

# Trial-to-Trial Modulations of the Simon Effect in Conditions of Attentional Limitations: Evidence From Dual Tasks

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Interference effects are reduced after trials including response conflict. This sequential modulation has often been attributed to a top-down mediated adaptive control mechanism and/or to feature repetition mechanisms. In the present study we tested whether mechanisms responsible for such sequential modulations are subject to attentional limitations under dual-task situations. Participants performed a Simon task in mixed single- and dual-task contexts (Experiment 1), in blocked contexts with dual-task load either, in trial<sub>N</sub> (Experiment 2a), in trial<sub>N-1</sub> (Experiment 2b), or in both trials (Experiment 3). Results showed that the occurrence of a sequential modulation did not depend on dual-task load per se as it occurred predominantly in conditions of lowest and highest task load. Instead, task factors such as the repetition of task episodes and stimulus-response repetitions determined whether a sequential modulation occurred.

*Keywords:* Simon effect, dual-task, conflict, cognitive load, conflict adaptation, episodic retrieval, cognitive control

Distinguishing and selecting task relevant from interfering task irrelevant stimulus attributes to pursue goal-directed behavior is a major ability of our cognitive system. The interference that is encountered when different stimulus attributes compete for control of action (i.e., response conflict) has been widely studied in various paradigms of selective attention, such as Stroop, Eriksen flanker, or Simon tasks. In a typical reaction time paradigm that involves response conflict, for example, participants are required to respond with left and right key presses to the identity of a stimulus. At the same time, the location of the stimulus (left vs. right) is task irrelevant. In such a Simon task (Simon, 1969; see Lu & Proctor, 1995; Simon, 1990, for overviews), responses are usually fast in compatible conditions, when the stimulus assigned to the left key also appears on the left, and thus, stimulus-identity and stimulus location activate the same corresponding response. Conversely, responding takes usually longer in Simon incompatible conditions, when relevant and irrelevant dimensions activate

different responses (e.g., the stimulus assigned to the left key appears on the right location). Although completely task irrelevant, it is assumed that the location information automatically activates the spatially corresponding response and thus, produces a response conflict (e.g., Kornblum, Hasbroucq, & Osman, 1990). Within this paradigm, the Simon effect denotes the degree of interference between relevant stimulus dimension (identity) and irrelevant dimension (location).

Recently, the consequences of such interference due to response conflict have been a topic of interest to study the adaptability of the cognitive system to flexibly adjust to varying task demands. It has been observed that the size of the interference effect depends critically on the nature of the previous trial. That is, it has frequently been demonstrated that typical interference effects are largely reduced if not completely eliminated after trials of response conflict compared to conditions without a response conflict in selective attention tasks, such as the Simon task (Akçay & Hazeltine, 2007; Stürmer, Leuthold, Soetens, Schröter, & Sommer, 2002; Wühr, 2005; Wühr & Ansorge, 2005), Eriksen flanker task (Gratton, Coles, & Donchin, 1992; Ullsperger, Bylsma, & Botvinick, 2005), the Stroop task (Kerns et al., 2004), and in response priming tasks (Kunde, 2003; Kunde & Wühr, 2006).

Such trial-to-trial sequential modulations of interference effects have been interpreted in two popular ways. One line of argumentation, as mentioned above, is based on online adaptations of cognitive control processes. It has been argued that the experience of a response conflict may automatically activate adjustments of control processes that serve to regulate and guarantee error-free subsequent behavior (e.g., Gratton et al., 1992; Kerns et al., 2004; Stürmer et al., 2002). In other words, cognitive control serves to shield subsequent processing of task relevant information from

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interfering information, and thus, serves to reduce susceptibility to interference on subsequent trials (see also Botvinick, Carter, Braver, Barch, & Cohen, 2001).

Alternative accounts explain sequential modulations in terms of bottom-up driven stimulus-response (S-R) feature repetitions and/or feature binding accounts (Hommel, Proctor, & Vu, 2004; Mayr, Awh, & Laurey, 2003; Nieuwenhuis et al., 2006; Notebaert, Soetens, & Melis, 2001; Wendt, Kluwe, & Peters, 2006). These accounts attribute sequential modulations to an unbalanced proportion of complete or partial repetitions of S-R features. Complete repetitions (and also complete alternations) facilitate responding. That is, a previously used event file can either be used again (all S-R features repeat) or the whole event file can be disregarded as old (all S-R features alternate). Conversely, partial repetitions of event files are associated with response time (RT) costs. In these cases, the previously used event file can neither be used again because certain features are substituted, nor can it be completely disregarded from processing because certain features repeat. This partial unbinding and binding takes time and increases RTs (cf. Hommel, 1998b). Together, this can also explain typical sequential modulations as observed for Simon interference effects (for more details, see Hommel et al., 2004).

Much effort has been made to distinguish between these accounts (e.g., Akçay & Hazeltine, 2007; Hommel et al., 2004; Kunde & Wühr, 2006; Nieuwenhuis et al., 2006; Notebaert & Verguts, 2007; Ullsperger et al., 2005; Wendt et al., 2006). One strategy is to exclude or control the involved stimulus and response repetitions between a sequence of trials, resulting either in a demonstration of still reliable sequential modulations (Ullsperger et al., 2005) or conversely in an elimination of sequential modulations (Mayr et al., 2003). However, current understanding suggests that both mechanisms seem to be involved in varying degrees, strongly depending on task context, experimental setting, and the amount of feature transitions (Akçay & Hazeltine, 2007, 2008; Egner, 2007; Kerns et al., 2004; Notebaert, Gevers, Verbruggen, & Liefoghe, 2006; Wühr & Ansorge, 2005).

With respect to sequential modulation of interference effects and its underlying mechanism(s), the present study pursued a somewhat different approach by investigating the conditions under which such sequential modulations do or do not occur. Determining the boundary conditions of the mechanism that is responsible for sequential modulation of interference effects may be informative regarding the architecture and functionality of this (these) mechanism(s). With respect to the aforementioned theoretical accounts, we investigated two candidate factors that could determine the occurrence of sequential modulations of the Simon effect: the availability of cognitive resources and the similarity of task-context parameters. The following sections are dedicated to describe why and how these factors might affect the sequential modulation of the Simon effect.

### The Sequential Modulation of the Simon Effect and the Availability of Cognitive Resources

As a first approach, we aimed at testing boundary conditions derived from predictions of cognitive control accounts of sequential modulation effects. In particular, if these effects are caused by cognitively mediated control processes, they might be sensitive to attentional limitations due to increased cognitive (task) load. Of course,

there is an immense amount of studies demonstrating that task performance in itself is hindered if there are additional task requirements to fulfill (e.g., Navon & Gopher, 1979; Welford, 1952; see below for further elaboration). To manipulate the availability of cognitive resources for the assumed conflict-induced adaptation, participants performed a conflict task either alone as single task (ST) or in the context of a dual task (DT). The question was whether the simultaneous performance of two single-component tasks, which includes active control and DT-specific coordination processes (e.g., Logan & Gordon, 2001), limits the occurrence of conflict-induced adaptation (for a detailed description of the DT procedure see below). If this would be the case, one could conclude that conflict-induced adaptation does not occur exclusively in a bottom-up manner but would confirm the influence of the availability of cognitive resources on the adaptation process.

However, currently little is known about the impact of such attentional limitations on conflict triggered control adjustments. Combining a number comparison task (i.e., smaller vs. larger than five) with a Simon task, Fischer, Dreisbach, and Goschke (2008), for example, showed that conflict-induced adaptation is sensitive to specific attentional requirements of processing task-relevant stimulus features in the conflict trial  $N - 1$ . In particular, the sequential modulation of the Simon effect depended on the numerical distance of the numbers in  $N - 1$  to five (Moyer & Landauer, 1967). Reduced sequential modulations of the Simon effect were found when numbers in  $N - 1$  were close to the standard, associated with an effortful and controlled comparison process, compared to stronger sequential modulations when numbers in  $N - 1$  were far from the standard, associated with an automatic precategorization process (e.g., Fischer, Miller, & Schubert, 2007; Oriet, Tombu, & Jolicoeur, 2005). Furthermore, Stürmer, Seiss, and Leuthold (2005) pointed to the role of task load determining conflict-induced adaptation. These authors demonstrated that conflict triggered adaptation effects in a Simon task were somewhat smaller in blocks in which a subsequent secondary Eriksen flanker task had to be performed with a response-stimulus interval (RSI) of 0 ms compared to blocks in which no secondary task accompanied the Simon task (single task). This apparent "impairment" was found irrespective of flanker congruency in the Eriksen task. The authors argued that this reduction is a consequence of the cognitive system's need to monitor ongoing response activation of an intervening task.

Based on these results one could assume that if online adaptations of cognitive control are subject to DT-specific attentional limitations, this should affect the pattern of the sequential modulation found in trial<sub>*N*</sub>. That is, any factor that impairs cognitive control would also reduce or eventually eliminate the sequential modulation. We will get back to more detailed predictions later.

### The Sequential Modulation of the Simon Effect and the Manipulation of Task-Context Similarity

As mentioned earlier, sequential modulations of the Simon effect might also be explained in terms of bottom-up driven S-R feature repetitions and/or feature binding accounts. In this view, the processing of a current event  $N$  leads to an automatic retrieval of former events/episodes in  $N - 1$  that are related to the current

event (e.g., stimulus or response features). Previous studies, however, argued that the episodic representation of an event (e.g., Hommel, 2004) does not only contain stimulus or response codes. Moreover, also task parameters, context parameters, conflict status, or control parameters might be integrated into the event representation. More important, if conflict status and control parameters are integrated in an event file, a feature binding account is not necessarily at odds with the view of conflict-induced behavioral adaptation (see Spapé & Hommel, 2008, for a detailed argumentation). If this is correct, it is easy to see that a precondition for this retrieval is at least some similarity between an event<sub>N-1</sub> and an event<sub>N</sub>. Therefore, assuming that retrieval processes can explain sequential modulation effects, our second aim was to test the role of similarity of task-context parameters as a potential prerequisite for the sequential modulation of the Simon effect.

First of all, there are some recent studies demonstrating that sequential modulations of interference effects depend on similarities between previous and current task requirements. In a study by Wendt et al. (2006), for example, participants performed a Simon task and an Eriksen flanker task in alternating runs (Experiment 3). We find it interesting that sequential effects in trial<sub>N</sub> (e.g., in the Simon task episode) were found when the response conflict was based on the same task episode, that is, the Simon task in  $N - 2$ . Conflict in the immediately preceding Eriksen flanker task episode in trial<sub>N-1</sub> did not lead to a sequential modulation in the Simon task in trial<sub>N</sub>, which can be taken as evidence for the importance of task-episode similarity (i.e., task specificity) for sequential modulations (see also Kiesel, Kunde, & Hoffmann, 2006; Notebaert & Verguts, 2008).

More important, findings from the aforementioned studies reveal that mechanisms responsible for the sequential modulation of interference effects can in fact outlive switches from one task to the other or the in-between performance of a completely different task. Yet, the effects of these mechanisms (i.e., the sequential modulation itself) will only be visible in tasks with similar or even identical task characteristics or task contexts (e.g., Egner, Delano, & Hirsch, 2007; Kiesel et al., 2006; Notebaert & Verguts, 2008). The particular role of task-context similarity for the occurrence of conflict-induced adaptation effects has been especially advocated by Spapé and Hommel (2008). These authors proposed that the appearance of conflict adaptation (e.g., sequential modulation) is more likely when two subsequent events are similar. In an auditory-vocal Stroop task a salient but task-irrelevant change in the episodic context (i.e., a change in gender of the voice from trial<sub>N-1</sub> to trial<sub>N</sub> that spoke the irrelevant distractor words) completely eliminated sequential modulations of the interference effects whereas intact sequential modulations were found when the gender of the voice remained the same. The authors concluded that the sequential modulation, interpreted as conflict-induced adaptation effects, is eliminated within the same task when an abstract task-irrelevant feature switches from one trial to the next.

Taken together, sequential modulations of interference effects seem to depend on the similarity of the global task context. In the present study we aimed to extend this aspect by broadening the concept of task context. In particular, we asked whether the repetition or change of more global task-context parameters, such as the repetition of the general task episodes (i.e., ST vs. DT) deter-

mine the occurrence of trial-to-trial modulations of interference effects irrespective of the attentional load.

### Manipulating Cognitive Load in DT Situations

With respect to the first aim of manipulating the availability of cognitive resources, we increased attentional processing requirements by means of performing another completely unrelated task simultaneously with the selective attention task. These DT episodes allowed us to investigate whether the sequential modulation of the Simon effect might be sensitive to DT-specific attentional limitations in the DT episode compared to when the selective attention task was performed alone as ST in the ST episode. In the ST episode, participants performed a version of a Simon task (Simon, 1990) by responding with left and right key presses to the identity of stimuli presented to the left or right of fixation. In the DT episode, however, participants were required to perform a tone task as Task 1 (T1) and the Simon task as Task 2 (T2).

