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ORIGINAL ARTICLE

The impact of free-order and sequential-order instructions on task-order regulation in dual tasks

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Abstract Dual tasks (DTs) are characterized by the requirement for additional mechanisms that coordinate the processing order of two temporally overlapping tasks. These mechanisms are indicated by two types of costs that occur when comparing DT blocks with fixed and random orders of the component tasks. On a block level, task-order control costs are reflected in increased reaction times (RTs) in random-order compared to fixed-order blocks, indicating global, monitoring-based, coordination mechanisms. On a trial level, within random-order blocks, order-switch costs are indicated by increased RTs on order switch compared to order repetition trials, reflecting memory-based mechanisms that guide task-order in DTs. To test the nature of these mechanisms in two experiments, participants performed DTs in fixed- and random-order blocks. In random-order blocks, participants were either instructed to respond to both tasks according to the order of task presentation (sequential-order instruction) or instructed to freely decide in which order to perform both tasks (free-order instruction). As a result of both experiments, we demonstrated that task-order control costs were reduced under the free-order compared to the sequential-order instruction, whereas order-switch costs were not affected by our instruction manipulation. This pattern of results suggests that the task-order control costs reflect global processes of task-order regulation such as engaging monitoring processes that are sensitive to changes in order instructions, while order-switch costs reflect rather local memory-based mechanisms that occur irrespective of any effort to coordinate task-order.

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Introduction

Human performance is usually impaired in situations in which multiple tasks are performed simultaneously compared to situations in which the same tasks are performed separately. This can be shown in the dual-task (DT) paradigm, in which two choice reaction time tasks are performed simultaneously. In this paradigm, DT costs occur, which are reflected in slower reaction times (RTs) and/or increased error rates relative to single-task situations. DT costs are often explained by the assumption of a central capacity limitation (i.e., a bottleneck) at the response selection stage that requires the serial processing of both tasks (Pashler, 1994; Schubert, 1999, 2008). In previous years, research has addressed various questions regarding this bottleneck, for example, whether it is structural (Pashler, 1994) or strategic (Meyer & Kieras, 1997) in nature. However, irrespective of this and similar debates, until now, it still remains unknown how the processing order of two tasks is regulated at the central bottleneck stage. The aim of the current study is to investigate the mechanisms enabling humans to schedule the processing of two temporally overlapping tasks, and how these mechanisms are affected by different environmental demands such as task instructions.

Classical bottleneck models (Pashler, 1994) assume a rather passive scheduling mechanism that allocates the bottleneck to both tasks according to their arrival time at the bottleneck stage. However, many studies suggest that bottleneck processing does not necessarily result from a passive first-come-first-served scheduling. Instead, DT situations require additional mechanisms that regulate and guide the processing order of two tasks that compete for access to a capacity-limited or serially operating bottleneck (DeJong, 1995; Logan & Gordon, 2001; Luria & Meiran, 2003, 2006; Schubert, 1999, 2008; Sigman & Dehaene, 2006; Szameitat, Schubert, Müller, & von Cramon, 2002; Szameitat, Lepsien, von Cramon, Sterr, & Schubert, 2006).

Evidence for these mechanisms in DT situations comes from studies comparing DT performance in blocks with constant order and blocks with random order of both tasks (DeJong, 1995; Strobach, Soutschek, Antonenko, Flöel, & Schubert, 2015; Stelzel, Kraft, Brandt, & Schubert, 2008; Szameitat et al., 2002): in the study of Szameitat and colleagues, participants performed a DT consisting of an auditory and a visual choice reaction time task. DT trials were presented in two types of blocks: in fixed-order blocks, both stimuli were presented with a constant order throughout the whole block, i.e., either the visual stimulus as the first stimulus, or the auditory stimulus as the first stimulus. In random-order blocks, on the contrary, the presentation order of both stimuli varied randomly from trial to trial and unbeknownst to participants. Most importantly, participants were instructed to respond to both stimuli according to the order of their presentation. When comparing DT performance in these two kinds of blocks, task-order control costs arise, which are indicated by increased RTs and error rates for the tasks in random-order compared to fixed-order blocks. According to the authors, the increase in RTs reflects additional control processes that are required to coordinate the processing order of both tasks in random-order blocks but that are not required (or required to a lesser degree) in fixed-order blocks. Further evidence for these control processes comes from data of functional magnetic resonance imaging. These data revealed increased activation during random-order compared to fixed-order blocks in the lateral prefrontal cortex, a brain region reliably shown to be involved in cognitive control processes (Szameitat et al., 2002; see also Stelzel et al., 2008).

Moreover, evidence for mechanisms that guide the processing order in DTs comes from a similar line of research that investigated these mechanisms on a more fine-grained trial-by-trial level (DeJong, 1995; Luria & Meiran, 2003, 2006; Szameitat et al., 2006). In the study of Szameitat et al. (2006), participants performed a DT consisting of an auditory and a visual task in random-order blocks. Within these random-order blocks, the authors distinguished between two trial types: on same-order trials, response order was the same compared to the previous trial, e.g., on both trials, the visual task was responded to first and the auditory task second. On different-order trials, on the contrary, response order was reversed relative to the preceding trial, e.g., on the previous trial, the visual task was responded to first and the auditory task second, but on the next trial, the auditory task was responded to first and the visual task second. When comparing DT performance on both trial types, order-switch costs arise, which are indicated by slower RTs in different-order compared to same-order trials. In addition to blockwise task-order control costs, the occurrence of these trialwise costs provides sufficient evidence for control mechanisms that regulate and guide the processing order in DTs.

Although both task-order control and order-switch costs have been shown to be reliable phenomena (see also Stelzel et al., 2008; Strobach et al., 2015; Szameitat et al., 2002, 2006), the specific mechanisms underlying these two types of costs are still a matter of debate. Several studies have shown that performance parameters differ between task-order control costs and order-switch costs (Luria & Meiran, 2003) and that non-invasive stimulation protocols have differential impacts on these costs (Strobach et al., 2015). Hence, it is tempting to assume that both cost types reflect distinct mechanisms regulating and guiding the processing order of two tasks in DTs.

In more detail, recent studies proposed that order-switch costs may reflect memory-based mechanisms of task-order regulation. According to Schubert (2008; see also Hirsch, Nolden & Koch, 2017), the processing order of two tasks on a current trial can be prepared in advance based on the processing order on the previous trial: after the execution of a DT trial, information about task order is stored in episodic memory. This episodic order trace remains active over time and influences the DT performance on the subsequent trial. On same-order trials, this results in a performance benefit as the order trace primes the processing order of the previous trial. This is similar to single-task situations, in which automatic priming between repeating stimuli and/or responses in sequential task trials has been shown to have tremendous effects on response times in a number of studies (Hommel, 2004). On different-order trials, the activation of the order trace has to be overcome and the alternative processing order has to be initiated to switch the processing order, which causes additional processing costs. Thus, order-switch costs seem to reflect priming-related and transient memory-based mechanisms of task-order guidance that arise on a trial-by-trial level.

