given short SOA, any prolongation of processing stages before the response selection of Subtask 1, or at the response selection of Subtask 1, should cause the same delay also in Subtask 2. Note, that our framework also postulated that bottom-up activation could influence R1. However, we argued that this bottom-up activation should be larger for R2 than for R1. The reason is that bottom-up activation relies on “copying” the S1−S2 order, so it would be largest only after S2 presentation, but by this time R1 had been already selected, in most cases. In summary, the carryover hypothesis predicts identical effects in R1 and R2, whereas out framework predicts larger R2 effects.

Confirming our prediction, the size of the overadditive interaction between order switch and SOA was larger in R2 than in R1. In Experiment 1a, the size of the overadditive interaction was 101 ms in R2 but only 31 ms in R1. In Experiment 1b, the size of the overadditive interaction was 66 ms in R2 but only 19 ms in R1. In Experiment 2, the size of the overadditive interaction was 130 and 49 ms in R1 and R2, respectively. In Experiment 3 in the cue condition and given short preparation time, the size of the overadditive interaction was 78 ms in R2 but only 31 ms in R1. In the no-cue condition it was 58 ms in R2 and −14 ms in R1. When preparation time was long the size of the overadditive interaction was 35 ms in RT2 and 10 ms in RT1 (cue condition) and 112 ms in RT2, and 48 ms in RT1 (no-cue condition). Overall, the overadditive interaction was larger in R2 then in R1 (confirming our prediction). It also indicates that our results could not be fully accounted for by a carryover from R1 to R2, because the effects on R1 are not large enough to elucidate all the overadditive interaction found in R2.

Implications to theories of subtask order control

There are other models of complex task control that incorporate interacting bottom-up and top-down factors. For example, Cooper and Shallice (2000), based upon a previous model by Norman and Shallice (1986), proposed that the control structure of a complex task is represented within a hierarchically organized network of action schemas. A schema can be activated to satisfy a goal, or via the source schema, therefore by a top-down process. A schema also receives activation from bottom-up factors such as objects in the environment. However, in this model, bottom-up control is based on the perception of objects and not on the perception of object order. The current findings show that perception of the order in which objects are presented is a potent source for bottom-up control.

Other forms of order control

We investigated a specific class of bottom-up and top-down order processes. However, other processes probably participate as well in order control in the PRP paradigm, and also in general. In particular, it has been proposed that lateral inhibition (i.e., Norman & Shallice, Q4 1986), self inhibition (i.e., Mackay, 1987), and backward inhibition (Mayr & Keele, 2000) play an important role in controlling subtask sequence. Evidence for order control by self inhibition and lateral inhibition comes from a study by Li, Lindenberger, Runger, and Frensch (2000). In this study participants followed a well-practised sequence of seven stimulus categories (e.g., digit, letter, maths symbol, etc.). They monitored successive displays of stimuli and pressed a key whenever they saw an instance of the relevant category. Focusing on the subjects' mistakes, the researchers found fewer errors for neighbouring categories than for distant ones, indicating that lateral inhibition applies to neighbouring categories and thus prevents category confusion. In addition, Li et al. found more errors for anticipatory categories than for past categories (this difference was most evident when comparing errors in category $n-1$ and category $n+1$), suggesting that past categories were subjected to self-inhibition.

Although we obviously acknowledge the role of lateral, self-, and backward inhibition, we argue that these mechanisms cannot account for our results. In our paradigm, self- and backward inhibition would mean that each subtask is subjected to inhibition after execution, and lateral inhibition would mean that Subtask 1, when performed, is inhibiting Subtask 2, and Subtask 2, when performed, is inhibiting Subtask 1. However, none of these processes could account for the R2 order-switching cost. The reason is that such processes operate equally on order-switched and nonswitched trials. For example, when performing the sequence letter-then-colour, the letter subtask is being self-inhibited but also inhibits the colour subtask. The lateral inhibition of the colour subtask (Subtask 2) would be the same regardless of the preceding trial and thus could not account for the order-switching cost found in R2. Moreover, self- and lateral inhibition are general processes that do not depend upon the nature of the stimuli (Experiment 2) or the absence of an instructional order cue (Experiment 3). This further indicates that such processes could not by themselves account for the results of the present experiments.