We assume that performing two tasks instead of one leads to competition or division of attentional resources, which is in line with recent competitive models of DT performance (e.g., Desimone & Duncan, 1995; Logan & Gordon, 2001; Miller & Cohen, 2001). Indeed, researchers have often used DT designs that require the concurrent performance of two independent tasks to investigate effects of between-task interference, task load, and limits of attentional resources in general. It is known that when performing two tasks simultaneously compared to performing a ST alone, performance decreases dramatically in terms of access to memory (e.g., Jacoby, 1991; Moscovitch, 1992), response speed, and/or accuracy (e.g., Hazeltine, Teague, & Ivry, 2002; Pashler, 1984; Schubert, 1999; Schumacher et al., 2001; Tombu & Jolicoeur, 2002). Such performance decrements in DTs have often been attributed to additional resource requirements due to DT-specific coordination processes (Meyer & Kieras, 1997; Szameitat, Schubert, Müller, & von Cramon, 2002), online-order control (Luria & Meiran, 2003), or capacity sharing (Navon & Miller, 2002; Tombu & Jolicoeur, 2002, 2003). Most common accounts of DT costs assume that two information processing streams compete for access to a processing bottleneck, which represents a processing stage that is severely limited in attentional capacity (e.g., Pashler, 1984; Welford, 1952). In other words, certain processing stages (e.g., response selection) cannot proceed in parallel and, therefore, T2 processing needs to be postponed until bottleneck processing in T1 is completed (e.g., De Jong, 1993; Pashler, 1998; Schubert, 2008). Although access management to this bottleneck has sometimes been conceptualized as passive queuing (e.g., Jiang, Saxe, & Kanwisher, 2004; Pashler, 1994), recent behavioral and neuroscientific developments argue for the involvement of active monitoring/scheduling and attentional control processes (e.g., Logan & Gordon, 2001; Meyer & Kieras, 1997; Sigman & Dehaene, 2006; Stelzel, Kraft, Brandt, & Schubert, 2008; Szameitat et al., 2002). Furthermore, performing two tasks simultaneously is also associated with increased working memory demands. Several components of two task sets (e.g., stimuli, responses, task rules) have to be actively maintained in working memory (Cowan, 1999). It has been assumed that in a typical DT situation especially T2 processing is subject to increased working memory effort and particularly suffers from attentional processing limitations (Pashler, 1994; Schubert, 1999).

## The Sequential Modulation of the Simon Effect in DT Performance

In the context of models that assume conflict-induced behavioral adaptations on the basis of activation of cognitive control processes (e.g., Botvinick et al., 2001; Stürmer et al., 2002), one would expect that limitations of attentional resources (DT episode) affect the efficiency of the adaptation effect and thus, the occurrence of a sequential modulation. Moreover, we aim to extend previous studies investigating the influence of attentional load on sequential modulations (e.g., Stürmer et al., 2005) by determining at which point in processing attentional limitations become crucial. Therefore, we differentiate effects of attentional limitations first, in the trial in which the response conflict occurred ( $\text{trial}_{N-1}$ ) and second, in the trial that follows the response conflict and in which the sequential modulation typically occurs ( $\text{trial}_N$ ). This differentiation is important because recent studies either suggested that the activation of behavioral adaptations occurs after the conflict trial to prepare the system for the subsequent performance (e.g., Botvinick et al., 2001; Gratton et al., 1992) or proposed that mechanisms of behavioral adaptation are activated right in the trial of conflict (e.g., Fischer et al., 2008; Goschke & Dreisbach, 2008).

If attentional load in  $\text{trial}_{N-1}$  impairs the activation of control adaptation we do not expect a sequential modulation of the Simon effect in task transitions containing DT episodes in  $N-1$  (DT-ST and DT-DT, respectively). In contrast, task transitions containing ST episodes in  $N-1$  should then show regular sequential modulations (i.e., ST-ST and ST-DT). If however, attentional load impairs control adaptation specifically in  $\text{trial}_N$ , no sequential modulation should be found in task transitions containing DT episodes in  $N$  (ST-DT and DT-DT) but only in transitions containing ST episodes in  $\text{trial}_N$  (i.e., ST-ST and DT-ST). More important, the repetition or change in task-context parameters from  $N-1$  to  $N$  (i.e., task episode) should be of minor importance for conflict-triggered control activation.

Retrieval-based models predict that the sequential modulation of the Simon effect depends on the similarity of the task context or, more generally speaking, on the similarities between conflict and postconflict episodes. In this respect, the sequential modulation of the Simon effect should occur primarily in similar contexts of repeated task episodes, which occur when a ST follows a ST and a DT follows a DT.<sup>1</sup> Analogously, reduced sequential modulation of the Simon effect should occur in contextual dissimilarities, found in changes of task episodes. This is reflected in conditions in which a ST follows a DT episode or vice versa. More important, the attentional requirements of the episode (i.e., ST-ST vs. DT-DT) should be of minor importance as long as the task episode itself repeats (e.g., Hommel, 2005).

### Experiment 1

Experiment 1 was designed to test whether mechanisms as involved in the sequential modulation of the Simon effect are subject to DT-specific attentional limitations and to changes in the task episode. For this aim in 50% of trials participants performed the Simon task alone as ST and in the other 50% of trials as T2 in the context of a DT episode. In the DT episode, a tone stimulus was presented 85 ms prior to a visual stimulus and had to be responded to according to tone pitch. Thus, the tone-judgment task

slightly preceded the Simon task. In case of a tone presentation participants were required to respond as fast and as accurately as possible first to the tone (S1) and only afterwards to the arrow stimulus (S2) of the Simon task (T1 priority instruction).

It should be noted that some previous DT studies did not observe a reliable T2 Simon effect in conditions of maximum task overlap (Lien & Proctor 2000; see also McCann & Johnston, 1992). For the aim of the present study it is essential to ensure that S2 location-based response activation can occur in T2 and can affect the specification of T2 response code parameters thus, resulting in a reliable Simon effect.

First, to demonstrate that S2 location-based response activation occurs in conditions of attentional load in DT episodes, we calculated S2-R1 cross-task Simon effects, which are observed when the irrelevant location of S2 affects the selection of a spatially corresponding or noncorresponding response in T1 (see e.g., Lien & Proctor, 2000; Müssele, Koch, & Wühr, 2005; Müssele, Wühr, & Umiltà, 2006). Such S2-R1 cross-task Simon effects provide evidence that the S2 location information is automatically processed. In addition, we investigated R2-R1 backward cross talk effects on RT1 (e.g., Hommel, 1998a; Koch & Prinz, 2002; Lien & Proctor, 2002; Miller, 2006). Any delay or facilitation of response code activation in the T2 Simon task (e.g., Simon incompatible vs. Simon compatible) would directly affect R2-R1 backward cross-talk effects. Such an influence of S2-R2 Simon conflict status onto response selection in T1 would be evidence that the Simon conflict is present despite the processing bottleneck in conditions of maximum task overlap (see General Discussion for further elaboration).

Second, to prevent rapid decay of S2 location-based response activation (Hommel, 1994) during the assumed processing bottleneck we used a version of the Simon paradigm in which the location-based response activation is known to be insensitive to decay and thus, does not decrease with increasing RTs (Fischer, Plessow, & Kiesel, 2010). The stimuli consisted of large left and right pointing arrow heads as relevant stimulus dimension. Thus, the relevant stimulus dimension (identity) also contained a left-right dimension (e.g., Kornblum, Stevens, Whipple, & Requin, 1999; Stoffels, 1996).<sup>2</sup> In addition, and

<sup>1</sup> It should be noted that, a change/repetition of task episodes is not equal to and thus, needs to be distinguished from the conception of switching or repeating task sets (Rogers & Monsell, 1995). Instead, we emphasize the conception of less complex (or less attentionally demanding) ST episodes versus complex (or attentionally demanding) DT episodes. Of course, the latter includes local switches between the processing of certain task components (Logan & Gordon, 2001). However, we view those local switches as a typical control function that is an essential element to guarantee successful simultaneous task performance (Meyer & Kieras, 1997). Furthermore, recent studies suggested that sequential modulations of interference effects are not impaired by local task switches as long as major task characteristics are shared in the conflict and postconflict trial (e.g., Notebaert & Verguts, 2008; Wendt et al., 2006).

<sup>2</sup> In such a Stroop-like Simon task the irrelevant stimulus dimension (location) contains a dimensional overlap with both, the spatially assigned response keys (S-R compatibility) and the relevant stimulus dimension (S-S compatibility). More important, these two forms of dimensional overlap are perfectly confounded. Whenever the irrelevant stimulus dimension (location, e.g., left side) conflicts with the relevant stimulus attribute (identity, e.g., right pointing arrow) it also automatically conflicts with the response (e.g., right response) and vice versa. This served to increase the size of the Simon effect and to eliminate the impact of decay.

in contrast to Lien & Proctor (2000), we also used stimuli with high-signal quality (large arrow heads instead of line arrows) and low-stimulus eccentricity to obtain large Simon effects (see Hommel, 1993).

## Method

**Participants.** There were 26 students (17 women,  $M$  age = 23.1 years) from the Dresden University of Technology who took part in the experiment. All had normal or corrected-to-normal vision. Participants attended a single experimental session lasting about 1 hr and received €5 in payment.

**Apparatus and stimuli.** Right or left pointing white arrows ( $1.43^\circ \times 2.77^\circ$ ) were presented 2.8 cm left or right from the centre of a black screen (size of the global visual presentation field:  $6.56^\circ \times 2.77^\circ$ ). For the tone task, high (700 Hz) or low pitched tones (350 Hz) were used. Stimuli were displayed on a 17" color monitor that was connected to a Pentium I PC. Responding to the tones, participants used their index fingers of both hands to press the "X" or the ";" key of the standard computer keyboard. Responses to the arrow stimuli were made with middle fingers of both hands pressing the "Z" (QWERTY keyboard) or the "." key, respectively.

**Procedure.** Participants were instructed to respond to the direction of left or right pointing arrows. They were also informed that the arrow stimuli could appear on the left or on the right side of the screen center and that the location of the arrows is completely irrelevant. Furthermore, participants were instructed that in half of the trials a low or a high tone would be presented slightly prior to the visual stimulus. In this case participants were to respond first to the tone and only subsequently to the arrow stimulus. Although participants were instructed to respond as fast and as accurately as possible, in the DT situation priority was emphasized for T1.

ST trials started with the presentation of a fixation sign (plus sign) for 1,000 ms in the screen centre. After a blank of 600 ms a left or right pointing arrow was presented without fixation sign for 200 ms either to the left or to the right of the screen centre. DT trials started identically with a fixation sign (1,000 ms) followed by a blank screen for 600 ms. Then, however, a tone (S1) was presented for 150 ms constituting T1. Shortly after tone onset (85 ms) the arrow stimulus (S2) of T2 was displayed on the screen for 200 ms. Correct responses for ST and DT trials alike were recorded within a time slot of maximally 1,800 ms after stimulus onset (S1 onset in the DT). If no response was given within this time interval or a wrong response was executed (in either task for DT trials), the feedback "error" was provided for 300 ms. Instead of feedback, a blank screen was shown for 300 ms when the given responses were correct. Following the error feedback (or the blank) another 700 ms elapsed before the next trial started with the presentation of the fixation sign.

The trials were equally divided among the eight conditions defined by task (ST vs. DT), location of arrow (left vs. right), and orientation of arrow (left vs. right). Note that within the DT trials, half of the trials included a high pitched tone and half included a low pitched tone. The experiment consisted of 12 blocks and within each experimental block the eight conditions were presented eight times. Blocks were divided by short breaks. After a break the new block started with the presentation of the last trial of

the previous block to keep transition probabilities equal and to provide an appropriate  $N - 1$  history of the first trial (now second) in the present block. For the Blocks 2 to 12 this increased the number of trials to 65 per block. However, the first trial in each block was eliminated prior to analyses that resulted in again 64 trials for the Blocks 2 to 12 and in 63 trials in the first block (see also Fischer et al., 2008). Prior to the experiment, a short block of 12 practice trials was included.

## Results

The result section of Experiment 1 is organized in two separate parts. In the first part, we report the main RT and error results with respect to the sequential modulation of the Simon effect and effects of S-R repetitions on this sequential modulation. In the second part, we present additional analyses that serve to prove reliable S2 location-based response activation in the DT context.

**Response times and error rates.** Trials with erroneous responses in either task (6.0%) and all RTs (Simon and tone task alike) that did not fit the outlier criterion (2.8%;  $\pm 2.5$  SD per participant and condition mean) were not included in the RT analyses. In the following only Simon task data were analyzed. A repeated-measures analysis of variance (ANOVA) included the factors  $\text{task}_{N-1}$  (ST vs. DT),  $\text{task}_N$  (ST vs. DT) as well as the factors  $\text{Simon}_{N-1}$  (C [Simon compatible] vs. I [Simon incompatible]), and  $\text{Simon}_N$  (C vs. I), reflecting the sequential modulation of the Simon effect. Results are presented in Figure 1. Greenhouse-Geisser adjustments were applied when appropriate.