Unlike order-switch cost, task-order control costs seem to reflect rather global monitoring-based mechanisms of task-order regulation (Stelzel et al., 2008; Strobach et al., 2015). In fixed-order blocks, in which the two component tasks are presented with constant stimulus order, the demands on such monitoring-based mechanisms are reduced as participants can use the same task scheduling strategy throughout the entire block. In random-order blocks, however, the order of stimuli varies permanently. Since participants are asked to respond to the stimuli in the order of occurrence, they have to monitor the order of stimuli and permanently adjust the task processing order; this results in additional task-order control costs in random-order compared to fixed-order blocks. Preliminary evidence for the assumption that these costs reflect monitoring-based processes comes from a study showing that task instructions modulate DT performance (DeJong, 1995; see also Hendrich, Strobach, Müller, & Schubert, 2017 submitted). In this study, DeJong (1995, Experiment 2) presented DT trials in random-order blocks and tested two groups with different task instructions requiring different degrees of task-order monitoring: one group received a sequential-order instruction requiring participants to respond to both stimuli according to the order of their presentation. Thus, this group had to monitor and to adjust the processing order to a normative (pre-instructed) task-order specified by the stimulus sequence. The other group received a free-order instruction and could freely decide which task to perform first and which task second. The results showed that RTs for both tasks were faster in the free- compared to the sequential-order instruction group. Further, DeJong also analyzed the number of task-order reversal trials. In these trials, participants respond to the tasks in a reversed order relative to the order of stimulus presentation, e.g. if the visual stimulus is presented first and the auditory stimulus second, the response for the auditory task is given first and the response for the visual task second. When comparing both groups, the sequential-order instruction group produced less task-order reversals than the free-order instruction group.

According to DeJong (1995), these results indicate increased demands on global monitoring-based mechanisms of task-order regulation in the sequential-order group. The participants of this group have to monitor the sequence of stimuli, decide about the appropriate task-order corresponding to the perceived stimulus sequence, and adjust their processing order accordingly. This adjustment and the corresponding decrease in task-order reversals come, however, at the cost of increased RTs. In the free-order instruction group, in contrast, performance can be accomplished with less reliance to the stimulus order and with more reliance on an internally chosen order, which results in decreased RTs and increased task-order reversal rates relative to the sequential-order group.

The findings by DeJong (1995) give first evidence for the fact that instructions modulate task-order regulation processes in general. However, due to methodological issues, it is hard to draw clear conclusions about the specific effects of instructions on task-order control and order-switch costs, as well as their underlying mechanisms. First, DeJong only assessed DT performance on random-order blocks and did not include fixed-order blocks in his design. The latter would have been necessary to test the effect of instructions on task-order control costs, i.e., RT differences between fixed- and random-order blocks. Second, within the random-order blocks, the author did not distinguish between same-order and different-order trials, which makes it impossible to evaluate the impact of instructions on order-switch costs. The aim of this study was to disentangle the effect of instructions on task-order control and order-switch costs and their underlying mechanisms.

Rationale of the study

To dissociate the effects of instructions on monitoring- and memory-based mechanisms that are employed during DTs, we administered an instruction manipulation similar to the one used by DeJong (1995) and applied the following design logic (for a similar approach for task switching, see Rubin & Meiran, 2005): if an instruction manipulation affects monitoring-based mechanisms of task-order regulation, it should influence performance in random-order blocks compared to fixed-order blocks, i.e., the task-order control costs. In contrast, if the same manipulation has an impact on memory-based mechanisms of task-order guidance, the instruction would affect order-switch costs, i.e., the RT difference between same- and different-order trials.

In two experiments, participants performed a DT in fixed- and random-order blocks. In random-order blocks, participants received either a free-order or a sequential-order instruction. Under the free-order instruction, participants could respond to both tasks in the order they preferred, which should reduce the demands on monitoring-based mechanisms as there was neither a need to keep track of the stimulus order nor to match the processing order (like under the sequential-order instruction). We expected task-order reversal rates to increase under the free-order compared to the sequential-order instruction, as participants could base the processing order of both tasks on their free-order choice and not according to the normative stimulus order. In addition, we expected task-order control costs to decrease under the free-order compared to the sequential-order instruction due to decreased demands on monitoring-based mechanisms. Note that this hypothesis is in line with evidence from research on voluntary task switching, which showed faster RTs for situations with free task choice compared to situations with cued task choice (e.g., Mayr & Bell, 2006; but see Arrington & Logan, 2005).

Unlike task-order control costs, order-switch costs reflect mechanisms that guide the processing order by pre-activating an episodic memory trace containing the processing order of the tasks in the previous trial. These mechanisms should occur irrespective of any active effort to regulate the processing order according to instructions if they are based on a rather automatic activation of the processing order's memory trace from the previous trial. Several authors (Hommel, 2004; Mayr, 2002) showed that the repetition of certain task components between sequential trials can influence task performance independently of the operation of effortful control processes. Consequently, order-switch costs based on automatic pre-activation of the task order from a previous trial should be unaffected by an instruction manipulation requiring the adjustment of performance according to a normative task-order. Alternatively, it could be that in DT situations, task instructions affect priming-based mechanisms of response-order regulation, because some studies have shown that top–down control can interact with trial-based priming effects in task-switching situations (Dreisbach & Haider, 2006; Koch & Allport, 2006).

Experiment 1

In Experiment 1, the goal was to disentangle the effect of order instructions on monitoring- and memory-based mechanisms regulating and guiding task order in DTs. For that purpose, two groups of participants performed a DT in fixed- and random-order blocks under two different task-order instructions. One group was instructed to respond to both tasks according to stimulus order (sequential-order instruction) and the other group was instructed to freely decide about their response order (free-order instruction). We compared task-order control and order-switch costs under both instructions and hypothesized that task-order control cost should be reduced under the free-order compared to the sequential-order instruction.

Materials and methods

Participants

Fifty participants (40 female) took part in the experiment. Participants were randomly allocated to one of the two instruction groups. Half of the participants received the sequential-order and the remaining half the free-order instruction in random-order blocks. Mean age was 25.07 years (SD = 4.22 years). All participants reported normal or corrected-to-normal vision and hearing and received either course credit or payment (8 Euros/h) for their participation. Informed consent was obtained from all participants.

Apparatus and stimuli

The experiment was programmed in Presentation (Version 18.0 12.05.14) and run on a Dell Optiplex 760. Visual stimuli were presented on a 24 inch LCD monitor at a resolution of 1920 × 1080 pixels with a refresh rate of 144 Hz at a viewing distance of 80 cm. For the visual task, one of three white colored squares differing in size was presented centrally on a black background for 200 ms: a small square (1.8° × 1.8°), a medium-sized square (2.36° × 2.36°), or a large square (3.54° × 3.54°). Participants responded by pressing the ",", ".", and "-"-key on a QWERTZ keyboard with their right index, middle, and ring finger, respectively. Auditory stimuli were presented for 200 ms and consisted of three sine-wave tones with frequencies of 200, 650, and 1100 Hz. Participants were instructed to respond by pressing the "y", "x", and "c"-key with their left ring, middle, and index finger, respectively.