Bottom-up and top-down control in models of the PRP paradigm

We now turn to discuss whether current theories of the PRP paradigm can account for our results. To anticipate this discussion, we failed in extending any of these theories to account for the entire range of the effects that we report, which led us to suggest our own framework. It should be kept in mind, however, that some of these models were not originally designed to account for order control. Thus, our results only indicate that we failed in our attempt to extend the models, not that they were refuted in any sense.

The structural bottleneck model

According to the response selection bottleneck model (Pashler, 1994; Welford 1952), subtasks are treated on a first-come first-served basis. This assumption was challenged by De Jong (1995) and by Luria and Meiran (2003). The structural bottleneck model can account for order effects by assuming that the assignment of the bottleneck to tasks is controlled by a mechanism outside this bottleneck (such as our suggested order control) and that this control mechanism is invoked before any response selection takes place. However, even this extension seems incapable of accounting for the overadditive interaction found in Experiment 2 (see below).

Another route is trying to see whether other extensions of the bottleneck model will have better success in accounting for the present results. For example, in order to account for similar overadditive effects between task difficulty and SOA, Hartley and Q2

Little (1999) elaborated the original bottleneck model and assumed the existence of an additional processing stage preceding the response selection stage. This added stage is responsible for S–R mapping instantiation. When subtasks are relatively easy, S–R mapping instantiation for both subtasks takes place before the response selection stage of Subtask 1. But, when subtasks are difficult, this S–R mapping instantiation is performed sequentially, first for Subtask 1 and then for Subtask 2. When SOA is long, this added stage can take place during the SOA, not affecting RT2, but when the SOA is short, this stage precedes the response selection of Subtask 2, prolonging RT2. The result is an overadditive interaction between SOA and any manipulation affecting the difficulty of S–R rule instantiation.

We argue that even this extension of the bottleneck model cannot account for the results of Experiment 2. The reason is that, in Experiment 2, we increased the difficulty of S–R rule instantiation. According to our reasoning, using bivalent stimuli implies that the target stimulus can no longer serve as a retrieval cue for the S–R rules. As a result, S–R rule instantiation becomes more difficult than it is in a condition involving univalent stimuli. As would be predicted by Q2 Hartley and Little's (1999) model, we found an overadditive interaction between valence and SOA in RT2. Thus, it could be argued that both order switching and valence made S–R rule instantiation difficult. However, this line of reasoning encounters difficulties because we did not find an overadditive interaction between SOA and order switch within the bivalent condition, but this interaction was evident in the univalent condition.

It seems that a modified bottleneck model should assume that there is a duration difference between the response selection processes of the two subtasks (Logan & Gordon, 2001; Tombu & Jolicoeur, 2003), so that the response selection of Subtask 2 is easier than the response selection of Subtask 1 (at least when SOA is long). This assumption is important in accounting for RT2 being faster than RT1 given long SOA and for the overadditive interaction between order switch and SOA (Luria & Meiran, 2003, and the present experiments).

Strategic bottleneck

Meyer and Kieras (1997a, 1997b) proposed that the PRP effect is due to strategic partial lockout scheduling and deferred response transmission. They argued that the bottleneck results from satisfying task priorities and avoiding conflicts within the same motor processor, so that Subtask 2 is processed in a deferred mode. By applying the EPIC they simulated a wide range of PRP results, including variable subtask order (Pashler, 1990).

There are two assumptions made by EPIC in order to simulate a variable subtask order (Meyer & Kieras, 1997b). The first assumption is that when there is uncertainty regarding subtask order, both subtasks are put into a deferred mode until there is a decision regarding the current order. This decision could be based upon stimulus order, and thus EPIC includes bottom-up order control. The second assumption is that when both responses are manual, participants group their responses in the short SOA. This latter assumption explains why RT1 decreases as SOA increases (a pattern that was found in the current experiments, and also by Luria & Meiran, 2003, and Pashler, 1990).