**RTs.** Not surprising, responses were much faster in Simon ST (534 ms) than in Simon DT (939 ms),  $F(1, 25) = 208.97$ ,  $MSE = 81,749.05$ ,  $p < .001$ ,  $\eta_p^2 = .893$ . This dramatic RT difference suggests that performance in the Simon task as T2 in the DT trial suffered indeed from heavy processing restrictions (e.g., DT-specific attentional limitations) possibly resulting in an interruption of T2 processing (i.e., PRP). Furthermore, task-episode repetitions (ST-ST and DT-DT) were about 67 ms faster than task-episode switches (ST-DT and DT-ST), as revealed by the interaction between  $\text{task}_{N-1}$  and  $\text{task}_N$ ,  $F(1, 25) = 129.38$ ,  $MSE = 3,613.95$ ,  $p < .001$ ,  $\eta_p^2 = .838$ . An overall Simon effect of 48 ms was found, which is reflected in the main effect of the factor  $\text{Simon}_N$ ,  $F(1, 25) = 78.26$ ,  $MSE = 3,087.01$ ,  $p < .001$ ,  $\eta_p^2 = .758$ . Although, the size of this Simon effect seemed to be numerically somewhat smaller in DT (42 ms) than in ST (54 ms), statistically this interaction did not reach the level of significance,  $F(1, 25) = 2.90$ ,  $MSE = 1,371.35$ ,  $p = .101$ ,  $\eta_p^2 = .104$ . More important, a significant interaction between  $\text{Simon}_{N-1}$  and  $\text{Simon}_N$  suggests that trial characteristics in  $\text{trial}_{N-1}$  modulated the Simon effect in  $\text{trial}_N$ ,  $F(1, 25) = 74.16$ ,  $MSE = 472.87$ ,  $p < .001$ ,  $\eta_p^2 = .748$ . In particular, a large Simon effect of 68 ms in conditions of Simon compatible trials in  $\text{trial}_{N-1}$  was downsized to 30 ms when the current trial was preceded by an incompatible trial. Most important, however, this sequential modulation did not depend on the current task episode in  $\text{trial}_N$ , as the factors  $\text{task}_N$ ,  $\text{Simon}_{N-1}$  and  $\text{Simon}_N$  did not interact ( $F < 1$ ). Further significant effects include a main effect of the factor  $\text{Simon}_{N-1}$ ,  $F(1, 25) = 31.73$ ,  $MSE = 561.48$ ,  $p < .001$ ,  $\eta_p^2 = .559$ . Performance was slowed by 13 ms when  $\text{trial}_N$  was preceded by Simon incompatible compared to Simon compatible trials. This particular slowing was observed in DT (28 ms) but not in ST ( $-2$  ms),  $F(1, 25) = 25.74$ ,  $MSE = 916.33$ ,  $p < .001$ ,  $\eta_p^2 = .507$ .

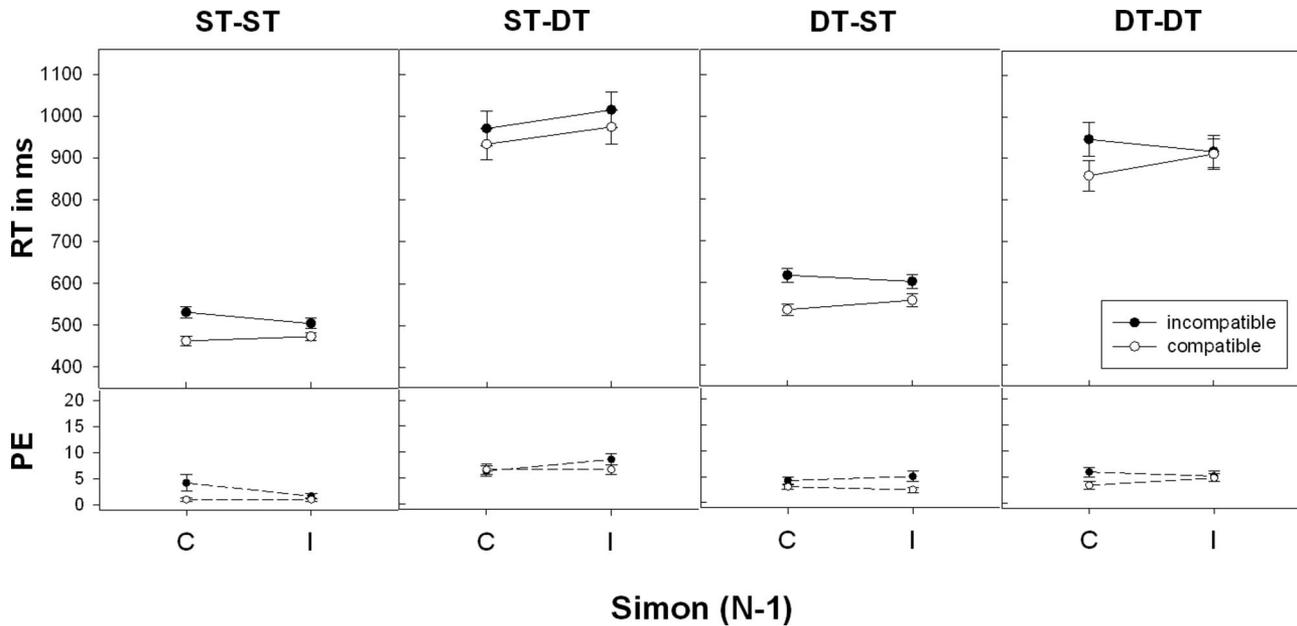


Figure 1. Response times (RTs in ms) and percentage error (PE) for the Simon task in Experiment 1. The Simon effect in trial<sub>N</sub> (N) is presented depending on Simon compatibility of the previous trial (N – 1) and with respect to task-type transitions from trial<sub>N-1</sub> to trial<sub>N</sub>. Error bars reflect standard error of mean. ST = single task; DT = dual task; C = Simon compatible; I = Simon incompatible.

Furthermore, we found a significant interaction between Simon<sub>N-1</sub>, task<sub>N-1</sub> and task<sub>N</sub>,  $F(1, 25) = 16.55, MSE = 586.13, p < .001, \eta_p^2 = .398$ . Whereas Simon<sub>N-1</sub> and task<sub>N-1</sub> had little influence on RTs in current ST (N), DT responses in trial<sub>N</sub> were substantially slowed when trial<sub>N</sub> contained a Simon incompatible trial in a ST. The interaction between task<sub>N-1</sub>, Simon<sub>N-1</sub>, and Simon<sub>N</sub>,  $F(1, 25) = 17.77, MSE = 379.61, p < .001, \eta_p^2 = .416$ , indicates that the sequential modulation in trial<sub>N</sub> (irrespective of task type) appears stronger when the previous trial contained a DT than when it contained a ST. Most important, however, we found a significant interaction of all four factors,  $F(1, 25) = 23.32, MSE = 568.83, p < .001, \eta_p^2 = .483$ . The sequential modulation of the Simon effect is more pronounced in repetitions of the task episode compared to changes of the task episode (see Figure 1). Subsequent ANOVAs showed sequential modulations of the Simon effect in ST-ST transitions,  $F(1, 25) = 34.40, MSE = 294.90, p < .001, \eta_p^2 = .579$ , in the DT-DT transition,  $F(1, 25) = 46.74, MSE = 1,031.10, p < .001, \eta_p^2 = .652$ , in the DT-ST transition,  $F(1, 25) = 26.55, MSE = 372.42, p < .001, \eta_p^2 = .515$ , but not in the ST-DT transition,  $F < 1$ .

**Errors.** Irrespective of task type a total of 4.4% errors were committed in the Simon task. Participants produced more errors in the DT (5.9%) than ST condition (2.8%),  $F(1, 25) = 27.36, MSE = 36.88, p < .001, \eta_p^2 = .523$ . Error rates were higher in Simon incompatible trials (5.1%) than in Simon compatible trials (3.6%),  $F(1, 25) = 15.96, MSE = 14.91, p < .01, \eta_p^2 = .390$ . The repetition of task episodes produced fewer errors (3.4%) than changes of task episodes (5.4%),  $F(1, 25) = 30.51, MSE = 13.81, p < .001, \eta_p^2 = .550$ . Furthermore, we found an interaction between Simon compatibility in the previous task and task<sub>N</sub>,  $F(1, 25) = 7.41, MSE = 5.95, p < .05, \eta_p^2 = .229$ . That is, in ST

slightly more errors were found after Simon compatible (3.1%) than incompatible trials (2.5%) whereas for DT this pattern was reversed (5.6% vs. 6.3%, for compatible and incompatible, respectively). More important, the error rates closely mirrored the RT data, which was shown in a quite similar four-way interaction of all factors,  $F(1, 25) = 13.82, MSE = 8.32, p < .01, \eta_p^2 = .356$ . Again, a sequential modulation was found particularly for task-episode repetitions. No other effects were significant.

**Analyses of S-R repetition in the Simon task.** To get a better grasp on the present results we additionally investigated the influence of S-R repetitions/switches from N – 1 to N in the Simon task on the sequential modulation of the Simon effect in Experiment 1. With S-R repetition we refer to the repetition of the relevant stimulus feature (arrow direction) and the required response. Previous research has shown that the investigation of S-R repetitions might provide additional insights into the mechanisms underlying the sequential modulation of interference effects (e.g., Mayr et al., 2003; Nieuwenhuis et al., 2006). For this reason we included the factor S-R repetition (response repetition vs. response switch in the Simon task) for the repeated-measures ANOVA (see also Table 1).

Responses were generally slower in S-R switches than in S-R repetitions,  $F(1, 25) = 97.57, MSE = 3,162.22, p < .001, \eta_p^2 = .796$ . This S-R repetition benefit was more pronounced in DT than in ST,  $F(1, 25) = 47.30, MSE = 2,221.87, p < .001, \eta_p^2 = .654$ , particularly when DT trials in N followed DT task trials in N – 1, as indicated by the interaction between task<sub>N-1</sub>, task<sub>N</sub>, and S-R repetition,  $F(1, 25) = 68.57, MSE = 1,977.27, p < .001, \eta_p^2 = .733$ . The S-R repetition benefit was generally larger when following Simon incompatible trials (47 ms) than following Simon compatible trials (30 ms),  $F(1, 25) = 18.84, MSE = 797.14, p < .001, \eta_p^2 = .430$ . Furthermore, the Simon effect was larger when

Table 1  
*Response Times and Percentage Error for the Simon Task Performance in Experiment 1*

	<i>N</i> - 1		<i>C</i>		<i>I</i>	
	<i>N</i>		<i>C</i>	<i>I</i>	<i>C</i>	<i>I</i>
Simon task SR switch						
ST-ST		<b>491 (14)</b>	<b>537 (13)</b>	<b>498 (11)</b>	<b>529 (15)</b>	
		1.4 (0.5)	3.5 (1.3)	1.3 (0.7)	2.2 (0.8)	
ST-DT		<b>959 (36)</b>	<b>969 (40)</b>	<b>994 (43)</b>	<b>1043 (45)</b>	
		6.4 (1.1)	5.8 (1.0)	8.2 (1.3)	9.9 (1.4)	
DT-ST		<b>528 (14)</b>	<b>607 (18)</b>	<b>566 (16)</b>	<b>592 (16)</b>	
		1.8 (0.5)	3.5 (1.0)	2.6 (0.7)	2.9 (0.8)	
DT-DT						
Tone SRsw		<b>914 (40)</b>	<b>939 (44)</b>	<b>923 (39)</b>	<b>960 (45)</b>	
		5.9 (0.9)	5.6 (0.9)	7.8 (1.0)	8.9 (1.2)	
Tone SRrep		<b>921 (43)</b>	<b>996 (43)</b>	<b>972 (43)</b>	<b>991 (43)</b>	
		3.8 (1.2)	8.0 (1.7)	4.2 (1.2)	6.1 (1.6)	
Simon task SR repetition						
ST-ST		<b>436 (9)</b>	<b>525 (13)</b>	<b>449 (9)</b>	<b>480 (11)</b>	
		0.5 (0.3)	4.8 (1.9)	0.6 (0.5)	1.0 (0.4)	
ST-DT		<b>907 (38)</b>	<b>973 (42)</b>	<b>956 (40)</b>	<b>990 (43)</b>	
		6.9 (1.5)	6.9 (1.3)	5.1 (1.0)	7.2 (1.1)	
DT-ST		<b>541 (14)</b>	<b>627 (18)</b>	<b>547 (15)</b>	<b>613 (20)</b>	
		4.3 (1.0)	5.0 (0.9)	2.4 (0.6)	7.2 (1.5)	
DT-DT						
Tone SRsw		<b>858 (38)</b>	<b>1016 (47)</b>	<b>918 (40)</b>	<b>964 (45)</b>	
		5.6 (1.0)	7.1 (1.2)	5.3 (0.9)	6.3 (0.9)	
Tone SRrep		<b>747 (34)</b>	<b>840 (35)</b>	<b>834 (32)</b>	<b>764 (31)</b>	
		1.9 (0.8)	3.2 (0.8)	2.2 (0.7)	3.2 (1.5)	

*Note.* Response times are given in means and are in boldface. Standard errors of mean are given in parentheses. C = Simon compatible; I = Simon incompatible; ST = single task; DT = dual task; SR = stimulus-response; Rep = repetitions; Sw = switches.

responses repeated in the Simon task (60 ms) than when they switched (40 ms),  $F(1, 25) = 30.98$ ,  $MSE = 736.34$ ,  $p < .001$ ,  $\eta_p^2 = .553$ . Most important for the present study, the sequential modulation of the Simon effect was much larger in conditions of S-R repetitions than in conditions of S-R switches,  $F(1, 25) = 27.44$ ,  $MSE = 1,081.57$ ,  $p < .001$ ,  $\eta_p^2 = .523$ . This pattern was stronger for DT than for ST,  $F(1, 25) = 21.84$ ,  $MSE = 1,124.87$ ,  $p < .001$ ,  $\eta_p^2 = .466$ , and furthermore, depended on the task-type transition from trial<sub>*N*-1</sub> to trial<sub>*N*</sub>, which is reflected in the significant interaction of all factors,  $F(1, 25) = 13.47$ ,  $MSE = 853.46$ ,  $p < .01$ ,  $\eta_p^2 = .350$  (see Table 1).