Design and procedure

The trial structure is shown in Fig. 1. Each trial began with the presentation of a fixation cross for 750 ms that was followed by a blank screen for 250 ms. Subsequently, both stimuli were presented sequentially for 200 ms each and separated by a constant SOA of 200 ms. After presentation of the stimuli, the screen was cleared for a response period of maximum 2850 ms, which was followed by an intertrial interval (ITI) of 750 ms. Error feedback was given for omitted responses as well as incorrect stimulus discrimination and consisted of the German words 'ZU LANGSAM' (too slow) or 'FALSCH' (incorrect), respectively. The feedback was presented centrally for 500 ms during the ITI.

DT trials were presented in fixed-order and random-order blocks. In fixed-order blocks, the order of stimulus presentation remained constant throughout the whole block (either blocks with the visual stimulus first or blocks with the auditory stimulus first). In random-order blocks, the stimulus order varied randomly from trial to trial with the visual task occurring first in half of all trials. In addition, we controlled for the occurrence of 50% trials with repetitions and switches of stimulus order relative to the previous trial.

Task instruction was manipulated on a group level: in random-order blocks, half of the participants received the free-order instruction, and the other half received the sequential-order instruction. In the sequential-order group,

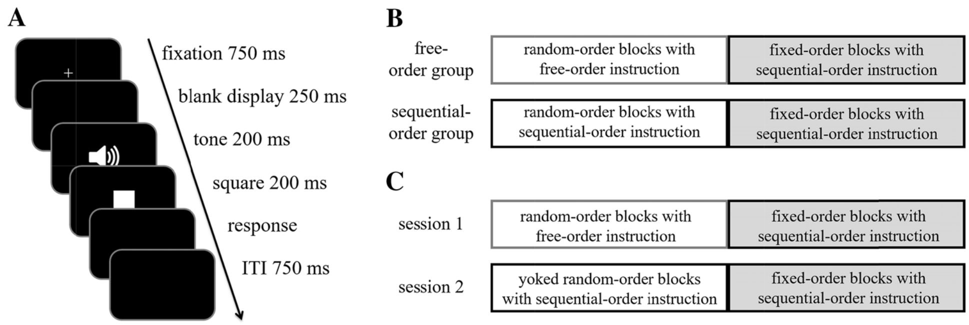

Fig. 1 Trial and block design for both experiments. **a** Time course for an exemplary DT trial in which the tone was presented first is shown on the *left*. **b** Block sequence for Experiment 1: on random-order blocks, the free-order group and the sequential-order group received the free-order and sequential-order instructions, respectively. After finishing the random-order blocks, participants of both groups performed fixed-order blocks with the sequential-order instruction. **c** Block and session sequence for Experiment 2: on session 1, participants first performed random-order DT blocks with a free-order instruction that were followed by fixed-order blocks with the sequential-order instruction. On session 2, participants first performed yoked random-order DT blocks with a sequential-order instruction, which were followed by fixed-order blocks with the same instruction. *ITI* intertrial interval, *white* and *light grey boxes* indicate random-order and fixed-order blocks, respectively, *grey* and *black frames* indicate blocks with the free- and the sequential-order instruction, respectively

participants were instructed to respond "on each trial as fast and accurately as possible to both stimuli in the same order in which they were presented". In the free-order group, participants were instructed to respond "on each trial as fast and accurately as possible to both stimuli and to freely decide which task to perform first". The free-order group was additionally instructed not to use a systematic response pattern, e.g., always reacting to the same task first or constantly alternating response orders between trials (DeJong, 1995). Note that this additional requirement might have increased processing demands during random-order blocks with the free-order instruction as participants have to exert top–down control to prevent systematic biases in their order choice. However, this additional instruction was necessary, as it prevents the most likely strategy, namely, to stay with a fixed response order, and, thus, guarantees a comparable amount of same- and different-order trials (for a similar approach in voluntary task switching, see Arrington & Logan, 2005).

In fixed-order blocks, all participants received the sequential-order instruction. This was necessary, as task-order control costs reflect additional processes that are required in DT blocks with variable task-order compared to DT blocks with fixed task-order. Thus, applying the sequential-order instruction in fixed-order blocks for both groups guaranteed a constant task-order in these blocks and allowed investigating whether additional processing demands in random-order compared to fixed-order blocks are modulated by different instructions.

At the beginning, participants completed four practice blocks: two single-task blocks with 12 trials and two random-order DT blocks with 18 trials each. The main experiment consisted of two parts: in the first part, participants performed six random-order blocks consisting of 72 trials each. These trials resulted from all possible combinations of visual stimuli (small, medium, and large square), auditory stimuli (200, 650, and 1100 Hz), order of stimuli on the present (auditory stimulus first and visual stimulus first), and the previous trial (repetition of stimulus order and switch of stimulus order). In the second part, after random-order blocks, DTs were presented in four fixed-order blocks under the sequential-order instruction for both groups with 72 trials each. In half of the fixed-order blocks, the auditory stimulus was presented first; in the other half, the visual stimulus was presented first. Random-order blocks were always administered before fixed-order blocks to avoid biasing participants' order choices in random-order blocks under the free-order instruction based on a previous fixed response order and its instruction in fixed-order blocks.

Results

Participants' RTs for the first task (task 1, RT1) and the second task (task 2, RT2) and task-order reversals, i.e., trials on which participants gave their responses in a reversed order relative to the order of stimuli, were used as dependent variables. For RT analyses, trials with RTs longer or shorter than ±2.0 standard deviations for each participant and condition as well as trials with incorrect or omitted responses were excluded ($m = 11.69\%$). In addition, for fixed- and random-order blocks with the sequential-order instruction, trials with task-order reversals ($m = 8.05\%$) were excluded from RT analyses, as participants were instructed to match their response order to the order of stimuli. We investigated RTs with two main analyses. First, to analyze task-order control costs, RTs from fixed- and random-order blocks were compared between both groups. In a second analysis, the effect of the instruction manipulation on order-switch costs was investigated by analyzing RTs from same- and different-order trials. Mean RTs for block and trial types were pooled across trials with the auditory and the visual stimulus presented first. Analyses of variances (ANOVAs) and post-hoc *t* tests were calculated using a significance threshold of 5%.

Task-order reversals

Under the free-order instruction, participants responded to the auditory stimulus first on 50.29% of the trials in random-order blocks, which indicates no strategic preference for one of the two potential response orders. Task-order reversals were analyzed to test whether participants followed the given instruction. According to DeJong (1995), larger amounts of task-order reversals should occur in the free-order compared to the sequential-order instruction group in random-order blocks. The percentages of task-order reversals are illustrated in Fig. 2 and were analyzed using an ANOVA with the within-subjects factor block type (fixed-order block, random-order block) and the between-subjects factor instruction group (sequential-order group and free-order group). This analysis revealed a main effect of the factor block type, $F(1, 48) = 137.39$, $p < .001$, $\eta^2 = .74$, showing that participants committed more task-order reversals in random-order [mean $(m) = 20.06\%$] than in fixed-order blocks ($m = 3.30\%$). Furthermore, the free-order group produced more task-order reversals ($m = 20.22\%$) than the sequential-order group ($m = 6.55\%$), $F(1,48) = 41.37$, $p < .001$, $\eta^2 = .46$. Most importantly, we found a significant block type × instruction group interaction, $F(1,48) = 19.37$, $p < .001$, $\eta^2 = .29$. Subsequent pairwise comparisons revealed that the increase in task-order reversals from fixed-order to random-order blocks was much larger in the free-order group ($m = 28.35\%$) compared to the sequential-order group ($m = 12.87\%$), $t(48) = 4.40$, $p < .001$. This pattern of results indicates that, in random-order blocks, the free-order group, in accordance with their instruction, performed both tasks with less reliance to the order of stimuli compared to the sequential-order group.