Although the EPIC architecture represents subtask order by giving a priority to Subtask 1, it does not encompass a memory of the order in which the subtasks were executed. This assumption should be incorporated into EPIC in order for it to explain the order-switching cost found in RT1 and RT2. In addition, the bottom-up mechanism in EPIC does not depend on SOA, but on the identification of S1 and S2 separately, while the results of Experiment 2 indicated that bottom-up activation is dependent upon the ease of perceiving the stimuli order.[1]

[1] We acknowledge the possibility that computational models such as EPIC (Meyer & Kieras, 1997a, 1997b) and the executive control theory of visual attention (ECTVA; Logan & Gordon, 2001) may be able to account for the data in some other way. Nonetheless, we are unaware of any such simulation to date.

ECTVA

Logan and Gordon (2001) proposed the executive control theory of visual attention (ECTVA) to explain a wide range of findings from the PRP paradigm. Although not modelled in their study, but similar to our model, ECTVA specifically assumes that subtask *order* is represented separately from the subtasks themselves, in a hierarchy (p. 396). Thus, ECTVA is able to account for the basic finding of order-switching cost, once the mechanisms of order representation are explicitly modelled. Moreover, this model assumes that both subtasks are activated (although not to the same extent) while performing Subtask 1 (counters for both subtasks are active during response selection), while only one subtask is active while performing Subtask 2 (only counters for Subtask 2 are active). This feature of ECTVA is similar to our framework and, as such, can account for the fact that RT2 is faster than RT1, given long SOA (Luria & Meiran, 2003).

Logan and Gordon (2001) showed that ECTVA is able to account for overadditive interactions between SOA and congruency. However, the size of the overadditive interaction modelled by ECTVA was much smaller than the actual size obtained by participants' performance. For example, the size of the overadditive interaction modelled by ECTVA in Experiment 1 (Logan & Gordon, 2001) was 55 ms, which is much smaller than the size of the overadditive interaction found in the real data (124 ms). A possible reason for this failure to account for the full size of the interaction may lie in a major difference between our framework and ECTVA. Whereas we argue that the control parameters change with SOA, in Logan and Gordon's simulations, these parameters remained constant. Another reason is that Logan and Gordon's simulations fixed their parameters and did not allow them to fit maximally to the data. Perhaps a reason was that the choice of parameter values was not optimal, and that ECTVA could account for the full size of the overadditivity with a better tuned set of parameters.

Central capacity sharing

Recent studies (Navon & Miller, 2002; Tombu & Jolicoeur, 2003) proposed that the capacity sharing of the response selection stage can account for the effects found in the PRP paradigm. To account for order-switching effects, Tombu and Jolicoeur argued that more capacity is allocated to the subtask that served as Subtask 1 in the previous trial, causing a bias towards repeating subtask order. However, this assumption cannot explain the order-switching cost found in Subtask 2 even given long SOA. Thus we argue that an assumption regarding an explicit representation of subtask order is essential, and we see no reason why such an assumption cannot be incorporated in the models.

Interestingly, the capacity-sharing models share some assumptions with our framework—namely, that both subtasks are activated in the initial processing stages but not to the same extent, and that only Subtask 2 is activated after Subtask 1 has been executed, resulting in a stronger activation in Subtask 2 than in Subtask 1 (especially with a long SOA). Moreover, Tombu and Jolicoeur (2003) argued that when subtask order changes, it should decrease RT1 as a function of SOA, a pattern that was observed in the current study, in Luria and Meiran (2003), by Pashler (1990), and by Tombu and Jolicoeur (2000). Like ECTVA, this model does not incorporate bottom-up control. Whether the results from our study could be accounted for by another mechanism remains an open question.

SUMMARY

Bottom-up (stimulus based) and top-down (cue-based) order control interacted in controlling subtask order in the PRP paradigm. We demonstrated that the overadditive interaction between order switch and SOA in RT2 was at least largely caused by bottom-up order control. When there was no bottom-up control, the overadditive interaction disappeared (became additive), and when bottom-up processes were enhanced by removing top-down control, the overadditive interaction became more pronounced. Thus, we argue that online order control is based upon the order cue, but also upon copying the stimulus presentation order, and therefore upon the ease of perceiving this order.