**Demonstrating reliable S2 location-based response activation in T2 of the DT.** As outlined above it is important to demonstrate the presence of location-based response activation in T2 to reveal a Simon effect even in conditions of maximum task overlap. For this (1) we calculated the S2-R1 cross-task Simon effect, (2) we investigated the effects of S2-R2 (Simon) conflict on T1 response selection (R2-R1 backward cross talk), and (3) we tested for potential decay of S2 location-based response activation in the Simon task.

**Cross-task Simon effect.** To test whether the S2 irrelevant location information got activated in T2 of the DT situation and affected T1 processing, we calculated the so-called cross-task Simon effect (Müsseler et al., 2005, 2006). This effect is reflected in a S2-location-R1-location correspondence with faster responses when S2-R1 locations correspond than when they do not. An ANOVA on RT1 for only DT trials revealed a significant S2-R1 location correspondence effect (cross-task Simon effect),  $F(1,$

$25) = 71.89$ ,  $MSE = 192.08$ ,  $p < .001$ ,  $\eta_p^2 = .742$ , indicating faster T1 responses for S2-R1 correspondence (802 ms) than for S2-R1 noncorrespondence (834 ms).

**Effects of S2-R2 conflict on T1 response selection.** We tested whether a conflict in specifying spatial response codes in T2 (Simon conflict) occurs despite a processing bottleneck in T2. This was tested via backward cross-talk effects on RT1 on the basis of R2-R1 spatial correspondence (e.g., R1 – left response and R2 – left response versus R1 – left response and R2 – right response). Backward cross talk represents faster responses in T1 when R1 and R2 activate the same spatial code than when they activate different spatial codes. Now, any present conflict between S2 location information and S2 identity information should affect the specification of R2 response code parameters. That is, R2 response code activation should be delayed in Simon incompatible conditions and facilitated in Simon compatible conditions. This influence should in turn affect R2-R1 backward cross-talk effects. We conducted an ANOVA on RT1 including the factors R2-R1 correspondence (corresponding vs. noncorresponding) and T2 Simon compatibility (compatible vs. incompatible). The main effect of R2-R1 correspondence showed that RT1 was shorter when both responses spatially corresponded (796 ms) than when they did not correspond (835 ms),  $F(1, 25) = 7.15$ ,  $MSE = 5,780.40$ ,  $p < .05$ ,  $\eta_p^2 = .222$ , reflecting the backward cross-talk effect. R1 were 37 ms faster when S2 and R2 corresponded (Simon compatible) than when they did not correspond (Simon incompatible),  $F(1, 25) = 21.87$ ,  $MSE = 1,592.17$ ,  $p < .001$ ,  $\eta_p^2 = .467$ . More important, we found an interaction between R2-R1 correspondence and T2 Si-

mon compatibility,  $F(1, 25) = 93.41$ ,  $MSE = 356.76$ ,  $p < .001$ ,  $\eta_p^2 = .789$ . That is, spatially mediated R2-R1 backward cross talk onto T1 processing was more pronounced when R2 response codes were specified faster (i.e., Simon compatible trials of Task 2) compared to when R2 response codes were specified slower (i.e., Simon incompatible trials of Task 2). Thus, the time to specify R2 response codes also determined the temporal overlap between tasks providing more vs. less time for backward cross talk to affect T1 response selection.

#### Analysis of decay of S2 location-based response activation.

To confirm that the present version of the Simon task is insensitive to decay of response codes we analyzed cumulative distribution functions (e.g., De Jong, Liang, & Lauber, 1994). Therefore, we computed percentiles (10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, and 90%) for each participant and factorial combination (Simon Compatibility  $\times$  Task Episode). Most important for the present aim, the Simon effect did not decrease but grew even larger with increasing RTs,  $F(8, 200) = 7.33$ ,  $MSE = 1,917.86$ ,  $p < .01$ ,  $\eta_p^2 = .227$ . That is, we obtained Simon effects of 42, 43, 43, 45, 45, 46, 50, 52, 77 ms for the percentiles 10 to 90%, respectively. This pattern of an increasing Simon effect appeared somewhat more pronounced for STs than for DTs, yet the interaction between Simon Compatibility  $\times$  Task Episode  $\times$  Percentile was only marginally significant,  $F(8, 200) = 2.59$ ,  $MSE = 1,436.40$ ,  $p = .081$ ,  $\eta_p^2 = .094$ .

## Discussion

In Experiment 1 we investigated whether mechanisms responsible for sequential modulations of the Simon effect first, are impaired by additional task load due to DT performance and second, depended on the contextual similarity. For this reason, we compared the sequential modulation of the Simon effect in ST episodes with that of DT episodes and between repetitions versus changes of task episodes.

First of all, we found significant performance decrements in DT compared to ST performance. In line with DT theories (e.g., Meyer & Kieras, 1997), responses in the Simon task were much slower (about 400 ms) and more erroneous when the Simon task was performed as T2 compared to when performed as ST. These results show that the DT manipulation is sufficient to produce substantial attentional limitations revealed in typical DT costs. Furthermore, and equally important, the Simon effect was only little, if at all, affected by the attentional task load. In particular, even in DT trials in which Simon task processing is prolonged due to T1 bottleneck stage processing, the Simon effect was not smaller compared to the Simon effect in the ST condition. In addition, T2 Simon compatibility not only affected response code activation of R2 but also determined R2-R1 cross-talk effects resulting in Simon effects in both tasks (we will explain this finding and its consequences in more detail in the General Discussion). For now it is important to note that the finding of reliable S2 location-based response activation and thus, a reliable Simon effect in attentionally demanding DT episodes secures that the particular version of the Simon paradigm in the present study is able to produce fairly robust and decay-insensitive Simon compatibility effects (see also Fischer et al., 2010) and thus, justifies the chosen design for the aim of the study.

Of most interest, however, were the results with respect to the sequential modulation of the Simon effect under the manipulations of attentional limitations and task-episode similarity. First of all, typical sequential modulations of the Simon effect were found in repeating ST episodes (ST were performed in  $\text{trial}_{N-1}$  and in  $\text{trial}_N$ , ST-ST), which replicates numerous studies on sequential modulations in a Simon task (Akçay & Hazeltine, 2007; Fischer et al., 2008; Hommel et al., 2004; Stürmer et al., 2002; Wühr, 2005; Wühr & Ansorge, 2005). More important, the sequential modulation of the Simon effect was reduced when attentionally demanding DT episodes occurred specifically in  $\text{trial}_{N-1}$  (DT-ST) or in  $\text{trial}_N$  (ST-DT). Surprisingly, however, a strong sequential modulation of the Simon effect was also found in conditions of highest attentional limitations, that is, when a DT episode was performed in  $\text{trial}_{N-1}$  and in  $\text{trial}_N$ . This finding suggests that task-load manipulations alone, although sufficient in creating severe performance decrements, seem not to determine whether sequential modulations occur.

At present, the results fit perfectly with the assumptions derived from the hypothesis of task-episode similarity as a determining factor of the occurrence of the sequential modulation of the Simon effect. As already mentioned, strong sequential modulations of the Simon effect were found in conditions of task-episode repetitions (ST-ST and DT-DT) but not consistently in conditions of task-episode switches (e.g., ST-DT). This observation received further support by an additional ANOVA with the factors task episode (repetition vs. change),  $\text{Simon}_{N-1}$  and  $\text{Simon}_N$ , which all three interacted,  $F(1, 25) = 10.77$ ,  $MSE = 522.82$ ,  $p < .01$ ,  $\eta_p^2 = .301$ . To investigate the effects of task-episode similarity in more detail, we studied the influence of S-R repetitions in the Simon task. As expected, the sequential modulation of the Simon effect was more pronounced in conditions of S-R repetitions compared to S-R switches.

The only condition without any evidence of a sequential modulation of the Simon effect was the ST-DT transition. Therefore current results suggest that task-episode similarity determines the occurrence of sequential modulations of the Simon effect whereas attentional limitations seem to be of less importance. However, it is possible though that, unpredictable task-episode switches instead of task-episode dissimilarities might be responsible for the not observed (or small) sequential modulations of the Simon effect in conditions of task-episode changes (i.e., ST-DT and DT-ST). Experiments 2 and 3 were designed to investigate this aspect in more detail.

## Experiments 2a and 2b

To further study the impact of attentional resources and task-episode similarity on the sequential modulation of the Simon effect, in Experiments 2a and 2b  $\text{trial}_{N-1}$  and  $\text{trial}_N$  were presented in pairs of trials, so-called prime and probe trials, respectively. We chose pair wise presentation with fixed task type in prime and probe trials, because such a design contains several advantages: First, each prime-probe pair is separated from other prime-probe pairs by an additional event. That is, after the probe trial, participants self-initiate the next trial pair by pressing a separate response key. This is supposed to separate the prime trial from influences of the former probe trial (see also Fischer & Hagendorf, 2006). Second, participants know about the structure of events (task

episode). In Experiment 2a, for example, a ST episode in the prime trial was always followed by a DT episode in the probe trial (ST-DT task transition). That is, participants knew that once they had performed a ST a DT would follow in all cases, which makes the change of task episodes from prime to probe perfectly predictable in Experiment 2 compared to Experiment 1. Furthermore, such predictable task episodes ensure that participants can reliably prepare for a ST episode, for example, when they know that a ST episode will come next. In contrast, in the unpredictable task episode condition of Experiment 1, a ST episode might not have been perceived as a true ST because participants still might have expected a DT to occur on a random individual trial, which consequently could increase attentional load also for ST episodes.

The prime-probe manipulation of task episodes further tests the assumption that the similarity of task episodes determines sequential modulations. If the sequential modulation of the Simon effect does depend on the similarity of the task episodes, strongly reduced or no sequential modulations of the Simon effect would be expected in the ST-DT or DT-ST condition. If however, the unpredictability of changes in task episode was the critical factor for the small or even not observed sequential modulation of the Simon effect in task-episode changes (e.g., ST-DT), sequential modulations of the Simon effect should be found in the current setting.

Therefore, in Experiment 2a we investigated the condition of a task-episode change in which participants consistently performed a ST in the prime trial and a DT in the subsequent probe trial (ST-DT). In Experiment 2b, probe trials always consisted of ST trials and the attentionally demanding DT episode was placed in prime trials only (DT-ST). In addition to the blocks of task-episode changes (ST-DT vs. DT-ST), participants in Experiment 2a and 2b also performed a separate block with predictable ST episode repetitions (ST-ST).

## Method

**Participants.** A fresh sample of 24 students (18 women,  $M$  age = 25.4 years) and 28 students (22 women,  $M$  age = 21.6 years, range 19 to 33 years) from the Dresden University of Technology took part in Experiment 2a and 2b, respectively. All had normal or corrected-to-normal vision and received €5 in payment.

**Apparatus and stimuli.** Stimuli and apparatus were identical to those in Experiment 1 unless noted otherwise. Because in Experiment 2 participants performed separate blocks with ST-ST task episodes and blocks with ST-DT or DT-ST task episodes, Simon ST were performed more often than DT. For this reason, we decided to switch the response finger mapping so that participants responded now with the index fingers to the more frequent Simon task and with the middle fingers to the tone task. The task specific S-R mapping was held constant (left pointing-left, right pointing-right, low tone-left, and high tone-right, for Simon and tone task, respectively).

**Procedure.** In Experiment 2 trials were presented in pairs and consisted of a prime trial ( $\text{trial}_{N-1}$ ) and an immediately following probe trial ( $\text{trial}_N$ ). In Experiment 2a as well as in Experiment 2b participants performed two blocks with 160 prime-probe pairs each. In one block of Experiment 2a the prime as well as the probe trial consisted of a single Simon task (ST-ST). For the other block

the prime trial was made of ST episodes and the probe trial consisted of DT episodes (ST-DT). In Experiment 2b, participants also performed a ST block and another block of trials in which the prime trial consisted of a DT episode and the probe trial contained a single Simon task (DT-ST). In each experiment the order of blocks was counterbalanced between participants.

The trial structure was almost identical to Experiment 1. The prime trial was followed by the probe trial. After responding to the probe trial, the German word for *next* (*weiter*) was presented. Participants initiated the start of the following prime-probe pair by pressing the space bar with their right thumb. This procedure ensured that prime and probe were closely linked as a trial pair. The ST block was preceded by four, the DT block by 16 prime-probe pairs serving as practice.