Note, however, that the participants' processing order under the free-order instruction was still biased in a bottom–up way by the order of stimuli. Though task-order reversal rates in random-order blocks were higher in the free-order ($m = 34.84\%$) compared to the sequential-order group ($m = 12.98\%$), $t(48) = 7.64$, $p < .001$, this percentage differed from a task-order reversal rate of 50% that one would expect in the free-order group if participants based their order choice solely on a "free" decision, $t(24) = 8.92$, $p < .001$. Thus, under the free-order instruction, the processing order of both tasks was not only influenced top–down by participants' free order choices, but also bottom–up by the order of stimuli on a given trial.

Task-order control costs

To test whether task-order control costs were reduced in the free-order group, we performed an ANOVA on RTs with the within-subjects factor tasks (task 1 and task 2) and block type (fixed-order and random-order blocks) and the between-subjects factor instruction group (sequential-order group and free-order group). This analysis revealed a significant main effect of the factor task, $F(1, 48) = 37.19$, $p < .001$, $\eta_p^2 = .44$. As can be seen in Table 1, RTs for task 1 ($m = 994$ ms) were faster than those for task 2 ($m = 1082$ ms). The main effect of the factor block type was also significant, $F(1, 48) = 190.87$, $p < .001$, $\eta_p^2 = .80$, indicating task-order control costs, i.e., slowed responses in random-order ($m = 1151$ ms) compared to fixed-order blocks ($m = 926$ ms).

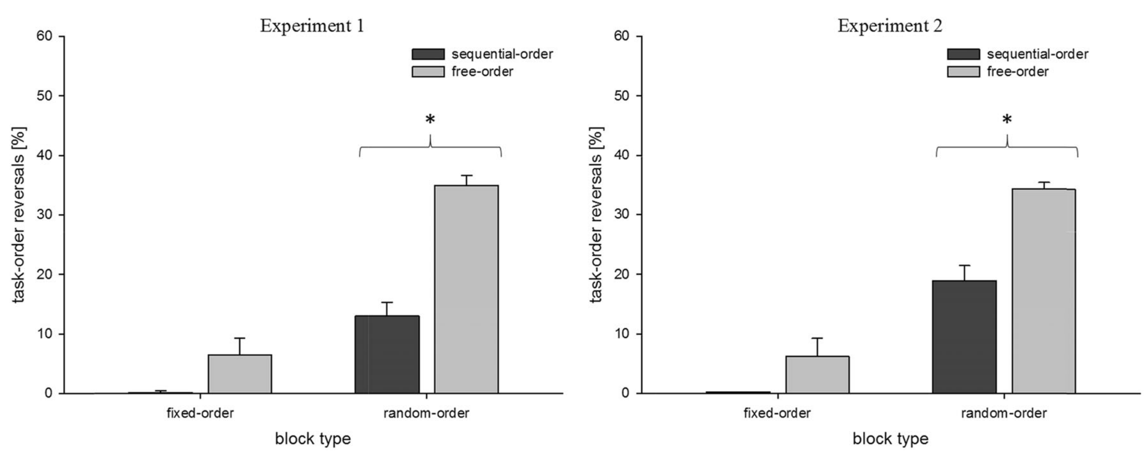

Fig. 2 Task-order reversals in % from Experiment 1 (*left panel*) and Experiment 2 (*right panel*) as a function of the factor block type (fixed-order blocks and random-order blocks), and instruction (sequential-order instruction and free-order instruction). *Error bars* denote the standard error of the mean. *Asterisks* denote a significant difference in task-order reversals between both instruction groups in random-order blocks ($p < 0.01$)

Table 1 Mean reaction times (and standard error of the mean) (in milliseconds) from Experiment 1 and Experiment 2 for Task 1 (RT1) and Task 2 (RT2) for each block (left) and trial type (right) depending on the instruction condition

Group	Experiment 1							
	Block type				Trial type from random-order blocks			
	Fixed-order blocks (with sequential-order instruction)		Random-order blocks (with group specific instruction)		Same-order trials (with group specific instruction)		Different-order trials (with group specific instruction)	
	RT1	RT2	RT1	RT2	RT1	RT2	RT1	RT2
Free-order	909 (209)	988 (242)	1056 (196)	1153 (238)	1021 (191)	1114 (235)	1092 (207)	1191 (246)
Sequential-order group	869 (257)	938 (252)	1143 (281)	1250. (282)	1110 (277)	1219 (275)	1176 (289)	1282 (295)

Session	Experiment 2							
	Block type				Trial type from random-order blocks			
	Fixed-order blocks (with sequential-order instruction)		Random-order blocks (with session specific instruction)		Same-order trials (with session specific instruction)		Different-order trials (with session specific instruction)	
	RT1	RT2	RT1	RT2	RT1	RT2	RT1	RT2
Session 1	939 (205)	1038 (252)	1119 (190)	1255 (254)	1081 (179)	1210 (255)	1156 (190)	1300 (260)
Session 2	909 (190)	990 (242)	1208 (233)	1319 (267)	1165 (236)	1272 (275)	1251 (238)	1366 (267)

The main effect of instruction group was not significant, $F(1, 48) < 1$, $p = .97$, $\eta_p^2 < .001$. However, we found a significant block type × instruction group interaction, $F(1, 48) = 17.82$, $p < .001$, $\eta_p^2 < .27$, suggesting that the factor instruction group modulated RT differences between fixed- and random-order blocks. Subsequent comparisons revealed that task-order control costs, i.e., the RT increase from fixed- to random-order blocks, were larger in the sequential-order ($m = 294$ ms) compared to the free-order group ($m = 156$ ms), $t(48) = 4.22$, $p < .001$ (see Fig. 3). This finding is in line with the assumption that the instruction manipulation affects monitoring-based mechanisms of task-order regulation.

In the following, we analyzed in more detail what the observed instruction-based influence on task-order control costs means for the specific response times of the two instruction groups in the fixed- and random-order blocks. According to DeJong (1995), one would expect that the free-order group should show faster RTs in random-order blocks compared to the sequential-order group, because in these blocks, the free-order group can perform DTs with less reliance on monitoring-based task-order regulation processes compared to the sequential-order group. In fixed-order blocks, on the contrary, groups should show similar DT performance as they both received the sequential-order instruction. As can be seen in Table 1, RTs on fixed-order blocks did not differ between the free- ($m = 948$ ms) and the sequential-order group ($m = 903$ ms), $t(48) = .68$, $p = .50$. On random-order blocks, on the contrary, the free-