REFERENCES

Allport, A., & Wylie, G. (2000). Selection-for-action in competing (Stroop) tasks: "Task-switching" stimulus–response bindings, and negative priming. In S. Monsell & J. S. Driver (Eds.), *Control of cognitive processes: Attention & performance XVIII* (pp. 35–70). Cambridge, MA: MIT Press.

Q5 Botvinick, M., & Plaut, D. C. (2003). Representing task context: Proposal based on a connectionist model of action. *Psychological Research, 66*, 298–311.

Botvinick, M., & Plaut, D. C. (2004). Doing without schema hierarchies: A recurrent connectionist approach to routine sequential action and its pathologies. *Psychological Review, 111*, 395–429.

Cooper, R., & Shallice, T. (2000). Contention scheduling and the control of routine activities. *Cognitive Neuropsychology, 17*, 297–338.

De Jong, R. (1995). The role of preparation in overlapping-task performance. *Quaterly Journal of Experimental Psychology, 48A*, 2–25.

Duncan, J. (1977). Response selection rules in spatial choice reaction tasks. In S. Dornik (Ed.), *Attention and performance VI* (pp. 49–61), Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Fagot, C. (1994). *Chronometric investigations of task switching.* Unpublished doctoral dissertation, University of California, San Diego.

Garavan, H. (1998). Serial attention within working memory. *Memory and Cognition, 26*, 263–276.

Goschke, T., & Kuhl, J. (1993). Representation of intentions: Persisting activation in memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 19*, 1211–1226.

Q1 Grafman, 1995

Q2 Hartely, A. A., & Little, D. M. (1999). Age related differences and similarities in dual task interference. *Journal of Experimental Psychology: General, 128*, 416–449.

Hommel, B. (2000). The prepared reflex: Automaticity and control in stimulus–response translation. In S. Monsell & J. Driver (Eds.), *Control of cognitive processes: Attention and performance XVIII* (pp. 247–273). Cambridge, MA: MIT Press.

Hübner, R., Futterer, T., & Steinhauser, M. (2001). On attentional control as a source of residual shift costs: Evidence from two-component task shifts. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 27*, 640–653.

Koch, I. (2001). Automatic and intentional activation of task sets. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 27*, 1474–1486.

Lashley, K. S. (1951). The problem of serial order in behavior. In L. A. Jeffress (Ed.), *Cerebral mechanisms in behavior* (pp. 112–136). New York: Wiley.

Li, K. Z. H., Lindenberger, U., Runger, D., & Frensch, P. A. (2000). The role of inhibition in the regulation of sequential action. *Psychological Science, 11*, 343–347.

Logan, G. D. (1978). Attention in character-classification tasks: Evidence for the automaticity of component stages. *Journal of Experimental Psychology: General. 107*, 32–63.

Logan, G. D., & Bundesen, C. (2003). Clever homunculus: Is there an endogenous act of control in the explicit task-cuing procedure? *Journal of Experimental Psychology: Human Perception and Performance, 3*, 575–599. Q6

Logan, G. D., & Gordon, R. D. (2001). Executive control of visual attention in dual-task situations. *Psychological Review, 108*, 393–434.

Luria, R., & Meiran, N. (2003). Online order control in the psychological refractory period paradigm. *Journal of Experimental Psychology: Human Perception and Performance, 29*, 556–574.

MacKay, D. G. (1987). *The organization of perception and action: A theory for language and other cognitive skills.* New York: Springer-Verlag. Q4

Marsh, R. L., Hicks, J. L., & Bink, M. L. (1998). The activation of completed, uncompleted, and partially completed intentions. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 24*, 350–361.

Marsh, R. L., Hicks, J. L., & Bryan, E. S. (1999). The activation of unrelated and canceled intentions. *Memory and Cognition, 27*, 320–327.

Mayr, U., & Keele, S. W. (2000). Changing internal constraints on action: The role of backward inhibition. *Journal of Experimental Psychology: General, 129*, 4–26.

Meiran, N. (1996). Reconfiguration of processing mode prior to task performance. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 22*, 1423–1442. Q7

Meiran, N. (2000). Modeling cognitive control in task switching. *Psychological Research, 63*, 234–249.

Q8 Meiran, N., Chorev, Z., & Sapir, A. (2000). Component processes in task switching. *Cognitive Psychology, 41*, 211–253.