## Results

**Experiment 2a.** Trials with an erroneous response in either task were excluded from probe RT analyses (7.2%). Furthermore, probe RTs of the Simon and tone task were outlier corrected (1.9%;  $\pm 2.5$  SD per participant and condition mean) before they entered a repeated-measures ANOVA with the factors task episode<sub>PROBE</sub> (ST vs. DT), Simon<sub>PRIME</sub> (C vs. I), and Simon<sub>PROBE</sub> (C vs. I) on probe RTs of the Simon task. Main results are presented in Figure 2.

**RTs.** RTs were strongly affected by the factor task episode<sub>PROBE</sub>,  $F(1, 23) = 327.06$ ,  $MSE = 52,995.54$ ,  $p < .001$ ,  $\eta_p^2 = .934$ . As expected, responses in the Simon task of the probe trial were drastically slower in DT (1,045 ms) compared to ST (444 ms). Irrespective of this RT difference between task episodes, we found a reliable Simon effect (43 ms),  $F(1, 23) = 38.26$ ,  $MSE = 2,359.39$ ,  $p < .001$ ,  $\eta_p^2 = .625$ . Most important, however, the Simon effect did not differ between ST and DT episodes in the probe trial,  $F < 1$ . That is, the task load in the probe trial and/or the repetition/change of task episode from prime to probe (ST-DT vs. ST-ST) did not affect the size of the Simon effect. The Simon effect in the probe trial was affected by previous Simon compatibility, indicating reduced Simon effects after incompatible (29 ms) compared to compatible trials (58 ms), as reflected in the interaction between Simon<sub>PRIME</sub> and Simon<sub>PROBE</sub>,  $F(1, 23) = 4.57$ ,  $MSE = 2,146.89$ ,  $p < .05$ ,  $\eta_p^2 = .166$ . This sequential modulation of the Simon effect was not found in DT episodes (38 ms vs. 38 ms, for incompatible vs. compatible in  $N-1$ ) but only when the Simon task was performed alone in ST episodes (20 ms vs. 78 ms, for incompatible vs. compatible in  $N-1$ ), as reflected in a significant three-way interaction between task episode<sub>PROBE</sub>, Simon<sub>PRIME</sub>, and Simon<sub>PROBE</sub>,  $F(1, 23) = 6.07$ ,  $MSE = 1,637.63$ ,  $p < .05$ ,  $\eta_p^2 = .209$  (see also Figure 2).

**Errors.** The repeated-measures ANOVA on error rates included the same factors as the ANOVA on RTs and mirrored the RT data closely. Participants committed 6.8% errors in the Simon task. Many more errors were committed when the Simon task was performed as T2 in a DT episode (10.9%) compared to performance in a ST episode (2.8%),  $F(1, 23) = 49.77$ ,  $MSE = 63.69$ ,  $p < .001$ ,  $\eta_p^2 = .684$ . More errors were also produced in Simon incompatible (8.8%) than in Simon compatible trials (4.9%),  $F(1, 23) = 24.58$ ,  $MSE = 29.03$ ,  $p < .001$ ,  $\eta_p^2 = .517$ . This Simon effect did not differ between ST and DT episodes,  $F < 1$ . As in the RT data, a sequential modulation of the Simon effect was only found when the Simon task was performed as ST but not in the DT

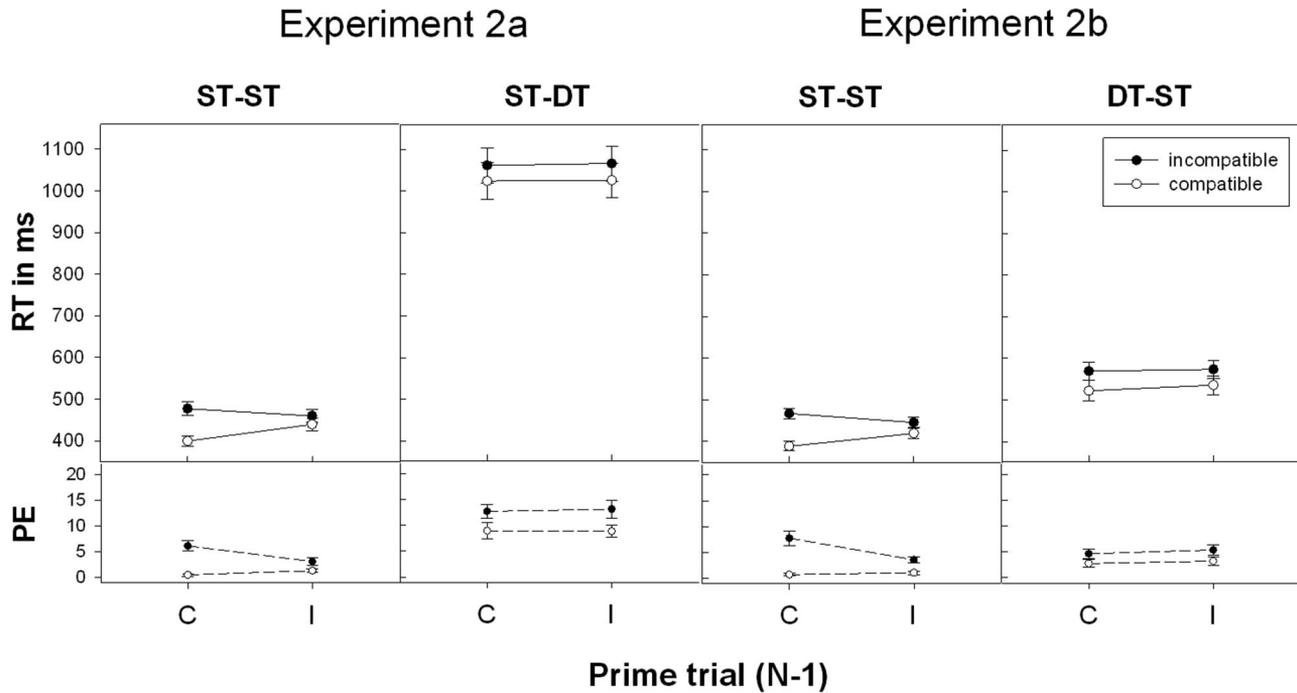


Figure 2. Response times (RTs in ms) and percentage error (PE) for the Simon task in Experiments 2a and 2b, respectively. The Simon effect in the probe trial ( $N$ ) is presented depending on Simon compatibility of the prime trial ( $N - 1$ ) and task-context transition from prime to probe (Experiment 2a: ST-ST vs. ST-DT; Experiment 2b: ST-ST vs. DT-ST). Error bars reflect standard error of mean. ST = single task; DT = dual task; C = Simon compatible; I = Simon incompatible.

episode (see Figure 2). This is confirmed by the significant interaction between task episode<sub>PROBE</sub>, Simon<sub>PRIME</sub>, and Simon<sub>PROBE</sub>,  $F(1, 23) = 5.17$ ,  $MSE = 11.08$ ,  $p < .05$ ,  $\eta_p^2 = .184$ .

**Analyses of S-R repetition in the Simon task.** As in Experiment 1 potential effects of S-R repetitions on RTs in the Simon task from prime trial to probe trial were investigated. The factor S-R repetition yielded overall faster responses in S-R repetition (734 ms) than in S-R switch conditions (754 ms),  $F(1, 23) = 8.15$ ,  $MSE = 4,434.90$ ,  $p < .01$ ,  $\eta_p^2 = .262$ . At the same time, S-R repetition did not affect the sequential modulation of the Simon effect,  $F < 1$ . However, benefits/costs of S-R repetition in the Simon task was mostly found in DT responses (36 ms) rather than in ST responses (4 ms),  $F(1, 23) = 6.13$ ,  $MSE = 3,667.52$ ,  $p < .05$ ,  $\eta_p^2 = .210$ . Because sequential modulations of the Simon effect were found only in the ST episodes, an additional repeated-measures ANOVA was conducted on RTs of the ST block alone (ST-ST). The sequential modulation of the Simon effect,  $F(1, 23) = 41.25$ ,  $MSE = 957.96$ ,  $p < .001$ ,  $\eta_p^2 = .642$ , was affected by the factor S-R repetition,  $F(1, 23) = 8.61$ ,  $MSE = 395.46$ ,  $p < .01$ ,  $\eta_p^2 = .272$ . That is, in trials of S-R repetition the sequential modulation of the Simon effect is more pronounced than in conditions of S-R switch. No such influence of S-R repetition on the sequential modulation was detectable in DT episodes,  $F < 1$  (see Table 2).

**Experiment 2b.** Error trials (3.6%) and RT outliers (2.8%;  $\pm 2.5$  SD per participant and condition mean) were omitted before probe trial RTs entered a repeated-measures ANOVA with the

factors task episode<sub>PRIME</sub> (ST vs. DT), Simon<sub>PRIME</sub> (C vs. I), and Simon<sub>PROBE</sub> (C vs. I). Main results are presented in Figure 2.

**RTs.** Responses in the single Simon task of the probe trial were slower when the prime trial contained a DT episode (550 ms) compared to a ST episode (430 ms), which is reflected in a main effect of the factor task episode<sub>PRIME</sub>,  $F(1, 27) = 64.28$ ,  $MSE = 12,593.90$ ,  $p < .001$ ,  $\eta_p^2 = .704$ . RTs were slightly increased (7 ms) following Simon incompatible compared to compatible trials,  $F(1, 27) = 6.90$ ,  $MSE = 386.82$ ,  $p < .05$ ,  $\eta_p^2 = .204$ . More important, we found a strong Simon effect (47 ms),  $F(1, 27) = 131.66$ ,  $MSE = 946.42$ ,  $p < .001$ ,  $\eta_p^2 = .830$ , that was not affected by task episode in the prime trial,  $F(1, 27) = 1.47$ ,  $MSE = 953.83$ ,  $p = .236$ ,  $\eta_p^2 = .052$ . This Simon effect, however, depended strongly on previous Simon compatibility,  $F(1, 27) = 19.95$ ,  $MSE = 657.29$ ,  $p < .001$ ,  $\eta_p^2 = .425$ , showing the typical sequential modulation with larger Simon effects after Simon compatible trials (62 ms) and decreased Simon effects after incompatible trials (32 ms). Most important for the present study, however, this sequential modulation of the Simon effect depended on the task episode in the prime trial,  $F(1, 27) = 14.92$ ,  $MSE = 444.33$ ,  $p < .01$ ,  $\eta_p^2 = .356$ . Subsequent analyses showed a reliable sequential modulation in ST-ST transitions,  $F(1, 27) = 84.93$ ,  $MSE = 226.05$ ,  $p < .001$ ,  $\eta_p^2 = .759$ , but none for DT-ST transitions,  $F < 1$  (see also Figure 2).

**Errors.** The same repeated-measures ANOVA was applied to the error data. The Simon effect in the RT data was also reflected in the error data. More errors were produced in Simon incompat-

Table 2  
*Response Times and Percentage Error for the Simon Probe-Task Performance in Experiments 2a and 2b*

Prime	(N - 1)	C		I	
Probe	(N)	C	I	C	I
Experiment 2a					
ST-ST	SR switch	<b>403 (14)</b> 0.6 (0.4)	<b>469 (16)</b> 7.1 (1.3)	<b>443 (16)</b> 1.1 (0.6)	<b>468 (18)</b> 3.5 (1.1)
	SR repetition	<b>395 (12)</b> 0.4 (0.3)	<b>485 (16)</b> 4.5 (1.1)	<b>435 (14)</b> 1.4 (0.5)	<b>451 (15)</b> 2.5 (0.8)
ST-DT	SR switch	<b>1,040 (47)</b> 14.1 (2.2)	<b>1,073 (47)</b> 17.5 (1.9)	<b>1,047 (42)</b> 13.6 (1.9)	<b>1,087 (41)</b> 18.0 (2.0)
	SR repetition	<b>1,008 (46)</b> 2.6 (0.9)	<b>1,051 (41)</b> 6.4 (1.1)	<b>1,005 (42)</b> 2.8 (0.8)	<b>1,045 (46)</b> 7.5 (1.6)
Experiment 2b					
ST-ST	SR switch	<b>393 (13)</b> 1.2 (0.4)	<b>464 (13)</b> 6.3 (1.4)	<b>426 (12)</b> 1.1 (0.4)	<b>457 (13)</b> 3.8 (0.6)
	SR repetition	<b>384 (11)</b> 0.3 (0.1)	<b>471 (13)</b> 9.3 (1.8)	<b>412 (12)</b> 1.1 (0.4)	<b>434 (12)</b> 3.4 (0.8)
DT-ST	SR switch	<b>536 (26)</b> 2.5 (0.8)	<b>560 (22)</b> 2.7 (0.7)	<b>540 (24)</b> 4.1 (0.7)	<b>579 (22)</b> 5.0 (1.1)
	SR repetition	<b>508 (25)</b> 3.0 (0.9)	<b>579 (24)</b> 6.6 (1.4)	<b>532 (23)</b> 2.3 (0.7)	<b>568 (25)</b> 5.7 (1.2)

*Note.* Response times are given in means and are in boldface. Standard errors of mean are reported in parentheses. C = Simon compatible; I = Simon incompatible; ST = single task; DT = dual task; SR = stimulus-response.

ible trials (5.3%) than in Simon compatible trials (1.9 %),  $F(1, 27) = 21.48$ ,  $MSE = 30.02$ ,  $p < .001$ ,  $\eta_p^2 = .443$ . We also found a sequential modulation of the Simon effect, which is confirmed in the interaction between  $\text{Simon}_{\text{PRIME}}$  and  $\text{Simon}_{\text{PROBE}}$ ,  $F(1, 27) = 6.34$ ,  $MSE = 10.13$ ,  $p < .05$ ,  $\eta_p^2 = .190$ . More important, this interaction was affected by task episode<sub>PRIME</sub>,  $F(1, 27) = 9.24$ ,  $MSE = 8.81$ ,  $p < .01$ ,  $\eta_p^2 = .255$ . As in RTs, a sequential modulation was present in the ST-ST transitions,  $F(1, 27) = 11.37$ ,  $MSE = 12.77$ ,  $p < .01$ ,  $\eta_p^2 = .296$ , but not in the DT-ST transitions,  $F < 1$ . Further significant results include the interaction between task episode<sub>PRIME</sub> and  $\text{Simon}_{\text{PRIME}}$ ,  $F(1, 27) = 11.10$ ,  $MSE = 7.89$ ,  $p < .01$ ,  $\eta_p^2 = .291$ . Specifically, in ST-ST transitions, more errors were committed when the prime trial was Simon compatible compared to incompatible. This pattern was reversed for the DT-ST transitions. Finally, there was an interaction between task episode<sub>PRIME</sub> and  $\text{Simon}_{\text{PROBE}}$ ,  $F(1, 27) = 17.72$ ,  $MSE = 6.05$ ,  $p < .001$ ,  $\eta_p^2 = .396$ . The Simon effect in the errors was more pronounced in the ST-ST than in the DT-ST transitions (see Table 2).