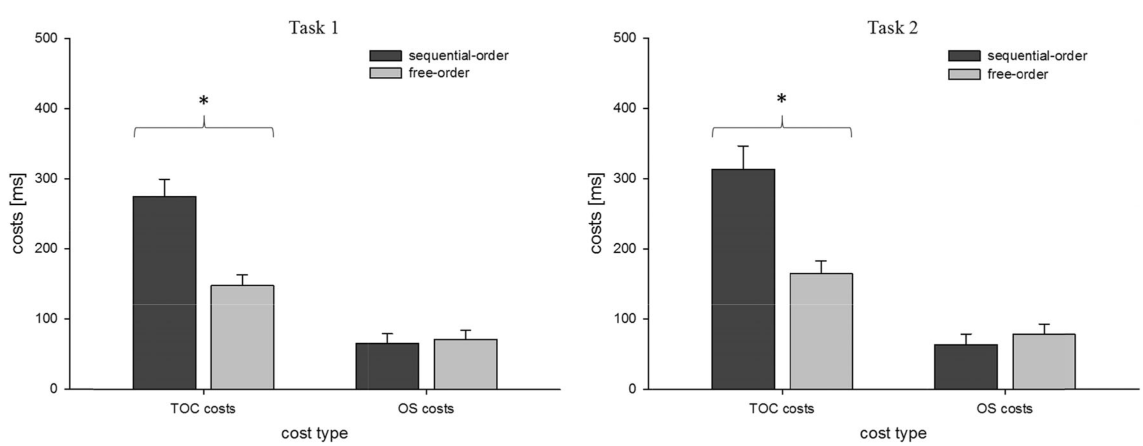

Fig. 3 Task-order control (TOC) costs and order-switch (OS) costs from Experiment 1 as a function of the factor instruction (sequential-order instruction and free-order instructions). *Error bars* denote the standard error of the mean. *Asterisks* denote a significant difference in task-order control costs between both instruction groups ($p < 0.01$). *Left panel* costs for task 1. *Right panel* costs for task 2

order group showed faster RTs ($m = 1105$ ms) relative to the sequential-order group ($m = 1197$ ms). However, this difference was not significant, $t(48) = 1.33$, $p = .19$. Note that despite the non-significant difference in RTs between both groups in random-order blocks, we found a decrease of task-order control costs in the free-order compared to the sequential-order group.

Furthermore, we found a significant task × block-type interaction, $F(1, 48) = 9.26$, $p = .004$, $\eta_p^2 = .16$, reflecting a reduced RT increase from task 1 to task 2 in fixed- ($m = 74$ ms) relative to random-order blocks ($m = 102$ ms), $t(48) = 3.03$, $p = .004$. In our view, this result suggests that if task-order is predictable under the condition of fixed-order blocks compared to random-order blocks, participants can also prepare for the switch from task 1 to task 2 (DeJong, 1995; Liepelt, Strobach, Frensch, & Schubert, 2011). Such a prepared switch allows for the reduced increase of RTs from task 1 to task 2 in fixed-order compared to random-order block for the two instruction conditions. Other interactions were not significant (all *p*s > .24).

Order-switch costs

To test whether order-switch costs were affected by instructions, we performed an ANOVA on RTs with the within-subjects factor tasks (task 1 and task 2), trial type (same-order trial and different-order trial), and the between-subjects factor instruction group (sequential-order group and free-order group). This analysis revealed a significant main effect of the factor task, $F(1, 48) = 39.18$, $p < .001$, $\eta_p^2 = .45$. As can be seen in Table 1, RTs for task 1 ($m = 1100$ ms) were faster than RTs for task 2 ($m = 1201$ ms). In addition, RTs increased from same-order ($m = 1116$ ms) to different-order trials ($m = 1185$ ms), $F(1, 48) = 49.55$, $p < .001$, $\eta_p^2 = .51$, indicating the occurrence of order-switch costs. There was no difference in RTs between both instruction groups, $F(1, 48) = 1{,}77$ $p = .19$, $\eta_p^2 = .04$. Importantly, the interaction of trial type and instruction was not significant, $F(1, 48) = .25$, $p = .62$, $\eta_p^2 < .01$, indicating that order-switch costs did not differ between instruction conditions[1]. No other interactions were significant (all *p*s = .24).

[1] To further analyze the lacking effect of the instruction manipulation on order switch costs, we applied Bayesian-like interference testing. According to Wagenmakers (2007), we tested the posterior probability ($Pr(H_0|D)$) of a hypothesis assuming a missing interaction of the factors Instruction group and Trial type versus a hypothesis assuming a significant interaction of these factors by calculating the Bayesian information criterion (BIC) between both. With $\Delta BIC = 3.66$ and $Pr(H0|D) = 0.86$ this analysis provides 'positive' evidence for the assumption that order-switch costs did not differ between both groups.

Discussion

The main finding of Experiment 1 is that (1) task-order control costs, i.e., RT differences between fixed- and random-order blocks, were reduced in the free-order compared to the sequential-order group and (2) order-switch costs, the RT difference between same- and different-order trials, were unaffected by the instruction manipulation. This is in line with the assumption that task-order control costs reflect monitoring-based processes of task-order regulation that are less employed under the free-order instruction. Order-switch costs, on the other hand, seem to reflect memory-based mechanisms of task-order guidance that are unaffected by the particular instruction manipulation applied in this study.

However, two puzzling findings of the current experiment need to be discussed and explored in a further experiment. First, although we found a modulation of task-order control costs by instructions, we could not replicate the finding of DeJong (1995) that RTs from random-order blocks differed between the two instruction groups. One reason for this result might be differences between the applied designs: in contrast to DeJong, we applied a fixed sequence of blocks (first random-order than fixed-order blocks). This fixed block sequence might have confounded our results. For example, different instructions on random-order blocks might have distinctively modulated performance on subsequent fixed-order blocks and, thus, led to differences in task-order control costs. Note that such carry-over effects would result in performance differences in fixed-order blocks between the two instruction groups. As reported, however, RTs on fixed-order blocks did not differ between both groups making the occurrence of instruction-dependent carry-over effects on fixed-order blocks rather unlikely. Alternatively, while in the present study, participants were tested on one single session and the different instructions were varied on a group level, DeJong manipulated his instruction on a within-subject level and tested his participants on three consecutive sessions. These differences in the study of DeJong may have, in contrast to the present study, facilitated observing RT differences between both instruction conditions on random-order blocks.

Second, a potential caveat of Experiment 1 is related to differences in the frequency of response order switches occurring during random-order blocks between the two groups. Research from task switching has shown that the frequency of task switches is usually reduced in voluntary task switching compared to situation with pre-defined task switches (e.g., Arrington & Logan, 2005; Reuss, Kiesel, Kunde, & Hommel, 2011). The reason for this is that when participants are instructed to freely choose between tasks, they usually tend to repeat tasks more often as this exposes less processing effort compared to frequent task switches. Similarly, in Experiment 1, during random-order blocks, participants from the free-order group showed a similar tendency to a reduced number of response-order switches ($m = 32.41\%$) relative to the sequential-order group ($m = 41.07\%$), $\chi^2(1) = 6.61$, $p = .01$. This difference in the order-switch frequency might have confounded our results. For example, it is conceivable that the overall task difficulty in random-order blocks increases with an increasing number of response-order switches. This may explain the observation of increased RTs on random-order compared to fixed-order blocks, which were especially prevalent in the sequential-order compared to the free-order group. Thus, an unequal number of order switches between groups might have resulted in increased task-order control costs in the sequential-order compared to the free-order group. In Experiment 2, we controlled for possible confounding influences of different-order-switch frequencies across conditions by applying a yoked design.