Meyer, D. E., & Kieras, D. E. (1997a). A computational theory of executive cognitive processes and multiple-task performance: Part 1. Basic mechanisms. *Psychological Review, 104*, 3–65.

Meyer, D. E., & Kieras, D. E. (1997b). A computational theory of executive cognitive processes and multiple-task performance: Part 2. Accounts of psychological refractory-period phenomena. *Psychological Review, 104*, 749–791.

Navon, D., & Miller, J. (2002). Queuing or sharing? A critical evaluation of the single bottleneck notion. *Cognitive Psychology, 44*, 193–251.

Niemi, P., & Nataanen, R. (1981). Foreperiod and simple reaction time. *Psychological Bulletin, 89*, 133–162.

Norman, D. A., & Shallice, T. (1986). Attention to action: Willed and automatic control of behavior. In R. Davidson, G. Schwartz, & D. Shapiro

Q9 (Eds.),

Pashler, H. (1984). Processing stages in overlapping tasks: Evidence for a central bottleneck. *Journal of Experimental Psychology: Human Perception and Performance, 10*, 358–377.

Pashler, H. (1990). Do response modality effects support multiprocessor models of divided attention? *Journal of Experimental Psychology: Human Perception and Performance, 16*, 826–842.

Pashler, H. (1994). Dual task interference in simple tasks: Data and theory. *Psychological Bulletin, 116*, 220–244.

Pashler, H. (1998). *The psychology of attention.* Cambridge, MA: MIT Press.

Pashler, H., & Johnston, J. C. (1989). Chronometric evidence for central postponement in temporally overlapping tasks. *Quarterly Journal of Experimental Psychology, 41A*, 19–45.

Posner, M. I., & Boies, S. J. (1971). Components of attention. *Psychological Review, 78*, 391–408.

Rubinstein, J. S., Meyer, D. E., & Evans, J. E. (2001). Executive control of cognitive processes in task switching. *Journal of Experimental Psychology: Human Perception and Performance, 27*, 763–797.

Schumacher, E. H., Lauber, E. J., Glass, J. M., Zurbriggen, E. L., Gmeindl, L., Kieras, D. E., et al. (1999). Concurrent response selection in dual task performance: Evidence for adaptive executive control of task scheduling. *Journal of Experimental Psychology: Human Perception and Performance, 25*, 791–814.

Shaffer, L. E. (1965). Choice reaction with variable S–R mapping. *Journal of Experimental Psychology, 70*, 284–288.

Shallice, T., Burgess, P. W., Schon, F., & Baxter, D. M. (1989). The origins of utilization behavior. *Brain, 112*, 1587–1598.

Szameitat, A. J., Schubert, T., Müller, K., & von Cramon, D. Y. (2002). Localization of executive functions in dual-task performance with fMRI. *Journal of Cognitive Neuroscience, 14*, 1184–1199.

Tombu, M., & Jolicoeur, P. (2000, November). *Can the central bottleneck be eliminated? Structural versus strategic accounts of the PRP effect.* Poster session presented at the 41st Annual Meeting of the Psychonomic Society, New Orleans, LA.

Tombu, M., & Jolicoeur, P. (2003). A capacity sharing model of dual-task performance. *Journal of Experimental Psychology: Human Perception and Performance, 19*, 3–18.

Waszak, F., Hommel, B., & Allport, A. (2003). Task-switching and long-term priming: Role of episodic stimulus–response bindings in task-shift costs. *Cognitive Psychology, 46*, 361–413.

Welford, A. T. (1952). The "psychological refractory period" and the timing of high-speed performance: A review and a theory. *British Journal of Psychology, 43*, 2–19.

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Queries

Q1	Grafman, 1995, not in refs.
Q2	Hartely in refs., Hartley in text
Q3	Number written as 11,4984. Comma moved; or should it be 11,—?
Q4	MacKay in refs., Mackay in text.
Q5	Botvinick & Plaut, 2003. Text citation?
Q6	Logan & Bundesen, 2003. Text citation?
Q7	Meiran, 1996. Text citation?
Q8	Meiran et al., 2000. Text citation?
Q9	Rest of ref. missing.