**Analyses of S-R repetition in the Simon task.** The sequential modulation of the Simon effect in RTs was affected by the factor S-R repetition,  $F(1, 27) = 8.63$ ,  $MSE = 1,194.87$ ,  $p < .01$ ,  $\eta_p^2 = .242$ . S-R repetitions produced stronger sequential modulations of the Simon effect than S-R switches. Subsequent repeated-measures ANOVAs were conducted on Simon task RTs separately according to transitions of task episodes. For ST-ST transitions, the sequential modulation of the Simon effect was stronger under S-R repetitions than under S-R switches,  $F(1, 27) = 10.60$ ,  $MSE = 221.73$ ,  $p < .01$ ,  $\eta_p^2 = .282$ . For DT-ST transitions, the factor S-R repetition also interacted with the factors  $\text{Simon}_{\text{PRIME}}$  and  $\text{Simon}_{\text{PROBE}}$ ,  $F(1, 27) = 5.33$ ,  $MSE = 1,700.09$ ,  $p < .05$ ,  $\eta_p^2 = .165$ , suggesting that there might be a sequential modulation of the Simon effect at least for conditions of

S-R repetition. Further testing revealed that this interaction missed the level of statistical significance,  $F(1, 27) = 3.68$ ,  $MSE = 2,294.30$ ,  $p = .066$ ,  $\eta_p^2 = .120$ .

**Between-experiment comparison.** ANOVAs on probe RT and percentage error in Experiments 2a and 2b, including the factors  $\text{Simon}_{\text{PRIME}}$ ,  $\text{Simon}_{\text{PROBE}}$ , and the between-experiment factor DT load ( $N - 1$  vs.  $N$ ), further demonstrated that the additive trial-to-trial modulation of the Simon effect did not depend on the locus of the DT-load manipulations ( $N - 1$  or  $N$ ), as the factor DT load did not show any interactions on RTs (all  $F$ s  $< 1$ ) or on percentage error,  $\text{Simon}_{\text{PROBE}} \times \text{DT Load}$ ,  $F(1, 50) = 2.26$ ,  $MSE = 22.90$ ,  $p = .139$ ,  $\eta_p^2 = .043$  (all other  $F$ s  $< 1$ ).

## Discussion

Performing different task transitions (i.e., ST-ST, ST-DT, DT-ST) in a block design closely replicated the findings of Experiment 1. Whereas sequential modulations of the Simon effect were found in predictable repetitions of task episodes (ST-ST), no sequential modulation was found for predictable changes of task episodes. The task-episode transitions in Experiments 2a (ST-DT) and 2b (DT-ST) differed in the respect that an intermediate (tone)-task had to be performed between the Simon tasks ( $N - 1$  and  $N$ ) in the ST-DT transitions, but no intermediate task was present in the DT-ST transitions. The fact that virtually identical results were obtained in both experiments with respect to the sequential modulation of the Simon effect suggests that local task switches do not influence sequential modulations in the present study (see also Wendt et al., 2006). Further, the constant knowledge about the specific task transition in a particular block of trials did not re-establish a sequential modulation of the Simon effect in the ST-DT or DT-ST transition. It is also unlikely that the long RSI

(2,600 ms) between prime and probe trial prevented the occurrence of any sequential modulation (see e.g., Notebaert et al., 2001) because reliable sequential modulations of interference effects have frequently been found also for long RSIs (e.g., Fischer et al., 2008, 2010; Notebaert et al., 2006). Instead, the results of Experiments 2a and 2b suggest that the specific type of task episode transition is responsible for the elimination of the sequential modulation of the Simon effect in the ST-DT and DT-ST transitions. The factor S-R repetition affected the sequential modulation of the Simon effect especially in ST-ST transitions, with more pronounced sequential modulations when the stimulus and the response of the Simon task repeated. No such effects were obtained in ST-DT transitions. Only in the DT-ST transitions of Experiment 2b, a slight but statistically unreliable sequential modulation of the Simon effect was found when the stimulus and the response of the Simon task repeated. Therefore, as already suggested by the findings of Experiment 1, task load in the prime or probe trial per se does not seem to determine whether sequential modulations of the Simon effect occur.

### Experiment 3

Experiment 3 aimed to replicate and extend the observation of a sequential modulation of the Simon effect in DT episodes of Experiment 1. Therefore, we tested the occurrence of the sequential modulation of the Simon effect under predictable repetitions of task episodes in a prime-probe design (DT-DT).

Because we reliably demonstrated sequential modulations of the Simon effect in ST blocks (ST-ST) in Experiments 2a and 2b, we omitted these blocks of ST-ST transitions in Experiment 3. Furthermore, we investigated the types of S-R repetition in more detail. Because, both tasks (tone and Simon task) were present in the prime and the probe trial, S-R repetitions/switches can occur in the tone task as well as in the Simon task. These S-R repetition conditions were captured in the factors SR-tone (repetition/switch) and SR-Simon (repetition/switch).

### Method

**Participants.** A fresh sample of 20 students (18 women,  $M$  age = 22.4 years, range 18 to 34 years) of the Dresden University of Technology participated in the experiment. All had normal or corrected-to-normal vision and received €5 in payment.

**Apparatus and stimuli.** Stimuli and apparatus were identical to those in Experiments 1 and 2.

**Procedure.** The procedure was identical to Experiment 2 except that prime- and probe-trials consisted of DT in which the Simon task served as T2. No ST block was conducted in Experiment 3.

### Results

One participant was excluded from analyses due to unusually high-probe trial error rates (>38%). Error trials in either task (11.0%) as well as probe RTs (Simon and tone task alike) that did not fit the outlier criterion (2.4%;  $\pm 2.5$  SD per participant and condition mean) were excluded from the RT analyses. Only Simon RTs were analyzed. The repeated-measures ANOVA on Simon RT and Simon errors included the factors SR-tone (S-R repetition vs.

switch), SR-Simon (S-R repetition vs. switch), Simon<sub>PRIME</sub> (C vs. I), and Simon<sub>PROBE</sub> (C vs. I).

**RTs.** Responses in the probe trial Simon task were slower in Simon incompatible conditions (1,004 ms) compared to compatible conditions (953 ms),  $F(1, 18) = 19.05$ ,  $MSE = 10,486.69$ ,  $p < .001$ ,  $\eta_p^2 = .514$ . This Simon effect was affected by the compatibility condition in the prime trial,  $F(1, 18) = 7.44$ ,  $MSE = 3,025.34$ ,  $p < .05$ ,  $\eta_p^2 = .292$ . Larger Simon effects were obtained after Simon compatible prime trials (69 ms) compared to Simon incompatible trials (34 ms), reflecting a typical sequential modulation of the Simon effect. This sequential modulation of the Simon effect depended on S-R repetitions in the tone task,  $F(1, 18) = 5.53$ ,  $MSE = 3,585.73$ ,  $p < .05$ ,  $\eta_p^2 = .235$ , as well as on S-R repetitions in the Simon task,  $F(1, 18) = 16.29$ ,  $MSE = 3,999.73$ ,  $p < .01$ ,  $\eta_p^2 = .475$ , which eventually, resulted in the interaction of all four factors,  $F(1, 18) = 13.42$ ,  $MSE = 3,549.37$ ,  $p < .01$ ,  $\eta_p^2 = .427$ . Figure 3 shows that we found only in conditions of S-R repetitions in both tasks (SRrep-SRrep) a sequential modulation of the Simon effect.

Finally, S-R switches in the tone task,  $F(1, 18) = 54.49$ ,  $MSE = 18,442.22$ ,  $p < .001$ ,  $\eta_p^2 = .752$ , as well as S-R switches in the Simon task,  $F(1, 18) = 59.20$ ,  $MSE = 12,469.40$ ,  $p < .001$ ,  $\eta_p^2 = .767$ , delayed T2 Simon task responses significantly. Both factors interacted,  $F(1, 18) = 70.16$ ,  $MSE = 9,308.83$ ,  $p < .001$ ,  $\eta_p^2 = .796$ , revealing that RTs were longest when responses in both tasks switched (1,039 ms) compared to when both responses repeated (826 ms), with intermediate RTs when only one response switched/repeated. The Simon effect was somewhat increased when responses switched from prime to probe trial. However, this effect was only significant for tone task response switches,  $F(1, 18) = 11.90$ ,  $MSE = 3,308.43$ ,  $p < .01$ ,  $\eta_p^2 = .398$ , but not for Simon task response switches,  $F(1, 18) = 1.62$ ,  $MSE = 4,300.82$ ,  $p = .219$ ,  $\eta_p^2 = .083$ .

**Errors.** Participants committed 9.3% errors in the probe Simon task. Overall, error data closely mirrored the RT data (see Figure 3). The repeated-measures ANOVA revealed more errors in Simon incompatible trials (11.5%) than in Simon compatible trials (7.1%),  $F(1, 18) = 11.06$ ,  $MSE = 137.55$ ,  $p < .01$ ,  $\eta_p^2 = .381$ . There was no overall sequential modulation of the Simon effect in the error data,  $F(1, 18) = 1.12$ ,  $MSE = 49.86$ ,  $p = .305$ ,  $\eta_p^2 = .058$ . However, the factor SR-tone as well as the factor SR-Simon interacted with the factors Simon<sub>PRIME</sub> and Simon<sub>PROBE</sub>,  $F(1, 18) = 5.34$ ,  $MSE = 19.95$ ,  $p < .05$ ,  $\eta_p^2 = .229$ , and  $F(1, 18) = 5.92$ ,  $MSE = 32.01$ ,  $p < .05$ ,  $\eta_p^2 = .247$ , respectively. The sequential modulation of the Simon effect was slightly reversed when responses switched in either task (see Figure 3). There was no four-way interaction,  $F < 1$ .

Furthermore, more errors were committed when responses switched in the tone task,  $F(1, 18) = 29.98$ ,  $MSE = 50.74$ ,  $p < .001$ ,  $\eta_p^2 = .625$ , than when responses repeated. This pattern was not significant in the Simon task,  $F < 1$ . However, both factors interacted,  $F(1, 18) = 9.04$ ,  $MSE = 55.36$ ,  $p < .01$ ,  $\eta_p^2 = .334$ . Finally, following Simon incompatible trials, participants made more errors when responses in the Simon task switched than when they repeated. This difference in errors was not found for compatible prime trials, resulting in the interaction between SR-Simon and Simon<sub>PRIME</sub>,  $F(1, 18) = 13.17$ ,  $MSE = 34.18$ ,  $p < .01$ ,  $\eta_p^2 = .423$ .