Experiment 2

The goal of Experiment 2 was to investigate the effect of instructions on monitoring-based processes of task-order regulation and to control for possible confounding effects that might have been related to different response order switch rates across the conditions in Experiment 1. For that purpose, we administered DT trials for both instruction conditions in a yoked design and varied task instructions as a within-subjects manipulation. To do so, we first administered random-order blocks with the free-order instruction, which provided us with a sequence of chosen task orders across the experimental condition individually for each participant. Subsequently, participants performed again a condition with random-order blocks but now with the sequential-order instruction; most importantly, in this sequential-order instruction condition, we presented the stimulus order for the two tasks on each DT trial in yoked fashion with the participants' chosen order in the initial free-order instruction condition (for a similar approach in task-switching, see also Masson & Carruthers, 2014). This yoking procedure should ensure similar order-switch rates in random-order blocks for both instruction conditions and it allowed us to apply a within-subjects manipulation of task-order instruction as was the case in DeJong (1995). As in Experiment 1, we hypothesized that task-order control costs should be reduced under the free-order compared to the sequential-order instruction.

Materials and methods

Participants

Twenty-five participants (23 female) took part in the experiment. Mean age was 22.16 years (SD = 2.69 years). All participants reported normal or corrected-to-normal vision and hearing and received either course credit or payment (8 Euros/h) for their participation. Informed consent was obtained from all participants included in the study. One participant did not return for the second session and her data were excluded from analyses.

Apparatus and stimuli

Apparatus and Stimuli were the same as in Experiment 1.

Design and procedure

Similar to Experiment 1, participants performed DTs in fixed- and random-order blocks. Differently to Experiment 1, the instruction manipulation was applied as a within-subjects factor. For this purpose, participants were tested on two sessions: on the first session (session 1), participants received the free-order instruction in random-order blocks, and on the second session (session 2), they received the sequential-order instruction. This sequence of the instruction conditions was chosen for two reasons. First, it guaranteed that participants' order choice in the free-order instruction condition was not affected by any prior experience with the sequential-order instruction. Second, in random-order blocks of session 2, stimulus order did not vary randomly, but instead, it was yoked with the individually selected response order of each participant in the session 1. The aim of this yoked design was to guarantee comparable order-switch rates across instruction conditions. On both sessions, after performing four random-order blocks, participant performed two fixed-order blocks with the sequential-order instruction (see Experiment 1). Blocks consisted of 72 trials each. Both sessions were separated by 7–10 days.

Results

The analytic procedure was similar to that of Experiment 1, except that session was included as a within-subjects factor in the analyses. Trials with RTs longer or shorter than ± 2.0 standard deviations for each participant and condition as well as trials with incorrect or omitted responses ($m = 12.81\%$) were excluded from RT analyses, as well as task-order reversals ($m = 8.43\%$) from blocks with the sequential-order instruction.

Task-order reversals

In random-order blocks under the free-order instruction, participants responded on 51.60% of trials to the auditory stimulus first, which indicated no preference for one of the two potential response orders. The percentages of task-order reversals are illustrated in Fig. 2 and were analyzed

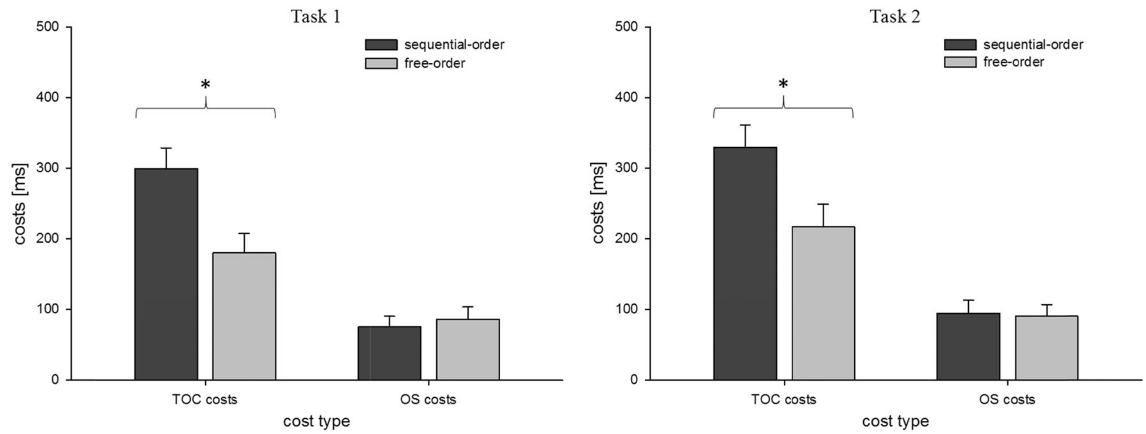

Fig. 4 Task-order control (TOC) costs and order-switch (OS) costs from Experiment 2 as a function of the factor Instruction (sequential-order instruction and free-order instructions). *Error bars* denote the standard error of the mean. *Asterisks* denote a significant difference in task-order control costs between both instruction groups ($p < 0.01$). *Left panel* costs for task 1. *Right panel* costs for task 2

by applying an ANOVA with the within-subjects factor block type (fixed-order block and random-order block) and session (session 1 with free-order instruction and session 2 with sequential-order instruction). This analysis revealed a main effect of the factor block type, $F(1, 23) = 148.70$, $p < .001$, $\eta_p^2 = .87$, suggesting that participants committed more task-order reversals in random-order blocks ($m = 26.59\%$) than in fixed-order blocks ($m = 3.18\%$). Furthermore, participants produced more task-order reversals in session 1 with the free-order instruction ($m = 22.22\%$) than on the session 2 with the sequential-order instruction ($m = 9.55\%$), $F(1,23) = 39.13$, $p < .001$, $\eta_p^2 = .63$. In addition, we also found a significant block type × session interaction, $F(1,40) = 9.36$, $p = .01$, $\eta_p^2 = .32$, revealing that the effect of block type differed between sessions. Pairwise comparisons revealed that the increase in task-order reversals from fixed- to random-order blocks was larger on session 1 with the free-order instruction ($m = 28.05\%$) compared to the session 2 with sequential-order instruction ($m = 18.75\%$), $t(23) = 2.18$, $p < .04$. Thus, on session 1, when receiving the free-order instruction on random-order blocks, participants performed both tasks with less reliance to the stimulus order compared to session 2 with the sequential-order instruction.

Under the free-order instruction, order reversal rates on random-order blocks ($m = 34.24\%$) differed significantly from a task-order reversal rate of 50% that one would expect if participants' processing order did only rely on their free order choice, $t(23) = 14.06$, $p < .001$. In line with the similar observation in Experiment 1, this pattern suggests that, in addition to their order choices, also the actual order of stimuli on a given trial influences participants' response order on random-order blocks with a free-order instruction. Nevertheless, task-order reversal rates on random-order blocks were still higher under the free-order instruction compared to the sequential-order instruction ($m = 18.93\%$), $t(23) = 6.30$, $p < .001$.

Task-order control costs

To test whether task-order control costs were reduced under the free-order instruction, we performed an ANOVA on RTs with the within-subjects factor tasks (task 1 and task 2), block type (fixed-order and random-order blocks), and session (session 1 with free-order instruction and session 2 with sequential-order instruction). This analysis revealed a significant main effect of the factor task, $F(1, 23) = 15.56$, $p < .001$, $\eta_p^2 = .40$. RTs for task 1 ($m = 1044$ ms) were faster than those for task 2 ($m = 1150$ ms, see Table 1). In addition, RTs from random-order blocks ($m = 1225$ ms) were slower compared to RTs from fixed-order blocks ($m = 969$ ms), $F(1, 23) = 110.26$, $p < .001$, $\eta_p^2 = .83$, indicating the occurrence of task-order control costs.

The main effect of session was not significant, $F(1, 23) < 1$, $p = .34$, $\eta_p^2 = .04$, showing that participants had no general practice effect across the experimental sessions. However, we found a significant block type × session interaction, $F(1, 23) = 11.98$, $p = .002$, $\eta_p^2 = .34$, suggesting that the RT difference between both block types, i.e., task-order control costs, generally differed between both sessions. Subsequent comparisons revealed that task-order control costs were increased in session 2 with the sequential-order instruction ($m = 314$ ms) compared to session 1 with the free-order instruction ($m = 198$ ms), $t(23) = 3.46$, $p < .01$ (see Fig. 4). This increase in task-order control costs was specifically driven by slower RTs in random-order blocks of session 2 relative to RTs in random-order blocks of session 1, $t(23) = 2.99$, $p < .01$ (DeJong, 1995; see also Hendrich et al., 2017, submitted). On fixed-order blocks, RTs did not differ between both sessions, $t(23) = 1.51$, $p = .15$. These finding are in line with the assumption that task instructions affect monitoring-based mechanisms of task-order regulation.

We also found a significant task × block-type interaction, $F(1, 23) = 9.46$, $p = .005$, $\eta_p^2 = .29$, reflecting a reduced RT increase from task 1 to task 2 in fixed- ($m = 90$ ms) relative to random-order blocks ($m = 124$ ms), $t(48) = 3.03$, $p = .004$. Similar to Experiment 1, this suggests that, within DT trials, participants are able to prepare the switch from task 1 to task 2 when the order of tasks is known beforehand (DeJong, 1995; Liepelt et al., 2011). The interaction task × session was also significant, $F(1, 23) = 4.26$, $p = .05$, $\eta_p^2 = .16$. Post-hoc comparison revealed that the RT increase from task 1 to task 2 was larger in session 1 ($m = 117$ ms) compared to session 2 ($m = 96$ ms), $t(23) = 2.07$, $p = .05$. The observation of reduced costs for task 2 on session 2 can be explained by improved intertask coordination due to practice on the session 2 (Liepelt et al., 2011). The triple interaction task × trial type × session was not significant ($p = .64$).

Order-switch costs

To test if order-switch costs were also modulated by instructions, we performed an ANOVA on RTs with the within-subjects factor tasks (task 1, task 2), trial type (same-order trial and different-order trial), and session (session 1 with free-order instruction and session 2 with sequential-order instruction). This analysis revealed a significant main effect of the factor task, $F(1, 23) = 18.18$, $p < .001$, $\eta_p^2 = .44$. As can be seen in Table 1, RTs for task 1 ($m = 1163$ ms) were faster than those for task 2 ($m = 1287$ ms). In addition, responses in different-order trials ($m = 1268$ ms) were slower compared to responses in same-order trials ($m = 1182$ ms), $F(1, 23) = 53.00$, $p < .001$, $\eta_p^2 = .70$, indicating the occurrence of order-switch costs. Furthermore, RTs in same- and different-order trials were faster on session 1 ($m = 1187$ ms) compared to session 2 ($m = 1264$ ms), $F(1, 23) = 8.96$ $p = .001$ $\eta_p^2 = .28$. Importantly, the interaction of trial type and instruction was not significant, $F(1, 23) = .10$, $p = .75$, $\eta_p^2 < .01$, suggesting that the RT differences between same- and different-order trials, i.e., order-switch costs, were unaffected by the instruction manipulation[2]. All other interactions were also not significant (all $ps > .08$).

[2] As in Experiment 1, we tested the posterior probability ($Pr(H_0|D)$) of a hypothesis assuming a missing interaction of the factors Instruction group and Trial type versus a hypothesis assuming a significant interaction of these factors by calculating the Bayesian information criterion (BIC). With $\Delta BIC = 3.07$ and $Pr(H0|D) = 0.82$ this analysis provides 'positive' evidence for the assumption that order-switch costs do not differ between the sequential- and the free-order instruction condition.

Discussion

The findings of Experiment 2 showed that (1) task-order control costs were reduced in conditions with the free-order compared to sequential-order instruction, (2) the reduction of task-order control costs was accompanied by lower RTs on random-order blocks under the free- relative to the sequential-order instruction (DeJong, 1995), and (3) order-switch costs did not differ between both instruction conditions. In addition to Experiment 1, by applying a yoked design, we demonstrated that the effect of instructions on task-order control costs occurred after controlling for different order-switch rates in both instruction conditions. Under the free-order instruction, participants switched their response order relative to the previous trial on 36.56% of trials from random-order blocks; under the sequential-order instruction, they switched their response order on 33.91% of trials, $\chi^2(1) = 1.53$, $p > .20$. Thus, the difference in task-order control costs between instruction conditions cannot be accounted for by different rates of response order switches. In addition, our results were not confounded by the applied sessionwise design of manipulating the instruction condition: RTs on random-order blocks were slower on session 2, with sequential-order instruction, compared to session 1 with free-order instruction. Thus, a potential practice effect would have counteracted against the hypothesis of increased RTs under sequential-order (session 2) compared to free-order (session 1) instruction condition.

General discussion

The aim of the present study was to disentangle the effect of instructions on task-order control and order-switch costs. For this purpose, participants performed DTs in fixed- and random-order blocks under two different instructions during random-order blocks: under the free-order instruction, participants could freely decide about the response order, while, in the sequential-order instruction, participants were instructed to respond to both tasks according to the order of stimuli. In two experiments, we demonstrated that task-order control costs, RT differences between fixed- and random-order blocks, were reduced under the free-order relative to the sequential-order instruction. Order-switch costs, the RT difference between same- and different-order trials, were unaffected by the instruction manipulation. In addition, in Experiment 2, we demonstrated that these effects cannot be accounted for by different rates of response order switches across both instruction conditions.