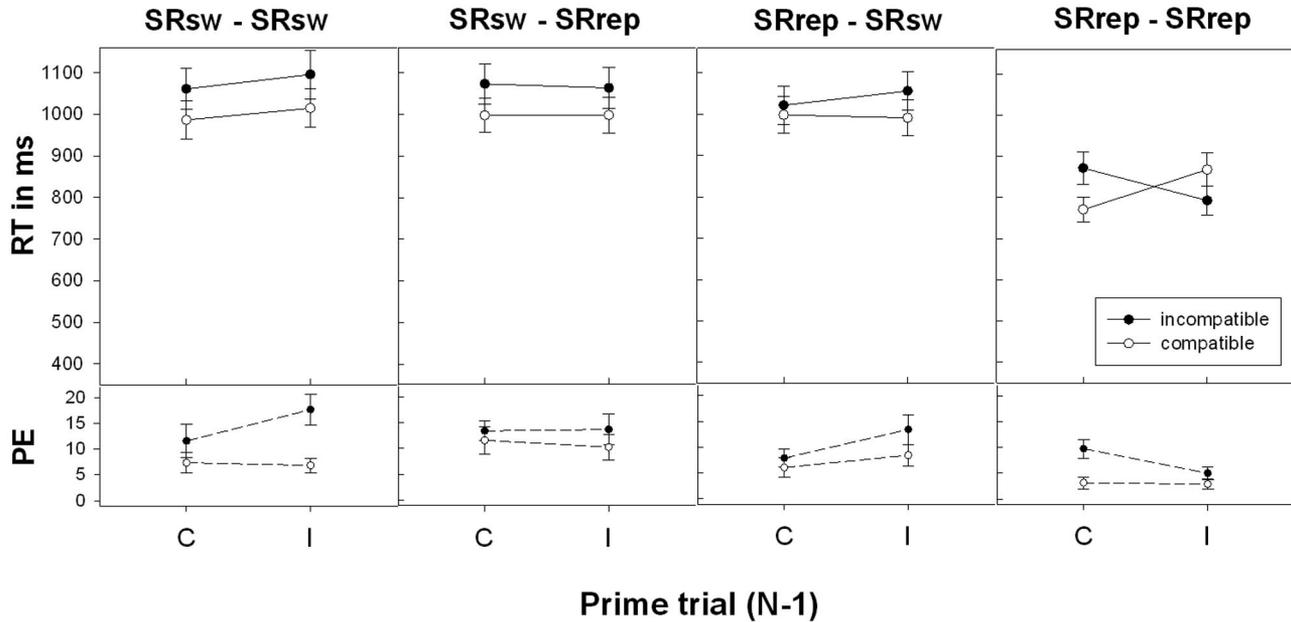


Figure 3. Response times (RTs in ms) and percentage error (PE) for the prime-probe Simon task in Experiment 3 depending on stimulus-response repetitions (SRrep) and stimulus-response switches (SRsw) for the auditory tone task and the visual Simon task, respectively. Error bars reflect standard error of mean. C = Simon compatible; I = Simon incompatible.

## Discussion

The results of Experiment 3 are quite clear and underline our previous findings in Experiment 1. That is, implementing DT specific attentional limitations in both, prime and probe trial did not prevent an overall reliable sequential modulation of the Simon effect. Further inspection of the data pattern revealed that the sequential modulation of the Simon effect was found only when stimuli and responses in the Simon task and tone task repeated but not so when they switched. That is, the only sequential modulation of the Simon effect in the DT-DT transitions was demonstrated in conditions of complete S-R repetitions in both tasks.

**The impact of S-R repetition in DT-DT transitions of Experiment 1.** Results of Experiment 3 show that a reliable sequential modulation of the Simon effect in predictable DT-DT transitions occurs only for complete S-R repetitions in both tasks. To investigate whether the same holds true for unpredictable DT-DT transitions, the data set of Experiment 1 was re-analyzed including the factors SR-tone (S-R repetition/switch in the tone task), SR-Simon (S-R repetition/switch in the Simon task),  $\text{Simon}_{N-1}$  (C, I) and  $\text{Simon}_N$  (C, I) for DT-DT transitions only. The sequential modulation of the Simon effect was more pronounced when responses repeated (compared to when they switched) in T1 (tone task),  $F(1, 25) = 7.28$ ,  $MSE = 3,107.44$ ,  $p < .05$ ,  $\eta_p^2 = .226$ . The same was observed when responses repeated in T2 (Simon task),  $F(1, 25) = 49.50$ ,  $MSE = 1,748.36$ ,  $p < .001$ ,  $\eta_p^2 = .664$ .<sup>3</sup> In contrast to Experiment 3, these effects cannot be accounted for solely by the condition of complete S-R repetitions. As illustrated in Figure 4 and tested by separate ANOVAs, sequential modulations of the Simon effect were found not only for complete S-R repetitions,  $F(1, 25) = 52.60$ ,  $MSE = 3,241.64$ ,  $p < .001$ ,  $\eta_p^2 =$

.678, but also for S-R repetitions in T1 and S-R switches in T2,  $F(1, 25) = 9.60$ ,  $MSE = 2,133.04$ ,  $p < .01$ ,  $\eta_p^2 = .277$ , and for S-R switches in T1 and S-R repetitions in T2,  $F(1, 25) = 22.52$ ,  $MSE = 3,652.55$ ,  $p < .001$ ,  $\eta_p^2 = .474$ . No sequential modulations were found for S-R switches in both tasks,  $F < 1$ .

## General Discussion

The aim of this study was to investigate the prerequisites of trial-to-trial sequential modulations of the Simon effect. For this purpose we specifically manipulated the availability of cognitive resources and the contextual similarity of repeating versus changing task episodes, respectively. In three experiments, the availability of cognitive resources was manipulated by performing a version of the Simon task either in a ST episode or as T2 of a DT episode. Contextual similarity, on the other hand, was investigated in form of repetitions of task episodes (ST-ST, DT-DT) versus

<sup>3</sup> Further significant results include the main effect of the factor SR-tone,  $F(1, 25) = 47.84$ ,  $MSE = 6,167.00$ ,  $p < .001$ ,  $\eta_p^2 = .657$ , and the factor SR-Simon,  $F(1, 25) = 73.53$ ,  $MSE = 10,104.95$ ,  $p < .001$ ,  $\eta_p^2 = .746$ . For each task, responses were faster for S-R repetitions than for S-R switches. Both factors also interacted,  $F(1, 25) = 87.42$ ,  $MSE = 9,456.87$ ,  $p < .001$ ,  $\eta_p^2 = .778$ . Larger Simon effects were obtained when responses switched in T1 (tone task) than when they repeated,  $F(1, 25) = 8.68$ ,  $MSE = 4,011.83$ ,  $p < .01$ ,  $\eta_p^2 = .258$ . A slightly reversed pattern was found for response repetitions in T2 which, however, was not significant,  $F(1, 25) = 3.03$ ,  $MSE = 2,668.44$ ,  $p = .094$ ,  $\eta_p^2 = .108$ . Finally, the size of the overall Simon effect depended on S-R repetitions in both tasks, which is statistically confirmed by the interaction between SR-Tone  $\times$  SR-Simon  $\times$   $\text{Simon}_N$ ,  $F(1, 25) = 32.89$ ,  $MSE = 2,258.70$ ,  $p < .001$ ,  $\eta_p^2 = .568$ .

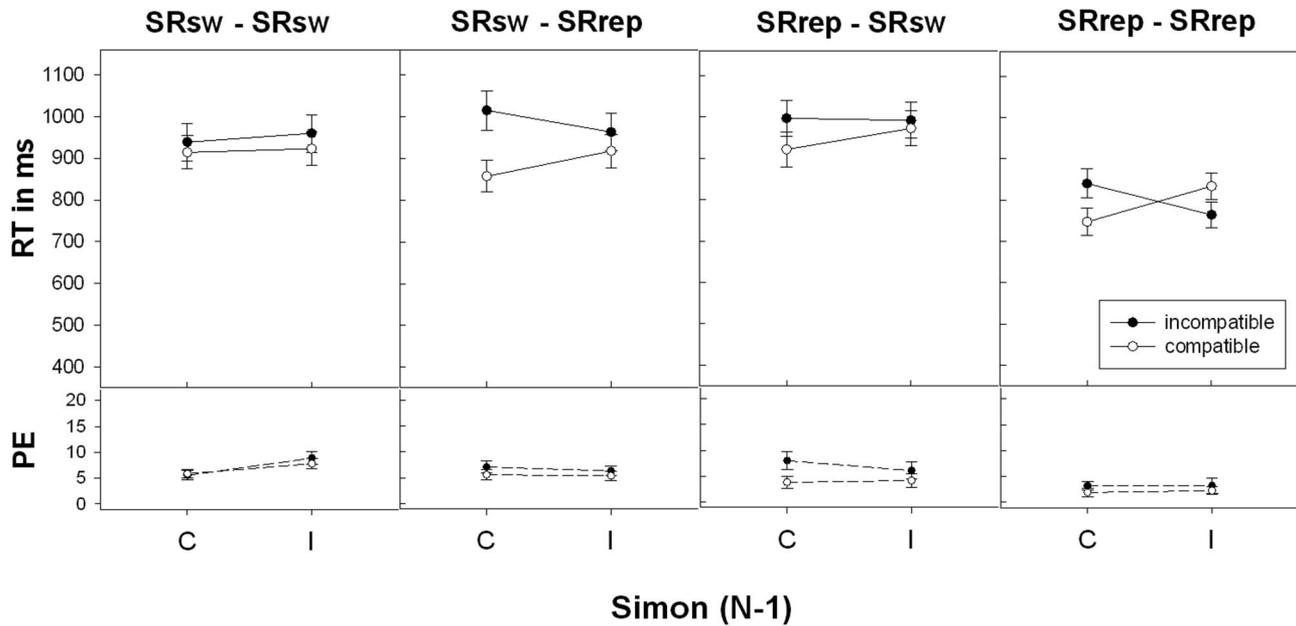


Figure 4. Response times (RTs in ms) and percentage error (PE) for the Simon task in Experiment 1 for task-episode repetitions ( $N - 1$  to  $N$ ) of dual-tasks only (DT-DT) displayed for stimulus-response repetitions (SRrep) and stimulus-response switches (SRsw) for the auditory tone task and the visual Simon task, respectively. Error bars reflect standard error of mean. C = Simon compatible; I = Simon incompatible.

changes of task episodes (ST-DT, DT-ST). Furthermore, we varied the transition of the task episode from  $N - 1$  to  $N$  presenting task episodes either unpredictable (Experiment 1) or completely predictable (Experiments 2 and 3).

First of all, our results showed that the manipulation of the availability of attentional resources was successful because large performance decrements (i.e., DT costs) were found in DT compared to ST performance. At the same time, a reliable Simon effect was observed in ST and DT episodes alike (see below for further discussion). Sequential modulations of the Simon effect were found in classical conditions of ST episodes in  $N - 1$  and in  $N$  (i.e., ST-ST, Experiments 1 and 2). As expected, the Simon effect was strongly reduced following incompatible trials but was reliably present to a much larger extent when following compatible trials, replicating a number of previous studies on trial-to-trial modulations of the Simon effect (Fischer et al., 2008, 2010; Stürmer et al., 2002; Wendt et al., 2006; Wühr & Ansorge, 2005). Under conditions of limited resources, however, the sequential modulation of the Simon effect was either small or eliminated when DT episodes were presented in  $N - 1$  (i.e., DT-ST, Experiments 1 and 2b, respectively) or completely eliminated when DT episodes were presented in  $N$  (i.e., ST-DT, Experiments 1 and 2a). This result pattern was generally the same irrespective of the predictability (Experiments 2a and 2b) or unpredictability (Experiment 1) of task load manipulations in  $N - 1$  and  $N$ . In contrast, reliable sequential modulations of the Simon effect were obtained when DT episodes were implemented in  $N - 1$  and in  $N$  (Experiment 1 and 3), representing the condition of maximum DT-specific attentional limitations. In sum, all three experiments revealed a consistent pattern of results by demonstrating that reliable sequential modulations of the Simon effect were consistently found only in con-

ditions of repeating task episodes (ST-ST, DT-DT) but not for changing task episodes (ST-DT, DT-ST). More important, in the conditions of contextual similarity the sequential modulation was demonstrated for both, lowest (ST-ST) and highest (DT-DT) DT-specific attentional load, respectively.

### Conflict Adaptation and Cognitive Control

Numerous studies have argued and provided evidence that the sequential modulation of interference effects can be explained by cognitive control processes that aim for adjusting, stabilizing and thus, regulating postconflict behavior (Botvinick et al., 2001; Botvinick, Cohen, & Carter, 2004; Kerns et al., 2004; Stürmer et al., 2002; Ullsperger et al., 2005). In previous studies, for example, it has often been suggested that conflict in a given trial triggers subsequent attentional changes in the next trial that alter processing in terms of enhanced target processing and/or suppression of distracting information (e.g., Botvinick et al., 2001; Goschke, 2000; Gratton et al., 1992).

Given that top-down behavioral control is strongly associated with slow, effortful, and resource demanding processing (Kornblum et al., 1990; Monsell, 1996; Norman & Shallice, 1986; Posner & Snyder, 1975) we assumed conflict-triggered adjustments due to cognitive control processes to be subject to manipulations of available cognitive resources. More important, in the present study we intentionally implemented DT-specific resource limitations (a) in the trial of conflict ( $N - 1$ ) to target immediate control activations (Fischer et al., 2008; Goschke & Dreisbach, 2008), (b) in the trial after the conflict to target potential conflict-triggered adaptive regulations (Botvinick et al., 2001; Gratton et al., 1992) or (c) in both trials at the same time ( $N - 1$  and  $N$ ).

In the context of control theory one would suggest that both, the immediate activation of control parameters ( $N - 1$ ) as well as the conflict adaptation in the postconflict trial ( $N$ ) is impaired when cognitive resources are limited due to performing DT episodes in either trial.

Surprising for this argumentation, however, sequential modulations of the Simon effect were obtained when cognitive resources were limited in each trial, that is, in conditions of maximum attentional load (Experiments 1 and 3). In fact, the sequential modulation of the Simon effect was most pronounced when the conflict trial in  $N - 1$  and the postconflict trial in  $N$  both contained a DT episode (DT-DT). This finding of trial-to-trial sequential modulations of the Simon effect in conditions of maximum attentional load (DT-DT) is, initially, hard to reconcile with assumptions of cognitive control processes regulating postconflict behavior. However, there are of course possibilities to pertain theories postulating the involvement of cognitive control mechanisms in those conditions. Further detailed analyses of DT-DT conditions, for example, revealed that the sequential modulation of the Simon effect was primarily or even exclusively (Experiments 1 and 3, respectively) observed when the required responses in the DT episode repeated from  $N - 1$  to  $N$  in T1 and also in T2. This finding could imply, that the sequential modulation of the Simon effect in DT-DT transitions is not related to conflict adaptation. Participants could follow a strategy like “if everything repeats—repeat the last responses.”<sup>4</sup> Although such a strategy might account for some of the data, however, it cannot explain findings from DT-DT transitions in Experiment 1. Here, sequential modulations of the Simon effect were also obtained for partial repetitions, in which responses repeated only in one but not in the other task. Therefore, we think that such a strategy is insufficient to account for our data set. Furthermore, scholars of cognitive control could argue that conflict triggered control adaptation is not an unconditional reactive mechanism that works automatically on the encounter of response conflict. Instead, this mechanism seems to critically depend on task parameters such as task structure or the amount of additionally involved top down mediated control processes (e.g., Akçay & Hazeltine, 2008; Fischer et al., 2008). One could speculate, for example, that conflict triggered control adaptation takes place when the required coordination of two simultaneous S-R translation processes in the DT episode is kept to a minimum. The repetition of the previously used S-R translation process in either task (Experiment 1) or even in both tasks (Experiment 3) provides the basis for an instantly established task set that allows conflict adaptation processes to be triggered. This reasoning, if true, suggests that, although conflict triggered adaptation processes are sometimes conceptualized as multiple, independent, and conflict-specific control mechanisms (cf. Egner, 2008), they don't seem that specific as that they would be independent of manipulations of the global DT context. Of course, at this stage this argumentation appears rather intricately. Further research is clearly needed to elucidate the involvement of cognitive control mechanisms in conditions of attentional load manipulations.

### Conflict Adaptation and Episodic Retrieval

The findings of sequential modulations of the Simon effect for repetitions of task episodes (ST-ST, DT-DT) but not for changes of task episodes (ST-DT, DT-ST) are more at ease with conceptions

of context dependencies of conflict processing and episodic integration accounts as explanations of sequential modulations of the Simon effect (e.g., Hommel et al., 2004; Mayr et al., 2003; Nieuwenhuis et al., 2006; Notebaert et al., 2001; Wendt et al., 2006). Along these lines it has been argued that performing a particular trial of a task leads to the formation of an episodic representation of that event (Hommel, 2004; Hommel, Müsseler, Aschersleben, & Prinz, 2001). Such an episodic event representation is assumed to comprise a number of features, such as stimulus features of the encoded stimulus and motor patterns of the performed motor action. Subsequent performance is then affected by the level of similarity between current and previous event representation.

Recent studies suggested that not only local task features are bound into an event representation but also parameters of conflict status and potential control parameters associated with an experienced response conflict (Spapé & Hommel, 2008). Our results can be interpreted in these lines, by extending the assumed idea of event binding to even more global parameters of the task context that are bound into an event file, such as whether a task is performed in a ST episode or in the context of a DT episode. In this vein, the repetition of the event file provides not only particular information about stimulus and response features, but moreover automatically instantiates the required task sets of the required ST or DT performance. Facing significant changes in the global task context (e.g., changes from ST episodes to DT episodes or vice versa), might have resulted in a “reset” of the system and the necessity of creating a new event file to avoid confusion (cf. Spapé & Hommel, 2008). This might indeed explain the finding of eliminated sequential modulations of the Simon effect when task episodes change from one trial to the next. Moreover, at the task level, this might also explain, why a sequential modulation of the Simon effect in DT-DT repetitions was especially found for S-R repetitions in both tasks. In other words, even in the repetition of the DT episode, a change of responses in either task might have resulted in a significant change that required the formation of a new event file. Subsequent research is needed to disentangle more closely which parameters are assumed to define an event file and what are the interactions between local features of S-R links and more global task context features within an event file.

For episodic retrieval accounts, the observation that sequential modulations of the Simon effect were found as soon as the responses in one task (tone task or Simon task) in the DT-DT transitions of Experiment 1 repeated is also interesting. In Experiment 3, S-R repetitions in both tasks were necessary to reveal a sequential modulation of the Simon effect (see Figures 3 & 4). A speculative interpretation of this finding could be that in the fixed prime-probe structure of Experiment 3, context predictability might provide participants with the possibility to re-adjust during preparation for the subsequent trial. In the unpredictable condition of Experiment 1, participants would have to adjust “on the fly” once the context of processing (i.e., task episode) is identified, which might increase the likelihood of context-specific processing (Crump, Gong, & Milliken, 2006; Heinemann, Kunde, & Kiesel, 2009; Lehle & Hübner, 2008; Wendt, Kluwe, & Vietze, 2008). This finding might hint to the flexibility of episodic binding

<sup>4</sup> We thank Mike Wendt for suggesting this possibility.

processes. Note that the DT-DT transitions of Experiment 1 made only one fourth of all trial transitions because DT episodes were intermixed with ST episodes. In Experiment 3, the whole experiment consisted of DT-DT transitions that allowed for the “lazy” mode of context prediction. Therefore, we suggest that the global experimental context seems to determine what gets integrated into an episode. If task episodes vary unpredictable, each task is separately integrated into an episode. If however, task episodes are predictable, two tasks form a single episode. Note that this explanation might also account for the finding of a sequential modulation of the Simon effect in unpredictable DT-ST transitions (Experiment 1), which was not obtained in fixed prime-probe DT-ST transition (Experiment 2b).

The finding of sequential modulations of the Simon effect in DT-DT transitions has important implications. First, the occurrence of the sequential modulation of the Simon effect in task-episode repetitions was not determined by the complexity and thus, the attentional demands of the task episode. That is, the simultaneous performance of an additional task (T1) between previous and current Simon task (T2), including local switches of task component processing, did not eliminate the trial-to-trial effects of the sequential modulation. Assuming that the retrieval of event files can account for sequential modulations, we demonstrated that the contextual similarity on the level of the performed global task episode (i.e., similarity between the previous task episode and the current task episode) provides a determining factor for the occurrence of trial-to-trial sequential modulations of the Simon effect.

Second, the present results also have implications for the theory of feature binding and for assumptions about the binding process itself. For example, we assumed that performing a particular event results in the binding of a variety of stimulus, response, and task-context features. Our results of intact feature binding in situation of simultaneous DT performance extend findings from a recent study by Hommel (2005), in which he investigated the attentional requirements of binding processes when stimulus and response features were spontaneously integrated into a single event file. Although Hommel (2005) found that attentional manipulations had virtually no effect on feature integration processes, it should be noted that the manipulations on attention were rather moderate. Attentional manipulations included, for example, the presence of task irrelevant stimuli (Experiment 1), manipulation of temporal relations between stimulus and response (Experiments 2 and 3), and go/no-go manipulations (Experiments 4 and 5). Hommel (2005) stated “we cannot exclude the possibility that more drastic manipulations would be more successful” (p. 1080). Therefore, scholars of binding theory might take the present results as a demonstration of binding processes to work in situations of heavy attentional processing limitations such as PRP like DT performance.

### Implications for Theories of DT Performance

The present results extend findings from previous PRP studies that investigated Simon effects in T2 of a DT situation. That is, several authors found strongly reduced and even eliminated Simon effects in T2 of a DT situation when the two tasks were performed with short SOA, that is, in close temporal succession (e.g., Lien & Proctor, 2000; McCann & Johnston, 1992). In the present study we

could show that reliable Simon effects can be obtained in such a PRP like setting.

One reason for this result might be based on the specific version of the Simon task in which S2 location-based response activation is insensitive to decay (Experiment 1, Fischer et al., 2010). In particular, we used a Stroop-like Simon paradigm (see Kornblum et al., 1999) that is known to incorporate both, S-S conflict and S-R conflict. Theoretically, it is conceivable that reduced interference effects at short SOAs in previous PRP studies might be based on decay of S2 location-based response activation during the cognitive slack in a standard Simon S-R conflict. In contrast, reliable Simon effects in the present study with short SOA might be attributed to a sustained S-S conflict (i.e., the relevant stimulus dimension does overlap with the irrelevant stimulus dimension) that might occur at a later time point in stimulus processing (e.g., longer RTs) while the S-R conflict decays over time. It is also possible that both kinds of conflict are not independent of each other but rather combine and thus, increase the level of overall conflict. This could explain why the Simon effect increases with longer RTs, as shown in the distribution analysis. Another manipulation that seems a likely candidate to have caused a reliable Simon effect in T2 of the DT situation was the brief presentation of S2. We intentionally restricted the duration of S2 presentation to 200 ms and thus forced participants to extract S2 features right on stimulus onset. Without an S2 presentation deadline, feature extraction of S2 may be delayed until most of the critical bottleneck stage processing in T1 is finished. By that time, response activation of S2 might have decayed and may not interfere with the selection of the appropriate response to S2. Therefore, immediate processing of S2 ensures that S2 location-based response activation coincides and thus, interferes (1) with specifying response code parameters of R1 (cross-task Simon effect); (2) with the identification of S2; and eventually (3) with the specification of response code parameters of R2 (S2-R2 Simon effect) thus, increasing the likelihood of interference. This might explain why previous PRP studies including long S2 presentation times found reduced Simon effects at short SOA even in conditions including S-S and S-R conflict of a Stroop-like Simon paradigm (e.g., Lien & Proctor, 2000). Further research seems necessary to differentiate between these possibilities.

Another interesting result of the present study is the finding that the Simon effect in T2 of the DT episode was not different in size to the Simon effect in a ST episode (Experiments 1 and 2a). This finding extends previous studies on attentional load manipulations on Simon task performance by demonstrating that not only the serial performance of two successive tasks (Stürmer et al., 2005), but even much stronger manipulations of additional task load, such as the simultaneous performance of two tasks, does at least in the present design not affect the size of the Simon effect. Within this regard it is interesting to note that the observation that the Simon effect is not reduced under conditions of attentional load is in line with the load theory of selective attention, which assumes that increased working memory load does not decrease but may even increase distractor interference (e.g., de Fockert, Rees, Frith, & Lavie, 2001; Lavie, Hirst, de Fockert, & Viding, 2004; Park, Kim, & Chun, 2007).

Furthermore, not only did we find the Simon effect in T2 of the DT episode but also in Task 1 of the DT episode (i.e., tone task). We now briefly provide a possible explanation for this finding.

First of all, we assume that the irrelevant S2 location-based response activation affects the determination of R2 response codes. In addition, we assume that R2 response codes will become activated earlier when S2 location-based response activation corresponds with the location of the required R2 (Simon compatible). Likewise, R2 response code activation will take longer when S2 and R2 location do not correspond (Simon incompatible). In other words, the Simon conflict status in T2 determines the speed of T2 response code activation (Schubert, Fischer, & Stelzel, 2008). More important, numerous studies have shown that T2 response code activation can (a) occur in parallel to critical T1 processing and (b) does not at all proceed in isolation to T1 (e.g., Hommel, 1998a; Koch & Prinz, 2002; Lien & Proctor, 2002; Logan & Gordon, 2001; Logan & Schulkind, 2000; Miller, 2006; Miller & Alderton, 2006; Schubert et al., 2008; Tombu & Joliceour, 2003). Provided there is feature overlap between response codes in T2 and T1 (e.g., spatial left–right assignments of manual responses in both tasks) typical R2–R1 backward cross-talk effects will be observed on RT1. Any speed-up or delay (e.g., due to S2–R2 conflict relation) of T2 response code activation will in turn enable backward cross-talk effects onto T1 response code activation to start earlier or later in time (cf. Schubert et al., 2008). Therefore, T2 Simon compatibility determines the onset of the R2–R1 backward cross talk seen in T1 processing, which again proves that Simon conflict occurred in T2. Via backward cross talk, the T2 Simon effect gets transferred onto T1 response selection and eventually will be observable in RT1. Moreover, T2 Simon compatibility that affects T1 prebottleneck/bottleneck response selection stages, will eventually back-propagate onto T2 after completion of bottleneck stage processing in T1 (Schubert et al., 2008). Consequently, this results in Simon effects in RT1 and in RT2, which is what we found.

The present study provided evidence that mechanisms responsible for the sequential modulation of the Simon effect are not affected by attentional manipulations but are determined by similarities of event episodes. Trial-to-trial sequential modulations of the Simon effect were found in conditions of task episode repetitions (i.e., ST–ST and DT–DT) irrespective of the attentional task load. In DT transitions, the sequential modulation depended further on the S–R repetitions in at least one or in both tasks. No reliable sequential modulation of the Simon effect was found in conditions in which task episodes changed from one trial to the next (i.e., ST–DT and DT–ST) irrespective of S–R repetitions. Thus, our work adds further understanding to the conditions under which mechanisms held responsible for the sequential modulation of the Simon effect can occur.

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