Task-order control costs and order-switch costs: the impact of instructions

Task-order control costs reflect monitoring-based mechanisms of task-order regulation, which can be observed when comparing DT performance in random-order compared to fixed-order blocks. According to Szameitat et al. (2002, 2006), the processing order of two tasks is regulated by a task-order control structure that represents a list of both tasks in a specific order. Performing a DT trial involves the implementation of the appropriate control structure in working memory, which then guides the processing order by sequentially activating the task sets of the component tasks. Similarly, Luria and Meiran (2003, 2006) proposed an order setting process that determines the processing order and takes place at the beginning of each DT trial. Because in fixed-order blocks, participants can employ the same scheduling strategy with the same activated order-control structure throughout the whole block, the demands on task-order regulation should be relatively low as compared to random-order blocks. In these latter blocks, the order of both tasks changes randomly from trial to trial, which causes that participants need to permanently change the task-order control structure and match it to the normative task-order specified by the order of stimuli. Therefore, to guarantee appropriate task performance, participants have to monitor the sequence of stimuli, make a decision on which stimulus was presented first, and activate the appropriate task-order control structure in random-order blocks much more frequently than in fixed-order blocks (Sigman & Dehaene, 2006; Stelzel et al., 2008; Strobach et al., 2015; Szameitat et al., 2002, 2006). As a result, RTs on random-order blocks were increased compared to RTs from fixed-order blocks, resulting in task-order control costs reflecting the occurrence of monitoring-based task-order regulation mechanisms.

Importantly, in random-order blocks under the free-order instruction, no normative task order is instructed and participants can freely decide about the response order. Consequently, participants do not have to engage monitoring processes to track the stimulus order and match the task-order control structure accordingly (DeJong, 1995). Instead, they can activate the task-order control structure based on their free order choice and can perform DTs with less reliance on monitoring-based mechanisms of task-order regulation. As we have shown in both experiments, these reduced demands on monitoring-based mechanisms result in decreased task-order control costs under a free-order compared to a sequential-order instruction.

Order-switch costs, the RT difference between same- and different-order trials, were not affected by the instruction manipulation. How can this lacking effect be explained? According to several authors (DeJong, 1995; Luria & Meiran, 2003, 2006; Schubert, 2008; Strobach et al., 2015; Szameitat et al., 2006), order-switch costs are associated with the pre-activation of task-order by an episodic memory structure of the previous DT trial: performing a DT trial results in the formation of a memory trace that contains information about the processing order and that is stored in episodic memory. This memory trace remains active over time and can influence the processing order on the next DT trial. In same-order trials, this results in a performance benefit, as the order of the previous trial is repeated, while in different-order trials, this results in impaired performance as the reactivated episodic memory structure needs to be overcome to switch the processing order of both tasks.

According to recent accounts, the ongoing activation of a task guiding memory structure seems to reflect a mechanism that inevitably (i.e., automatically) accompanies regular sensory-motor behavior. According to this understanding, the processing of any sensory-motor chain leads to an automatic storage of ‘stimulus–response’ event files in episodic memory, which will be activated in later episodes for guiding upcoming behavior (Hommel, 2004 see also Mayr, 2002). Most importantly, for the storage and activation of the episodic trace of task-order, it should not matter whether a certain response order is a result of a free- or a pre-determined (for the case of the sequential-order instruction condition) decision about task-order. The related order-switch costs should occur to the same degree, irrespective of whether participants have to match their task-order control structure to an externally pre-specified task order or whether they can freely decide about the processing order. In line with this assumption, we found that order-switch costs did not differ between the free- and the sequential-order instruction.

Extensions of former studies on task control

Several studies have already shown that task-order control costs (DeJong, 1995; Strobach et al., 2015; Stelzel et al. 2008; Szameitat et al., 2002) as well as order-switch costs (Luria & Meiran, 2003, 2006; Szameitat et al., 2006) are reliable characteristics of task-order control mechanisms during DT performance. However, evidence on the specific nature of these mechanisms has been scarce. In the study of DeJong (1995, see also Hendrich et al., 2017, submitted), the author could show that RTs from random-order DT blocks were lower when participants could freely decide about their response order than when they had to match the response order to the stimulus order. However, DeJong did not include fixed-order blocks nor did he investigate the effects of his order manipulation on same- and different-order trials, which makes it impossible to draw clear conclusions about how instructions influence the different mechanisms regulating and guiding task-order in DT situations.

The current study goes beyond earlier studies, because by including fixed-order blocks and by distinguishing between same-order and different-order trials, we disentangled the effect of different instructions on task-order control and order-switch costs within the same experiments and set of participants. In addition, we showed that the difference in task-order control costs cannot be explained by different rates of response order switches. In Experiment 1, we showed that when comparing random-order blocks with sequential- and free-order instructions, the rate of response order switches was reduced in the latter condition. This is in line with findings from studies with the voluntary task-switching paradigm that reported reduced frequencies of task switches (Arrington & Logan, 2005). As a result, the RT differences between the sequential- and the free-order instruction reported by DeJong (1995) as well as the differences in task-order control costs that we found in Experiment 1 could also be explained by different rates of order-switches in both instruction conditions. However, by applying a yoked design in Experiment 2, we demonstrated that task-order control costs differed between both instruction conditions, even if the frequencies of response order switches in the free- and sequential-order condition were controlled for. Thus, the difference in task-order control costs between both instructions cannot be accounted for by different-order-switch rates.

Order control in dual-task and task-switching situations

The assumption that task-order control and order-switch costs reflect distinct processes of task-order regulation is in line with evidence from task-switching studies. In the task-switching paradigm, participants perform single-task blocks, in which one task is repeated, and mixed-task blocks, in which one of two tasks is presented per trial and participants have to occasionally switch tasks (Kiesel et al., 2010). Similar to the current approach, two different types of costs can be distinguished. On a trial level, within mixed blocks, switching costs reflect the difference between task repetition and task switch trials (Rogers & Monsell, 1995). On a block level, mixing-costs reflect RT differences between single- and mixed-task blocks (Koch, Prinz, & Allport, 2005; Rubin & Meiran, 2005). In recent years, it has been suggested that mixing and switching costs represent distinct mechanisms of task control. Evidence for this assumption comes from studies showing that both types of costs can be dissociated on a behavioral level (e.g., Kray & Lindenberger, 2000) as well as from studies that found different neural correlates for both types of costs (Braver, Reynolds, & Donaldson, 2003). From this line of research, it has been assumed that switching costs reflect rather transient processes that are exclusively relevant for shifting from one task to another (Braver et al., 2003). Mixing-costs, on the other hand, seem to reflect rather sustained components of cognitive control that ensure flexible switching between tasks, such as engaging attentional monitoring processes that are sensitive to information signaling task changes (Koch et al., 2005; Rubin & Meiran, 2005). Such sustained control processes would be equivalent to the monitoring-based mechanisms necessary to regulate the processing order of two tasks in random-order DT blocks. In mixed blocks as well as random-order blocks, participants have to maintain different task sets and task-order control structures, respectively. In addition, they have to collect information on which task or which task-order to execute and employ attentional processes accordingly. Thus, mixing-costs and task-order control costs may reflect similar global and sustained control processes that are necessary to flexibly adapt to changing task demands in multitasking situations.

Conclusion

To conclude, we investigated the effect of instructions on additional mechanisms that arise in DT situations with varying task-order. We demonstrated that task-order control costs were reduced under a free-order compared to a sequential-order instruction. This type of costs that occurs on a block level seems to reflect global monitoring-based mechanisms of task-order regulation, such as employing monitoring processes and activating an appropriate task-order control structure in working memory. Contrarily, order-switch costs, that occur on a trial level and reflect memory-based mechanisms of task-order guidance, were not affected by the instruction manipulation. Based on this dissociation, we conclude that both types of costs reflect distinct mechanisms that regulate and guide the processing order of two tasks in DT situations.

Compliance with ethical standards

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Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

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